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PHYSICS
MATTERS

GCE 'O' Level

Textbook

5th
Edition

Dr Charles Chew

Dr Ho Boon Tiong

Low Beng Yew

Yeow Kok Han

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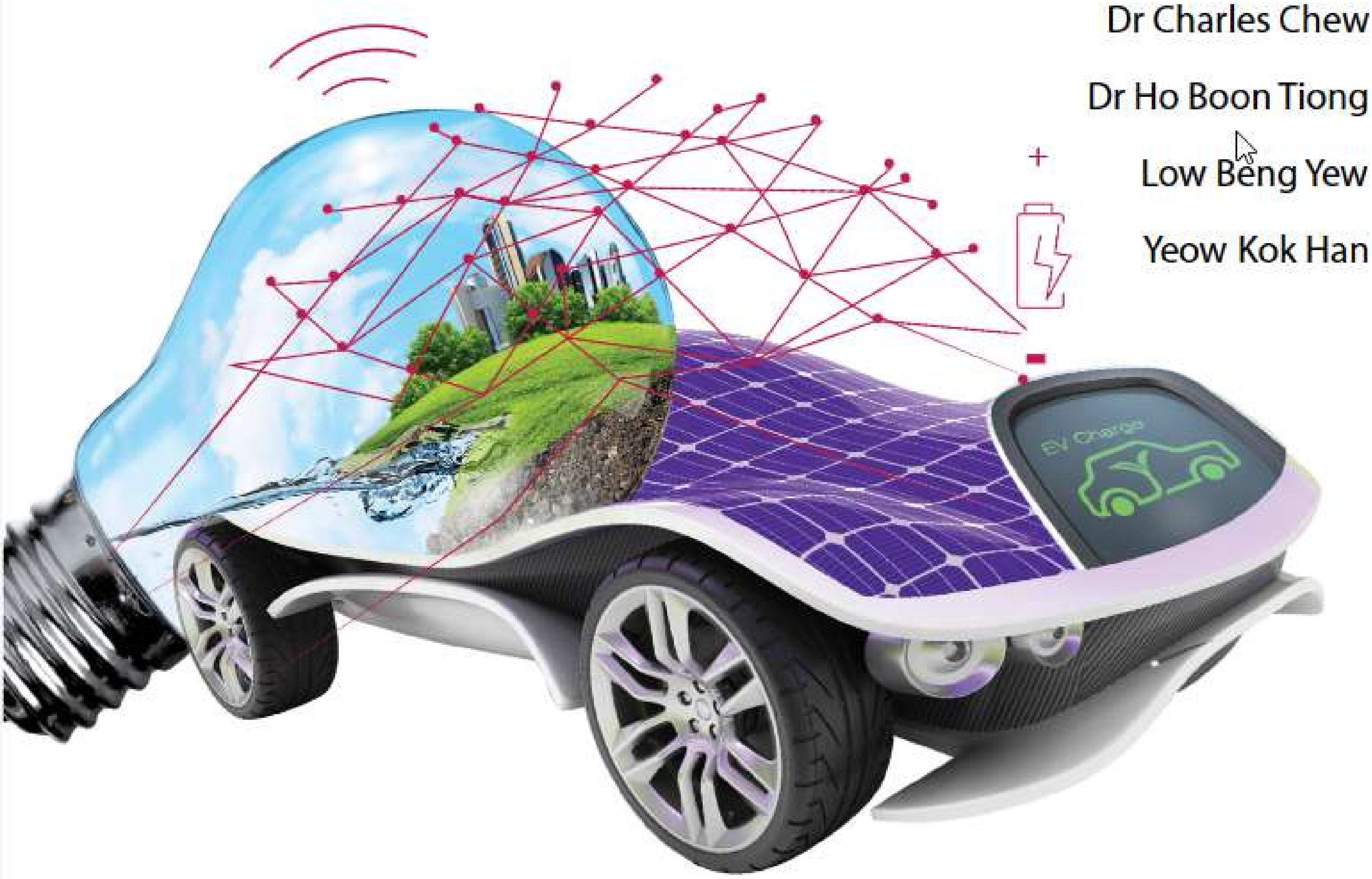

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About the Physics Matters Author Team

Dr Charles Chew

Dr Charles Chew was a Public Service Commission Teaching Scholar who joined the Singapore education service in 1986. In his 36 years of education service, he has had a wide range of experiences where he served as a junior college teacher, a head of department and the Vice-Principal of a secondary school, a Teaching Fellow at the National Institute of Education (NIE) and a Principal Master Teacher at the Academy of Singapore Teachers.

Beyond Singapore, Charles has served as the Singapore Governing Board Member for the SEAMEO QITEP Science from 2009 to 2011 and Singapore representative for the SEAMEO INNOTECH Regional Forum in Manila in 2019.

Charles has also co-authored an instructional package for IGCSE Physics. Besides being an established author of physics textbooks, he has also published journal articles and book chapters in the areas of physics education, inquiry-based learning and pedagogical content knowledge. For his valuable contributions rendered to the field of education, Charles was conferred the Public Administration Medal.

Dr Ho Boon Tiong

Dr Ho Boon Tiong is the Principal Consultant Educationist of an educational training and consulting firm for the past 16 years. He was an Assistant Professor with the Natural Sciences and Science Education academic group of the National Institute of Education (NIE). He obtained his Diploma-in-Education (with credit) in 1986 and holds a Master of Education degree, specialising in effective schools' research and management. He is also a Doctor of Philosophy in the field of Science teacher education, particularly in the domain of pedagogical content knowledge (PCK). Dr Ho has also co-authored an instructional package for IGCSE Physics.

Low Beng Yew

Beng Yew has been teaching in Temasek Polytechnic since 2012. His approach to teaching is to seek out the misconceptions that students have and understand their learning difficulties. Beng Yew has authored two conference papers and a textbook, and was a recipient of the Temasek Polytechnic School of Engineering Teaching Award. Prior to teaching, Beng Yew worked in the corporate world for about 20 years, and his experience ranged from semiconductors to financial software to polymers.

Yeow Kok Han

Kok Han received a Public Service Commission scholarship to study physics at the University of Oxford. After his training at the National Institute of Education, he was posted to Tampines Junior College as a physics teacher. In the next 15 years, he learnt how to teach physics better from both students and colleagues. He left the teaching service as Physics Level Head in 2012. After some years of exploring other projects and adjunct teaching, he resumed teaching physics full time at SIM International Academy. Currently, he is doing flexi-adjunct teaching.

Joan Fong

Joan Fong taught physics at Raffles Junior College for 15 years and at St Joseph's Institution for 10 years. During her tenure as distinguished physics teacher, she mentored hundreds of students to excel in their A-level and S-paper physics. Joan also mentored and coached specially selected students who participated in the International Physics Olympiad. The individual members of the Physics Olympiad Team won the gold, silver and bronze awards. A life-long learner and passionate educator, Joan has written physics textbooks since 1980, including the Exploring Science and Lower Secondary Science Series.

Dr Randall Cha

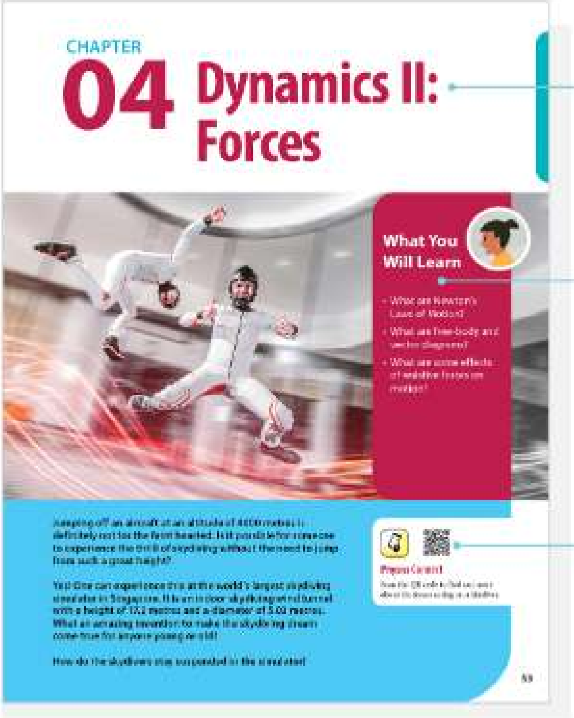
Dr Cha has a Doctorate in Electrical and Computer Engineering from the National University of Singapore. Dr Cha has authored more than 20 international journals and conference papers, and published several assessment books on physics. A STEM expert and an avid inventor with numerous worldwide patents under his name, he has also served as a technical advisor to various high-tech companies. He has also worked with MOE as a physics teacher. Dr Cha was conferred the Crescendas Medal and Prize for Outstanding Physics Lecturer (Polytechnics) in December 2015.

Tan Kay Yew

Kay Yew was awarded a teaching scholarship from the Public Service Commission Singapore to study physics at the National University of Singapore. He has 20 years of teaching experience in different learning institutes, and his passion for education focuses on the academic excellence and holistic development of students. Over the years, he has learned and used diverse techniques and strategies to teach young adults to acquire knowledge, skills, and attitudes in a changing learning landscape. He was conferred the Crescendas Medal and Prize for Outstanding Engineering Physics Lecturer (Polytechnics) in December 2016.

About This Book

The **Physics Matters for GCE 'O' Level Textbook (5th Edition)** is aligned with the latest GCE 'O' Level syllabus by the Ministry of Education. Designed for effective concept development and reinforcement, the Textbook includes tasks and activities at appropriate junctures for students to apply their critical and creative thinking skills. Real-life contexts, infographics and integrated videos and simulations are used to enhance learning and make Physics come alive.



CHAPTER 04 Dynamics II: Forces

What You Will Learn

Chapter Opener introduces the topic with engaging real-life contexts and trigger questions.

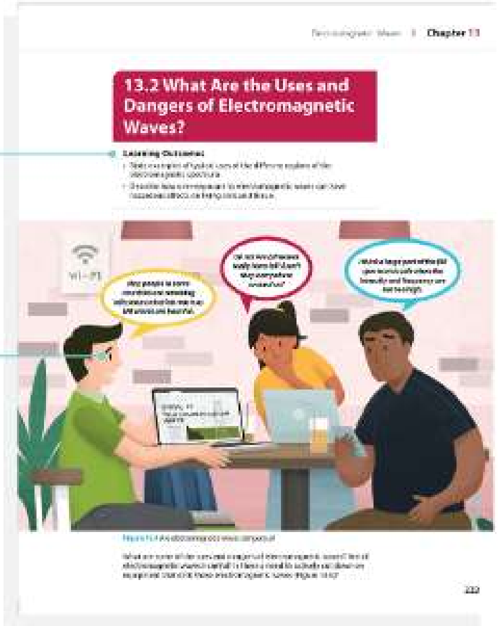
What You Will Learn provides an overview of the sections to be covered in the chapter in the form of inquiry questions.

Physics Connect allows students to scan the QR codes to access complimentary digital resources* such as videos and simulations that are interesting and informative, making science truly come alive.

* The digital resources used in Physics Connect have not been reviewed or endorsed by the Singapore Ministry of Education.

Learning Outcomes list the learning objectives at the start of each section to keep students focused.

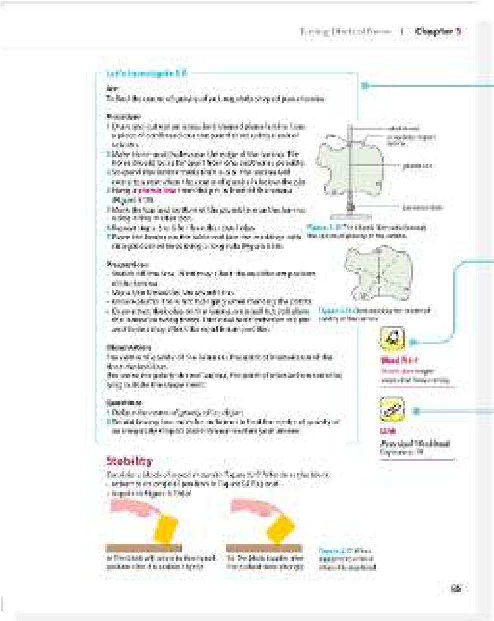
Concept Cartoon challenges students' ideas, triggers discussions and aids in clearing misconceptions.



Chapter 13

13.2 What Are the Uses and Dangers of Electromagnetic Waves?

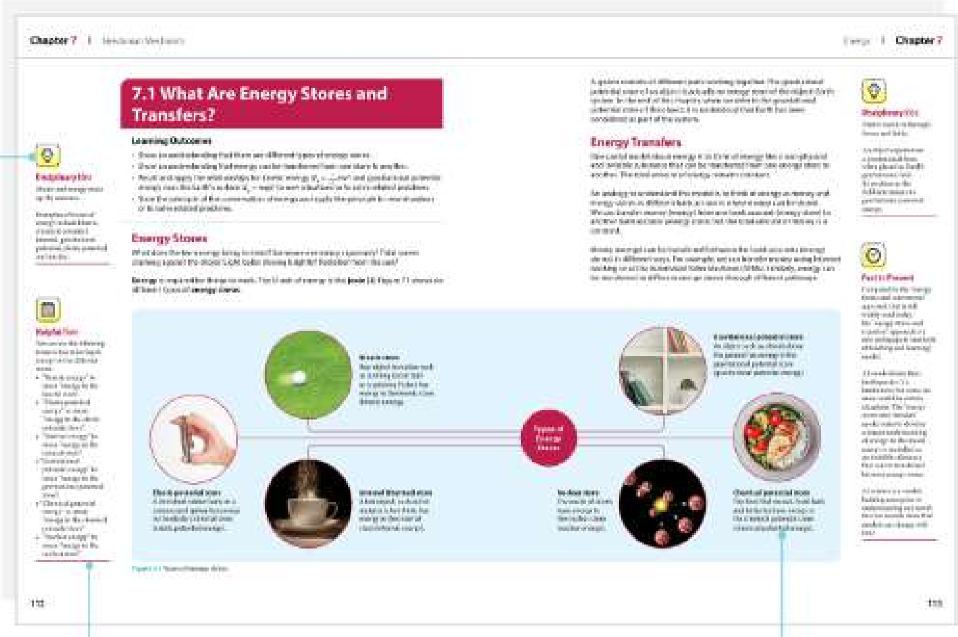
About This Book



Let's Investigate reinforces concepts through investigative procedures or hands-on activities.

Word Alert provides language support by supplying brief definitions of words that students may find challenging.

Link <to Theory Workbook/Practical Workbook> allows for seamless learning and reinforcement of concepts across the Textbook, Theory Workbook and Practical Workbook.



Disciplinary Ideas highlight the overarching ideas of Physics that can be applied to explain real-life problems or phenomena. The Disciplinary Ideas are:

- Matter and energy make up the Universe.
- Matter interacts through forces and fields.
- Forces help us understand motion.
- Waves can transfer energy without transferring matter.
- Conservation laws constrain the changes in systems.
- Microscopic models can explain macroscopic phenomena.

Helpful Note highlights misconceptions, tips and additional information to support students' learning.

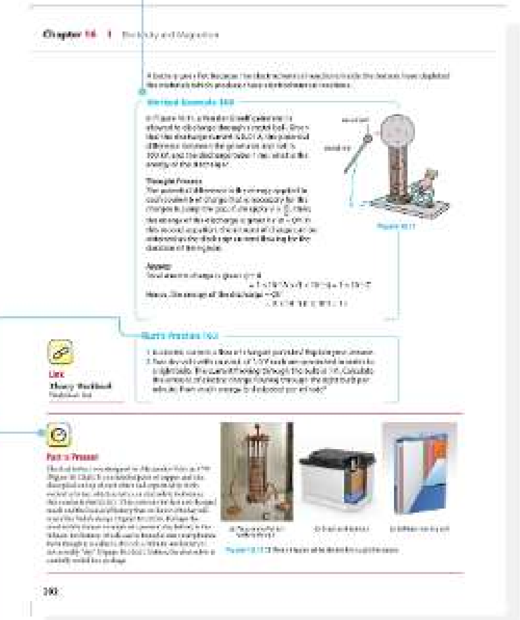
Infographics and stepwise presentations help students visualise abstract concepts and break down difficult concepts into bite-sized information that is easy to understand.

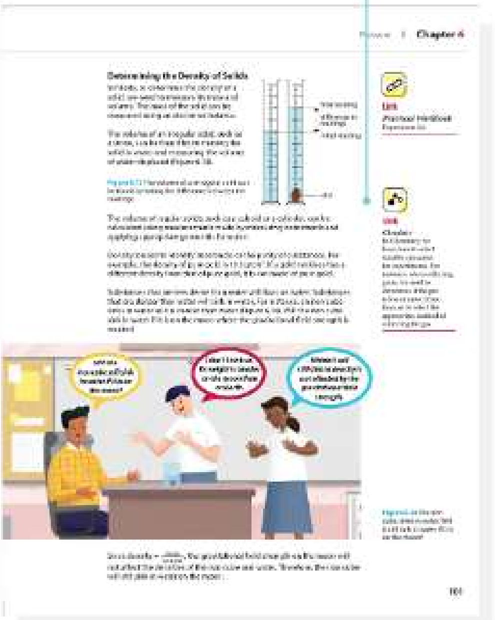
Worked Example guides students on how to interpret a question and work out the solution.

Link <to Chemistry/Biology> allows students to appreciate the interconnectedness of concepts between the various science subjects.

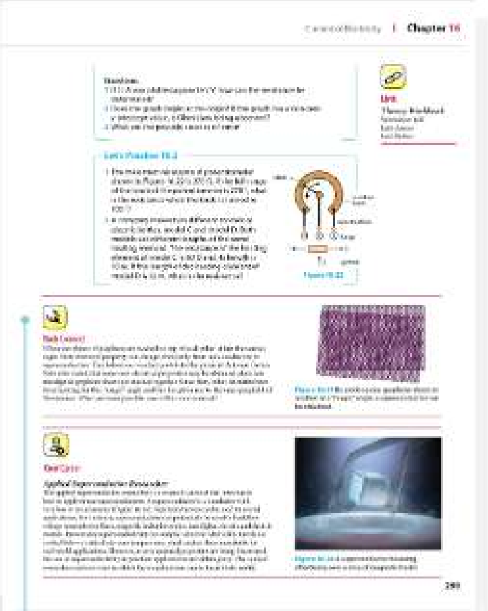
Let's Practise prompts immediate checks on understanding at the end of the section and facilitates the reinforcement of key concepts.

Past to Present inspires the spirit of scientific inquiry through examples of scientific innovation and the evolution of scientific developments over time, demonstrating the nature of science.





Link <forward/ backward> shows connections across chapters by linking back to students' prior learning and linking forward to prepare them for related chapters they will learn later.

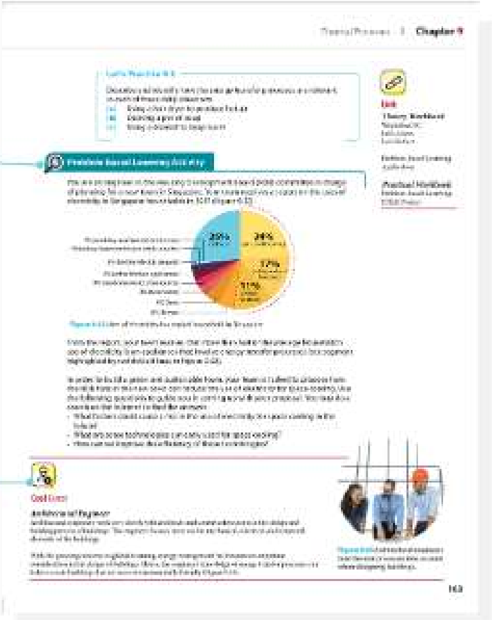


Tech Connect showcases cutting-edge technology used for the benefit of life, society and the environment. Critical thinking questions are included to encourage independent research and discussion.

About This Book

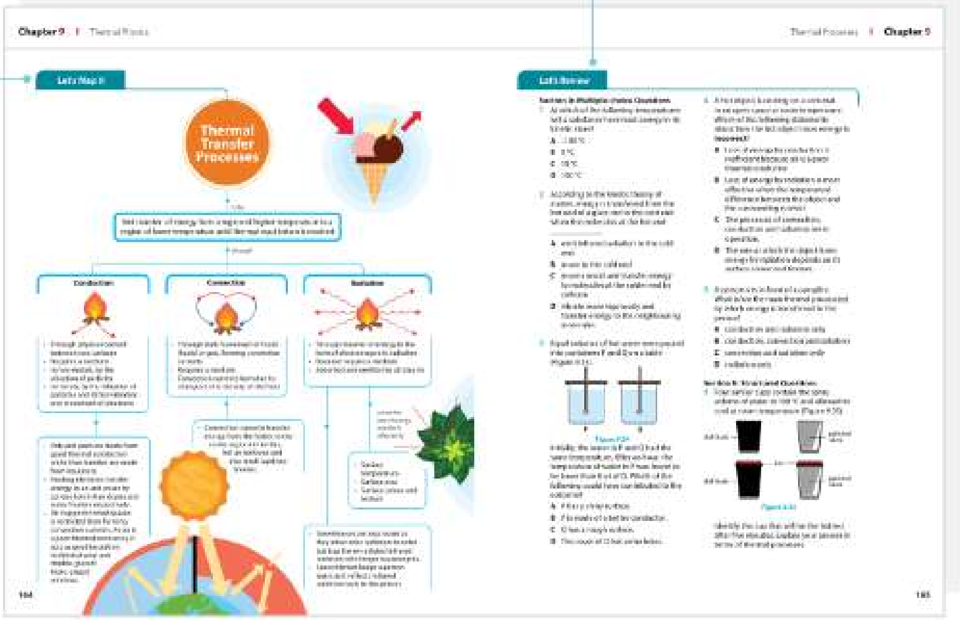
Problem-based Learning Activity hones problem-solving skills by encouraging students to develop solutions to a real-life problem.

Cool Career showcases a career related to the topic to inspire students and show them the relevance of science in the workplace.



Let's Review provides questions at the end of the chapter for students to review their understanding of concepts.

Let's Map It summarises the relationships between key concepts in the chapter through a visual concept map.



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

Answer Key lists the answers to Let's Practise and Let's Review (only answers to multiple-choice questions and numerical answers are included).

Quick Revision Guide consolidates key definitions and formulae at the back of the book for easy revision.

Index provides a list of key words with page references for easy searching.

Contents

*Chapters with Problem-based Learning Activities

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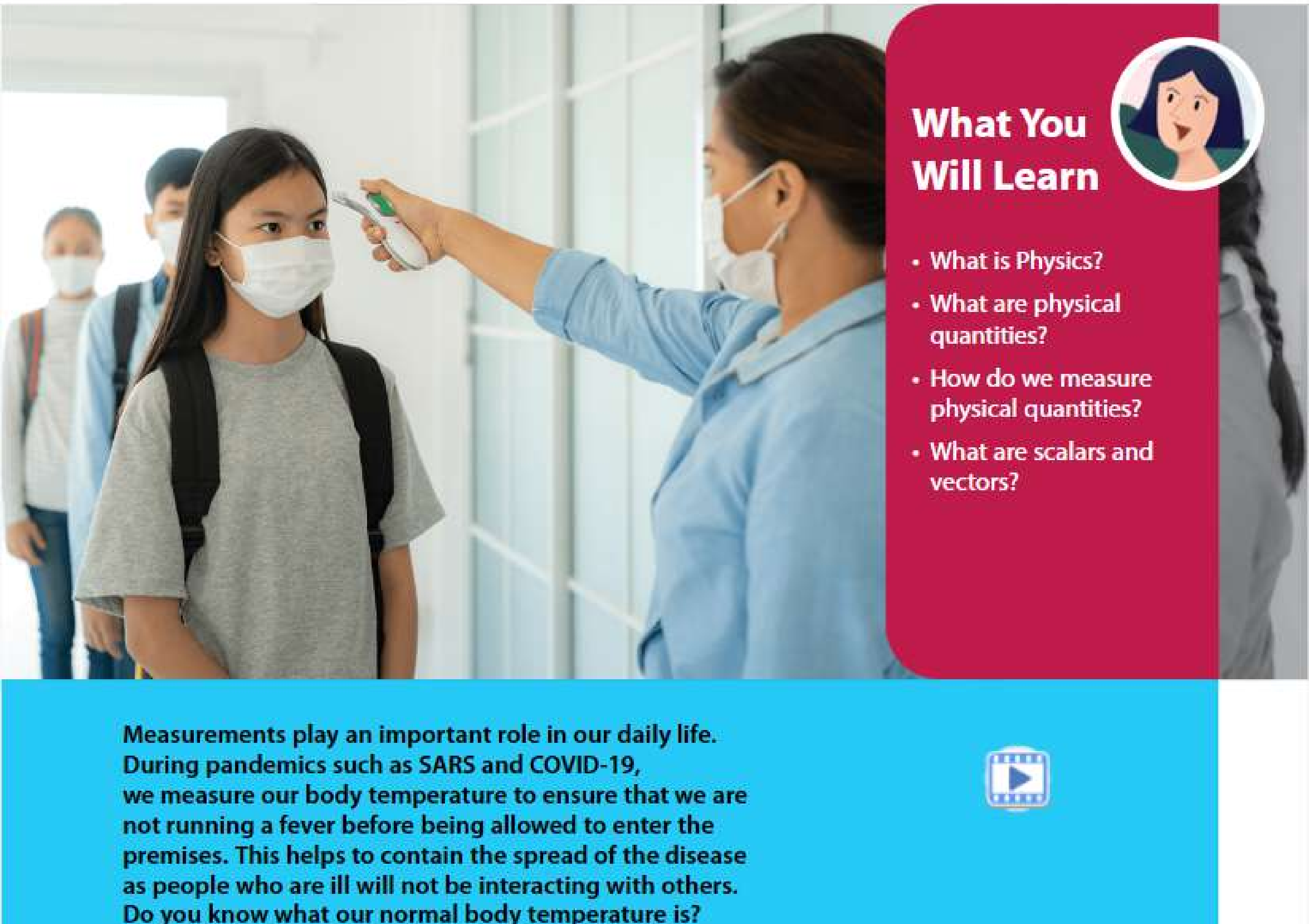
CHAPTER

01

Physical Quantities, Units and Measurements



What You Will Learn

- What is Physics?
- What are physical quantities?
- How do we measure physical quantities?
- What are scalars and vectors?

Measurements play an important role in our daily life. During pandemics such as SARS and COVID-19, we measure our body temperature to ensure that we are not running a fever before being allowed to enter the premises. This helps to contain the spread of the disease as people who are ill will not be interacting with others. Do you know what our normal body temperature is?

Using a measuring instrument such as a thermometer enables scientists to gather information about a physical quantity such as temperature. Besides temperature, there are other physical quantities. An example of a physical quantity is mass. What are other examples of physical quantities?

1.1 What Is Physics?

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 can be divided into major topics such as the ones shown in Figure 1.1. These topics are related to two main ideas — matter and energy.

The Disciplinary Ideas of Physics highlight the overarching ideas of Physics that can be applied to explain real-life problems or phenomena. The Disciplinary Ideas are:

- Matter and energy make up the Universe.
- Matter interacts through forces and fields.
- Forces help us understand motion.
- Waves can transfer energy without transferring matter.
- Conservation laws constrain the changes in systems.
- Microscopic models can explain macroscopic phenomena.

We will revisit the Disciplinary Ideas at relevant junctures of the book.

Disciplinary Idea

Matter and energy make up the Universe.

Mass is a property that we use to quantify the amount of matter. Energy is another physical quantity that has universal relevance and importance.

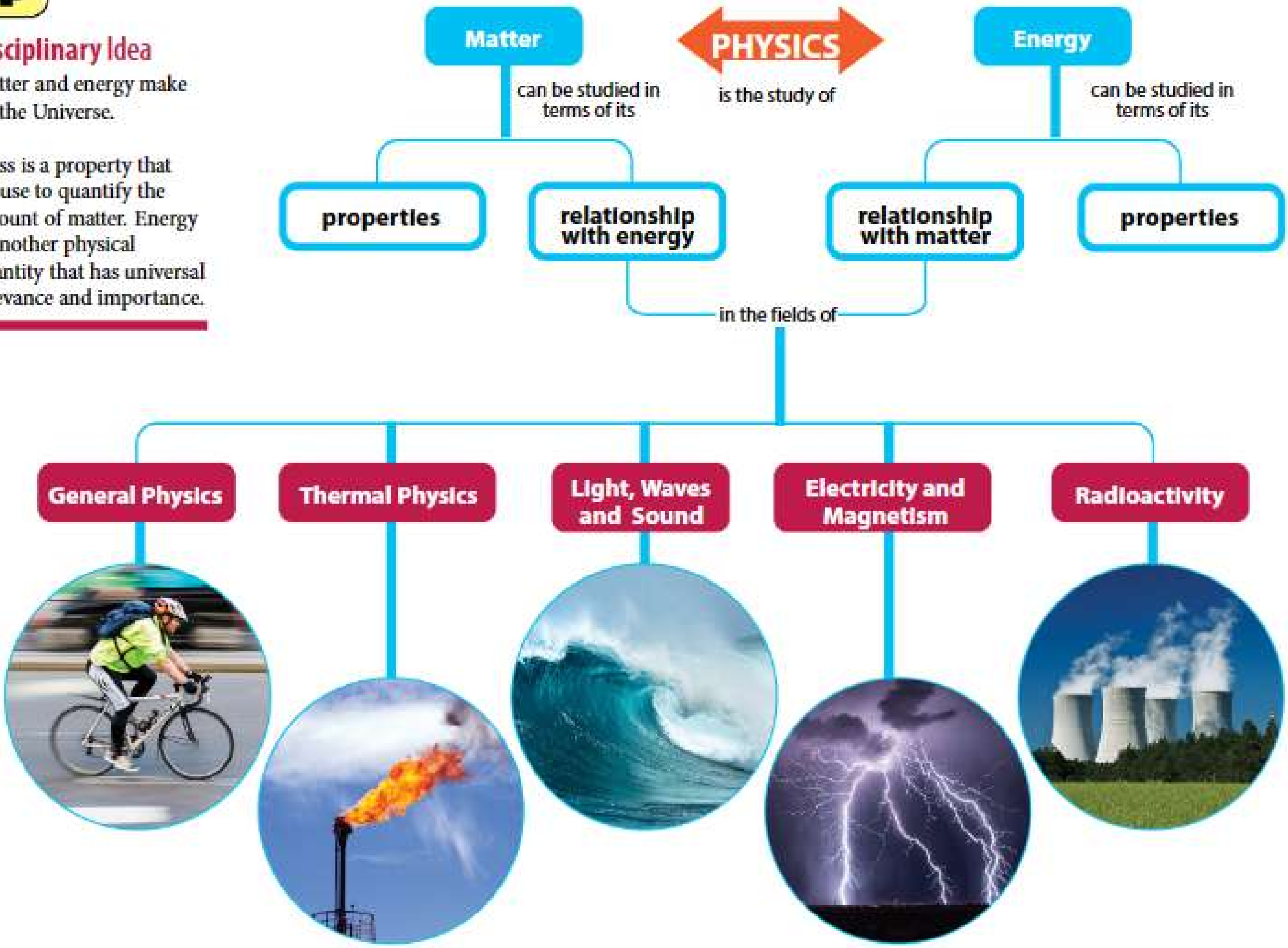


Figure 1.1
Overview of the study of Physics

The knowledge we have gained in Physics is the result of the collaborative work of many scientists over a long period of time. These scientists conducted many experiments to verify their ideas on matter and energy. When they carry out experiments, they need to make accurate measurements to obtain reliable results. At the same time, scientists use models to explain scientific observations and theories.

1.2 What Are Physical Quantities?

Learning Outcomes

- Show an understanding that physical quantities typically consist of a numerical magnitude and a unit.
- Recall the following base quantities and their units: mass (kg), length (m), time (s), current (A), temperature (K), amount of substance (mol).
- Use the following prefixes and their symbols to indicate decimal sub-multiples and multiples of the SI units: nano (n), micro (μ), milli (m), centi (c), deci (d), kilo (k), mega (M), giga (G), tera (T).

When travelling around Singapore, you may have noticed that overhead bridges have a sign with "4.5 m" printed on them. In Physics, height is a physical quantity — "4.5" is the numerical magnitude and 'm' is the unit (Figure 1.2).

Figure 1.2 This sign found on an overhead bridge warns drivers of vehicles above the height of 4.5 m not to pass underneath it.

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

Altogether, there are seven basic physical quantities, or base quantities. We use a system of standardised units called **SI units** or the International System of Units (abbreviated SI from French: *Système International d'Unités*).

Why do we need SI units? In the past, people used parts of their bodies and things around them for taking measurements. However, it created confusion because such measurements varied from individual to individual since the lengths of the parts of the bodies are different. The adoption of a universal set of units such as the SI units ensures that we follow a common standard when taking measurements.

Table 1.1 shows some base quantities and their corresponding SI units.

Table 1.1 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
amount of substance	mole	mol

Disciplinary Idea

Matter and energy make up the Universe.

In making physical measurements, a common system of units (e.g. SI units) is needed. For example, the SI unit for mass is the kilogram (kg), and the SI unit for energy is the joule (J).

Link

Chemistry

In Chemistry, we learn that the mole is the unit of the amount of substance. One mole contains 6.02×10^{23} particles. These particles may be electrons, atoms, ions, or molecules. The value 6.02×10^{23} is called the Avogadro's constant.

Other common physical quantities such as area, volume and speed are derived from these base quantities through an equation. For example, speed is defined as distance travelled per unit time (Speed = $\frac{\text{distance travelled}}{\text{time}}$).

Prefixes for SI Units

Using decimal notation, the distance between air molecules can be expressed as 0.00 000 001 m. If we need to mention this quantity often, it would not be efficient 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.

$\frac{1}{1\ 000\ 000}$ of a metre
= 0.000 001 m
= 1×10^{-6} m
= 1 µm (micrometre), where µ represents the submultiple 10^{-6}

When measuring long distances such as 1 000 000 000 000 metres, we simply express it as one terametre.

1 000 000 000 000 metres
= 1×10^{12} m
= 1 Tm, where T represents the multiple 10^{12}

The prefixes listed in Table 1.2 are useful for expressing physical quantities that are either very big or very small.

Table 1.2 Some common prefixes and their symbols

	Factor	Prefix	Symbol
Multiples	10^{12}	tera-	T
	10^{9}	giga-	G
	10^{6}	mega-	M
	10^{3}	kilo-	k
Sub-multiples	10^{-1}	deci-	d
	10^{-2}	centi-	c
	10^{-3}	milli-	m
	10^{-6}	micro-	µ
	10^{-9}	nano-	n

Helpful Note

A common unit of temperature is the degree Celsius. Temperatures in degree Celsius can be expressed in kelvin using this relationship:
Temperature in kelvin
= temperature in degree Celsius + 273

Disciplinary Idea

Matter and energy make up the Universe.

The measurement of various physical quantities like height, force and velocity helped us experiment and theorise. Eventually, we could identify the relationships between physical quantities and how these relationships lead to concepts of inertia and energy.

Word Alert

Prefixes: letters placed in front of words to make new words

Standard Form

Another convenient and acceptable way of expressing physical quantities is to use the standard form. A **standard form** is a way of writing numbers, in which a number between 1 to 10 is multiplied by an appropriate power of 10. For example, the following numbers are expressed in standard form as shown.

$0.00\,567 = 5.67 \times 10^{-3}$
$16\,800 = 1.68 \times 10^{4}$

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:

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

Worked Example 1A

The world's smallest playable guitar is 13 μm long. Express the guitar's length in standard form.

Answer

13 μm = 0.000 013 m = 13×10^{-6} m = 1.3×10^{-5} m
Expressed in standard form, the guitar's length is 1.3×10^{-5} m.

Worked Example 1B

Usain Bolt of Jamaica broke the 100 m sprint world record at the 2009 World Athletic Championships, with a time of 9.58 s. With this record, he became the world's fastest man. In contrast, a dog runs at a speed of 30 km/h. If a dog chases Usain Bolt, will it be able to catch up with him?

Answer

Note: First, we need to calculate the average speed of Usain Bolt.

$$\text{Average speed} = \frac{\text{distance}}{\text{time}} = \frac{100\text{ m}}{9.58\text{ s}} = 10.4\text{ m/s}$$

Note: To make meaningful comparison, the units of the values compared must be the same.

$$\text{Average speed} = \frac{100\text{ m}}{9.58\text{ s}} = \frac{\frac{100}{1000}\text{ km}}{\frac{9.58}{3600}\text{ h}} = 37.6\text{ km/h}$$

Since 37.6 km/h is greater than 30 km/h, Usain Bolt will outrun the dog over a distance of 100 m.

Let's Practise 1.1 and 1.2

1 Give **three** examples of base quantities and their SI units.
2 Express the Avogadro's number, 602 200 000 000 000 000 000 000, in standard form. Round off your answer to two decimal places.

Link
Theory Workbook
Worksheet 1A

1.3 How Do We Measure Physical Quantities?

Learning Outcomes

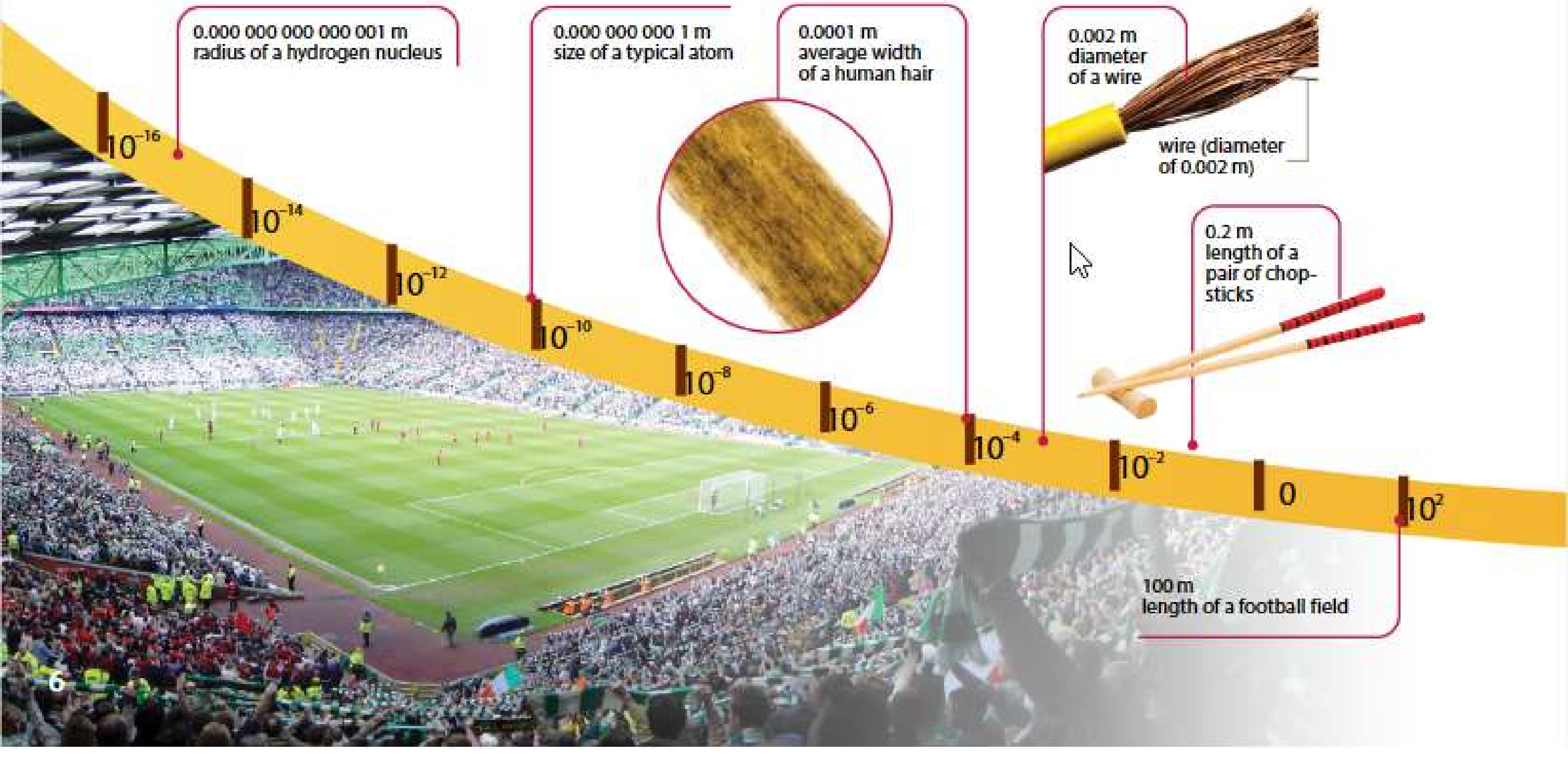
- Show an understanding of the orders of magnitude of the sizes of common objects.
- Select and explain the use of appropriate measuring instruments to measure or determine physical quantities.

Measurement of Length

We should use the appropriate instruments and methods to measure different types of length (Figure 1.3). The SI unit for length is the **metre (m)**. There is a wide range of lengths in this world (Figure 1.4).

Figure 1.3 Measuring the diameter of a tree trunk

Figure 1.4 We need to measure a wide range of lengths as the objects around us range from the very big to the very small.



Metre Rule and Measuring Tape

The metre rule and measuring tape are instruments that are commonly used to measure length (Figure 1.5). 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. A cloth measuring tape is suitable for measuring the length along a curved surface, such as a person's waist or the diameter of a tree trunk.

Figure 1.5 A metre rule and a retractable steel measuring tape are used to measure length.

Digital Calipers

The digital calipers are used to measure the internal and external diameters of an object accurately (Figure 1.6). The object is gripped gently using the jaws of the digital calipers and the diameter of the object is shown on the digital display.

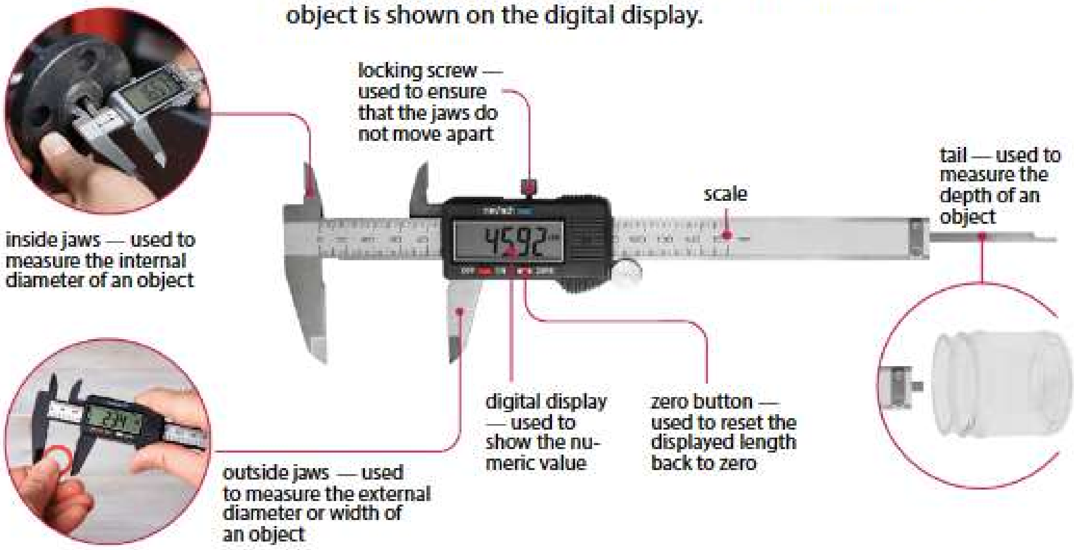
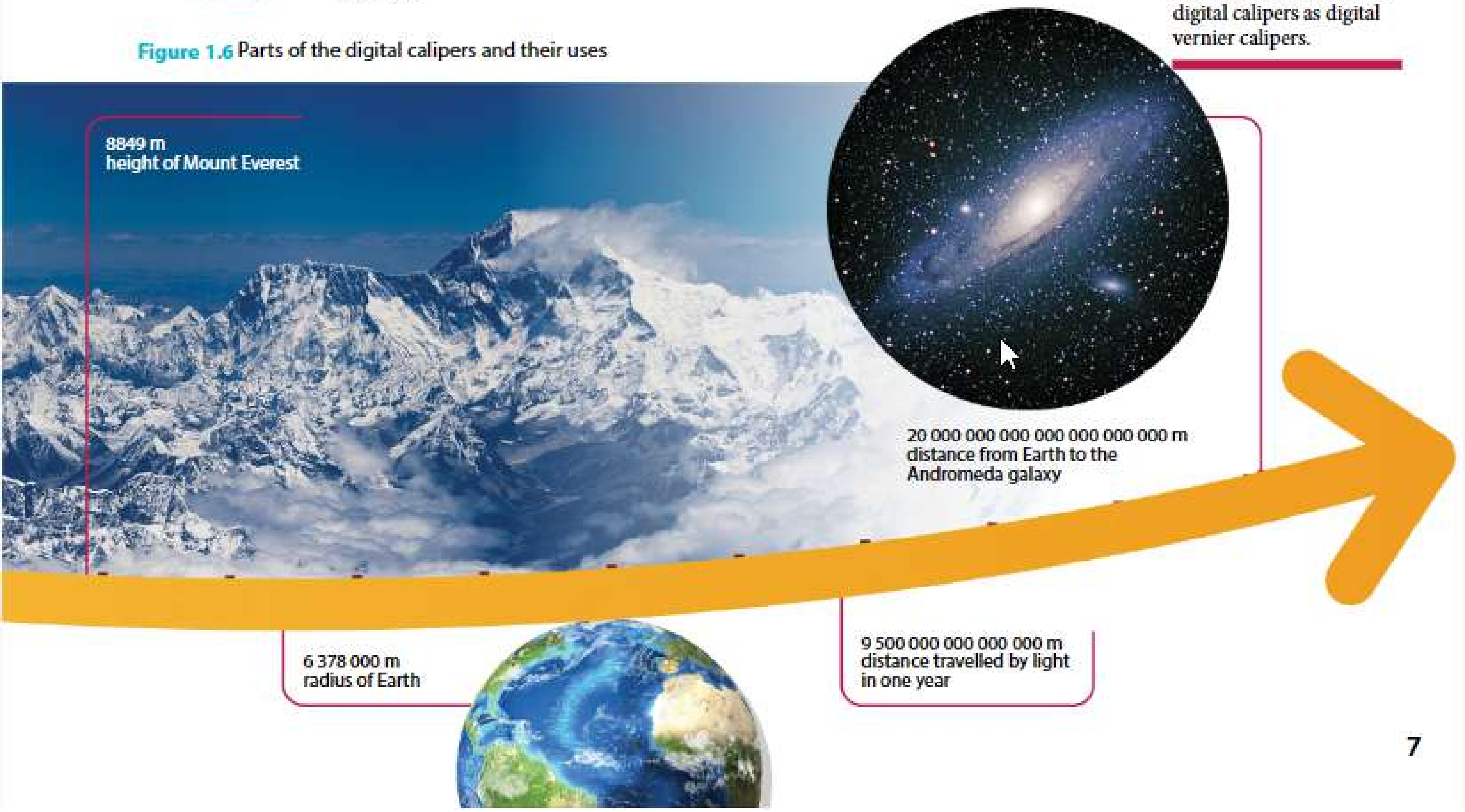


Figure 1.6 Parts of the digital calipers and their uses

Helpful Note

The digital calipers are sometimes incorrectly called the digital vernier calipers. Vernier calipers require users to read off the main scale and the vernier scale of the instrument. However, users using the digital calipers do not have to read off the vernier scale. Take note not to refer the digital calipers as digital vernier calipers.



Link

Practical Workbook
Experiment 1A

Digital Micrometer Screw Gauge

The digital micrometer screw gauge is used to measure objects that are too small to be measured using the digital calipers (Figure 1.7). The object is placed between the anvil and spindle of the digital micrometer screw gauge. The ratchet is turned until the spindle is in contact with the object. We need to ensure that the object is held tightly between the anvil and spindle. Do not tighten the ratchet too much.

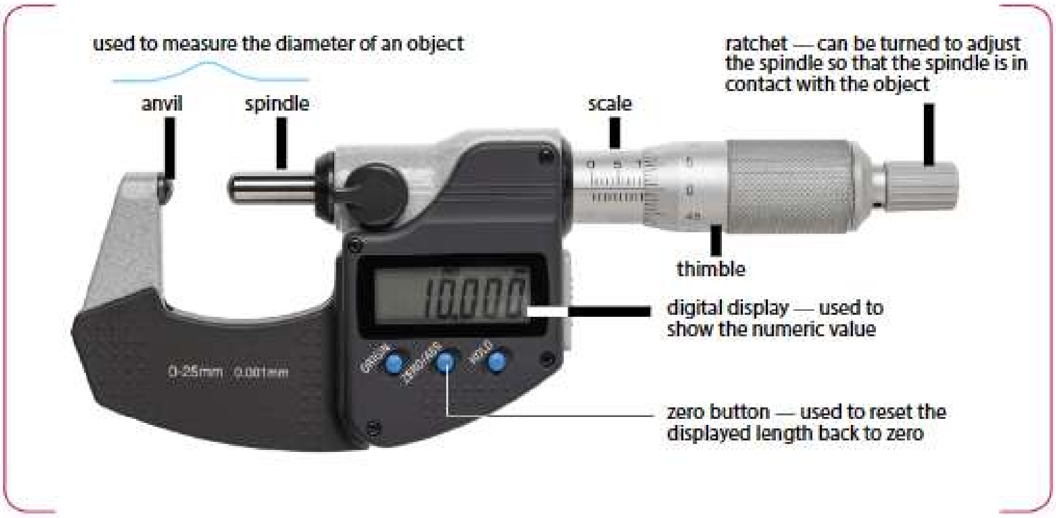


Figure 1.7 Parts of the digital micrometer screw gauge and their uses

Helpful Note

The digital displays of digital calipers and digital micrometer screw gauge show two to three decimal places in mm. To account for other more significant sources of error when using the instruments, we can record the measurement on the digital calipers to 0.1 mm and the measurement on the micrometer screw gauge to 0.01 mm.

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, we cannot directly measure the paper's thickness using a metre rule. We will have to estimate its thickness (Figure 1.8).

Figure 1.8 To estimate the thickness of a sheet of paper, we could measure the thickness of a stack of paper and then divide the thickness by the number of sheets in that stack.

Table 1.3 shows the measuring range, smallest division as well as the common usage of the measuring instruments.

Table 1.3 Common measuring instruments with their range, smallest division and usage

Instrument	Measuring Range	Smallest Division	Example of Usage
measuring tape	zero to several metres	0.1 cm or 1 mm	a person's waist
metre rule	zero to one metre	0.1 cm or 1 mm	height of a table
digital calipers	zero to 15 centimetres	0.001 cm or 0.01 mm	diameter of a test tube
digital micrometer screw gauge	zero to 2.5 centimetres	0.0001 cm or 0.001 mm	diameter of a wire

Link

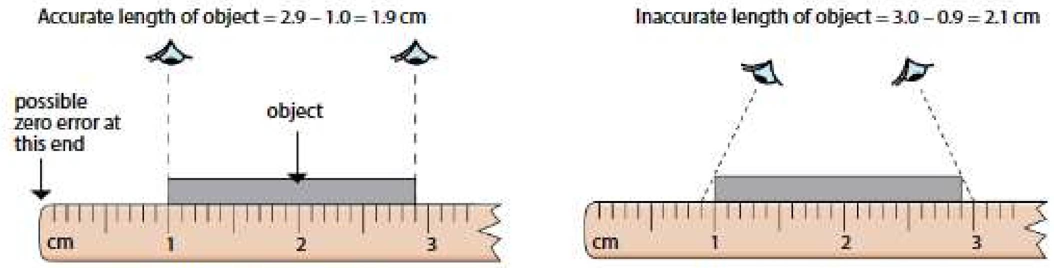
Chemistry
In Chemistry, we learn that there are various pieces of apparatus for measuring volumes of liquids. The measuring cylinder measures to the nearest 0.5 cm^3 while the burette measures to the nearest 0.05 cm^3. The pipette measures out fixed volumes of liquids.

When recording the measurements, we can record the measurements shown on the digital display of:

- the digital calipers to 0.1 mm; and
- the digital micrometer screw gauge to 0.01 mm.

Avoiding Errors of Measurement

When we use a metre rule, our eyes should be positioned such that our line of sight is perpendicular to (directly above) the rule (Figure 1.9(a)). Measurement errors introduced when this is not done are called **parallax errors** (Figure 1.9(b)).



(a) Accurate measurement (b) Inaccurate measurement

Figure 1.9 How to take accurate readings by avoiding parallax errors

A metre rule may have its zero marks at the very end of the rule. Wear and tear of the metre rule may make this mark unsuitable for measuring purposes. This worn end may introduce errors to the readings. Hence, it is better to measure from another point and subtract it from the final reading (Figure 1.9(a)). Taking several readings and calculating the average also minimises errors.

Measurement of 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 the 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.

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

Pendulum

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 (Figure 1.10).

▶ Each complete to-and-fro motion is one **oscillation**.

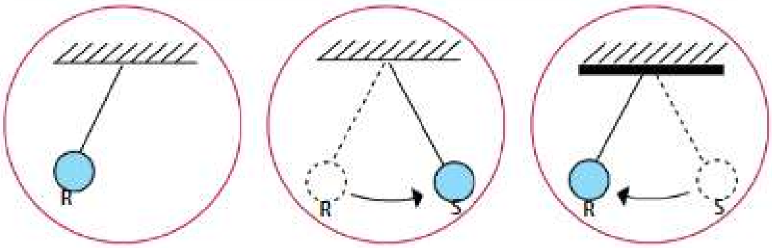


Figure 1.10 When the bob moves from R to S and back to R, the pendulum completes one oscillation.

Helpful Note

There are two types of observational errors — random error and systematic error.

Random error varies unpredictably from one measurement to another. Systematic error is constant and not random. It has the same value for every measurement.

Random errors are unavoidable, but cluster around the true value. Systematic error can often be avoided by calibrating equipment, but if left uncorrected, can lead to measurements far from the true value.

Word Alert

Calibrated: adjusted with reference to a known value

▶ 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 must be precisely measured. The period of the oscillations must not change. Most modern timepieces are calibrated using precise timekeeping devices called atomic clocks.

Figure 1.11 This atomic clock measures time to an accuracy of one second in two million years.

Pendulum Clock

All timepieces use 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 power.

Depending on the accuracy and precision needed, the instruments used will vary. For example, we would not use an analogue watch to measure the time taken for a runner to run a 100 m race, but we will use a digital stopwatch instead.

Human Reaction Time

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, unlike the electronic sensors used in data loggers, stopwatches need to be started and stopped by hand. This manual operation introduces a *random error* called human reaction time. Human reaction time is about 0.3–0.5 s for most people.

Past to Present

In 1949, Harold Lyons and his team at the National Bureau of Standards (now known as National Institute of Standards and Technology) invented the atomic clock. The first atomic clock invented was less accurate than existing quartz clocks. Harold Lyons and his team improved on their design and created the caesium atomic clock (Figure 1.11).

The atomic clock was invented out of need for a timing standard that would allow radio stations to stay on their assigned frequency. It is used as the primary standard for international time.

Let's Investigate 1A

Aim

To calibrate a simple pendulum to measure time in seconds

Procedure

1. Tie the pendulum to the clamp, and measure the length l of the string in metres (Figure 1.12).
2. Measure the time taken t_1 for the pendulum to make 20 oscillations. Repeat to find t_2.
3. Vary the length l of the string between 50 and 90 cm and repeat step 2.

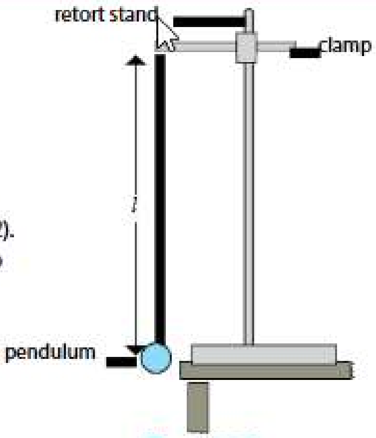


Figure 1.12

4 Find the average time $t_{average}$ for 20 oscillations, period T and T^2 as shown in Table 1.4.

Table 1.4

Length l / m	Time for 20 Oscillations			Period T / s	T^2 / s^2
	t_1 / s	t_2 / s	$t_{average}$ / s $[t_{average} = \frac{t_1 + t_2}{2}]$	$T = \frac{t_{average}}{20}$	
0.600					
0.700					
0.800					
0.900					

5 Plot a graph of period T / s against length l / m (Figure 1.13(a)), and find the length of the pendulum with a period of one second. Also plot a graph of T^2 / s^2 against length l / m (Figure 1.13(b)).

Results and Discussion

Figure 1.13(a) Graph of T vs l

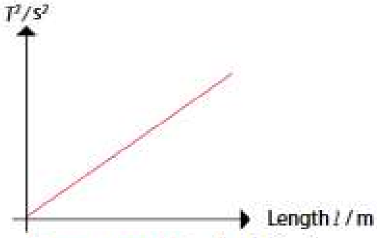


Figure 1.13(b) Graph of T^2 vs l

The length of the pendulum with a period of one second can be read off the graph. By using a pendulum with this length, we can measure time by counting the number of oscillations (e.g. if one oscillation takes one second, then 60 oscillations take 60 seconds or one minute).

Figure 1.13(a) shows that the period increases with length, but not linearly.
Figure 1.13(b) shows that the square of the period is directly proportional to the length. This gives rise to a straight-line graph when we plot T^2 against l. 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.

Let's Practise 1.3

1 What are some advantages of using digital calipers over a metre rule to measure the external diameter of a beaker?

2 Figure 1.14 shows an oscillating pendulum. If the time taken for the pendulum to swing from A to C to B is 3.0 s, what is the period of the pendulum?

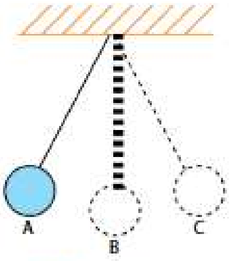


Figure 1.14 Oscillating pendulum

Helpful Note

Calculation
The period of the pendulum T is found by dividing $t_{average}$ by 20. That is,
$T = \frac{t_{average}}{20}$.
Note: A common mistake made during practical work is to take the average time for 20 oscillations (i.e. $t_{average} = \frac{t_1 + t_2}{2}$) as the period T of the pendulum.

Precaution
We need to take the time for 20 oscillations. The error decreases as the number of oscillations increases.

Link

The period of a pendulum also depends on the gravitational field strength of its location. You will learn more about this in Chapter 3.

Link

Theory Workbook
Worksheet 1B

Practical Workbook
Experiment 1B

1.4 What Are Scalars and Vectors?

Learning Outcomes

- State what is meant by *scalar* and *vector* quantities and give common examples of each.
- Add two vectors to determine a resultant by a graphical method.

▶ **Scalar quantities** are physical quantities that have only *magnitude*.

▶ **Vector quantities** are physical quantities that have both *magnitude and direction.*

Some scalar and vector quantities are shown in Table 1.5.

Table 1.5 Common scalar and vector quantities

Scalar	Vector
distance	displacement
speed	velocity
mass	acceleration
energy	force
time	weight

Distance and Displacement

Figure 1.15 shows the motion of an object between two points, A and B, via the green and blue paths. We will use it to illustrate the meanings of distance and displacement.

① **Distance**
- The total length covered by a moving object regardless of the direction of motion
- A scalar quantity (i.e. has magnitude only)
- SI unit: metre (m)
- The distance travelled by the moving object from A to B is either 7 km (blue path) or 10 km (green path)

② **Displacement**
- The distance measured in a straight line in a specified direction
- A vector quantity (i.e. has both magnitude and direction)
- SI unit: metre (m)
- The displacement of the object from A to B is 5 km due east of A, regardless of the actual path it takes

Figure 1.15 Distance and displacement between A and B

What if the object moves back to A along the same path (i.e. A ⟶ B ⟶ A)?
- The distance it travels is either 14 km (blue path) or 20 km (green path).
- Its displacement is zero, because it returns to A.

Helpful Note

For any object moving in a straight line (i.e. linear motion), we can assign the direction from a reference point as positive or negative.

For example, in Figure 1.15, if we assign the direction to the right of A as positive, the displacement of the moving object is +5 km.

Speed and Velocity

Let us look at the derived quantities of speed and velocity as common examples of scalar and vector quantities.

▶ **Speed** is the distance moved per unit time.

Speed is a scalar quantity. Its SI unit is the **metre per second (m/s)**.

▶ **Velocity** is the rate of change of displacement.

Velocity is a vector quantity. Its SI unit is also the **metre per second (m/s).**

▶ $$\textbf{Speed} = \frac{\textbf{distance}}{\textbf{time taken}}$$ ▶ $$\textbf{Velocity} = \frac{\textbf{displacement}}{\textbf{time taken}}$$

When we talk about the velocity of an object, we have to state the speed of the object and the direction in which it is travelling. This is because velocity is a vector quantity. It is speed in a specified direction.

Worked Example 1C

If the athlete in Figure 1.16 takes 25 s to complete a 200 m sprint event, find his speed and velocity.

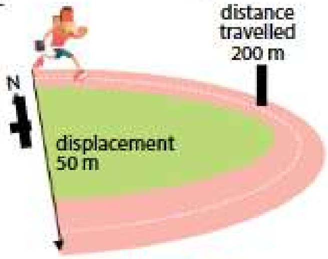


Figure 1.16

Answer

(a) Speed
$$= \frac{\text{distance}}{\text{time taken}}$$
$$= \frac{200\text{ m}}{25\text{ s}}$$
$$= 8.0\text{ m/s}$$

(b) Taking the direction due south of the athlete as positive,

Velocity
$$= \frac{\text{displacement}}{\text{time taken}}$$
$$= \frac{50\text{ m}}{25\text{ s}}$$
$$= 2.0\text{ m/s}$$

Adding Two Vectors by the Graphical Method

We can use a vector diagram to add up two vectors. 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.

Unlike scalars, vector quantities (or vectors) have 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*.

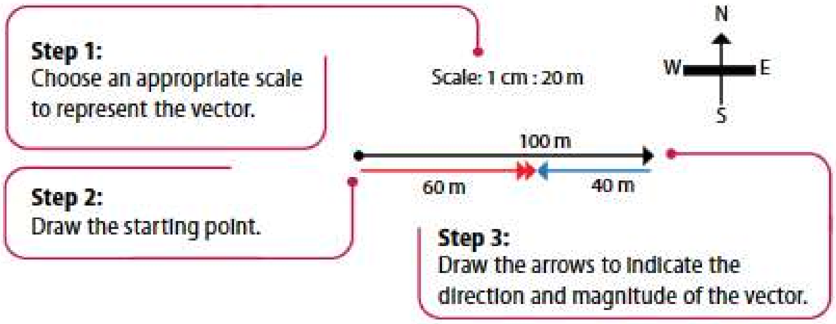
Disciplinary Idea

Microscopic models can explain macroscopic phenomena.

We use models to understand the world, and these models include mathematical models (e.g. representing physical quantities as scalars and vectors) that help us in our thinking and reasoning.

Adding Two Parallel Vectors

If a girl walks 100 m due east and then 40 m due west, what is her displacement? We can find her displacement by adding the vectors graphically (Figure 1.17).



Step 1:
Choose an appropriate scale to represent the vector.

Step 2:
Draw the starting point.

Step 3:
Draw the arrows to indicate the direction and magnitude of the vector.

Figure 1.17 Adding two parallel vectors graphically

Figure 1.17 shows that the displacement of the girl is 60 m due east.

Adding Two Non-Parallel Vectors

Consider the two forces acting on a block (Figure 1.18). The forces act at an angle to each other (i.e. they are not parallel). Figure 1.19 shows how we can obtain the resultant force by the head-to-tail method.

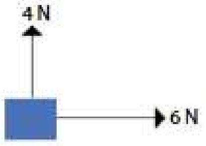
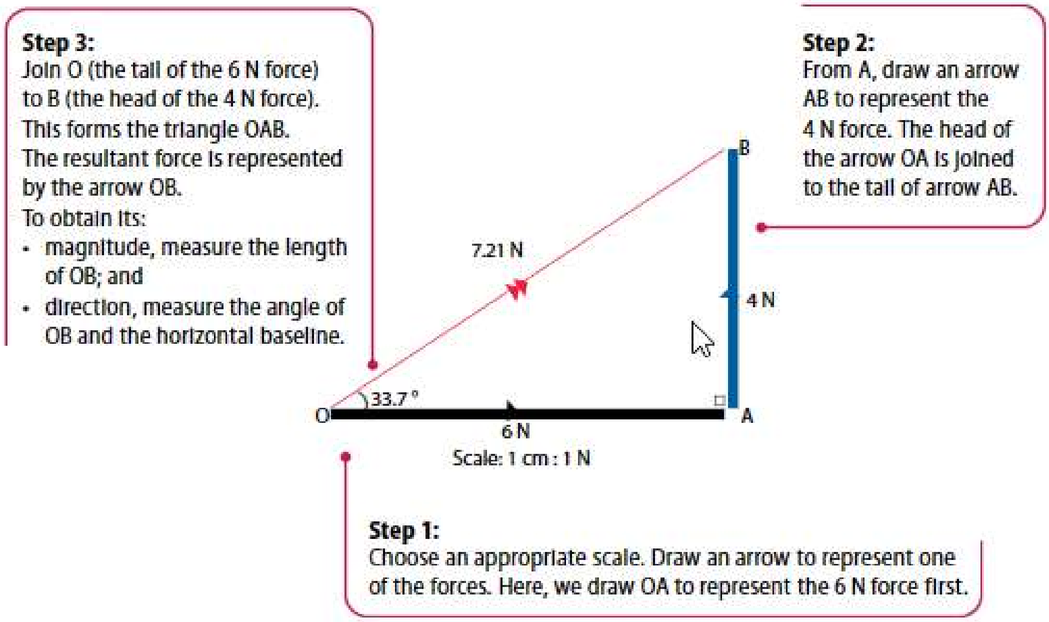


Figure 1.18 Forces acting at an angle to each other



Step 3:
Join O (the tail of the 6 N force) to B (the head of the 4 N force).
This forms the triangle OAB.
The resultant force is represented by the arrow OB.
To obtain its:
- magnitude, measure the length of OB; and
- direction, measure the angle of OB and the horizontal baseline.

Step 2:
From A, draw an arrow AB to represent the 4 N force. The head of the arrow OA is joined to the tail of arrow AB.

Step 1:
Choose an appropriate scale. Draw an arrow to represent one of the forces. Here, we draw OA to represent the 6 N force first.

Figure 1.19 Adding two non-parallel vectors graphically

Figure 1.19 shows that the resultant force has a magnitude of 7.21 N and acts at an angle 33.7 ° to the horizontal.

Disciplinary Idea

Matter interacts through forces and fields.

The net force on a body can be determined using vector addition of forces.

Gravitational, electric and magnetic fields can be represented by field lines. Various physical laws have been found relating the field with the force (e.g. gravitational force, electrostatic force, magnetic force).

Link

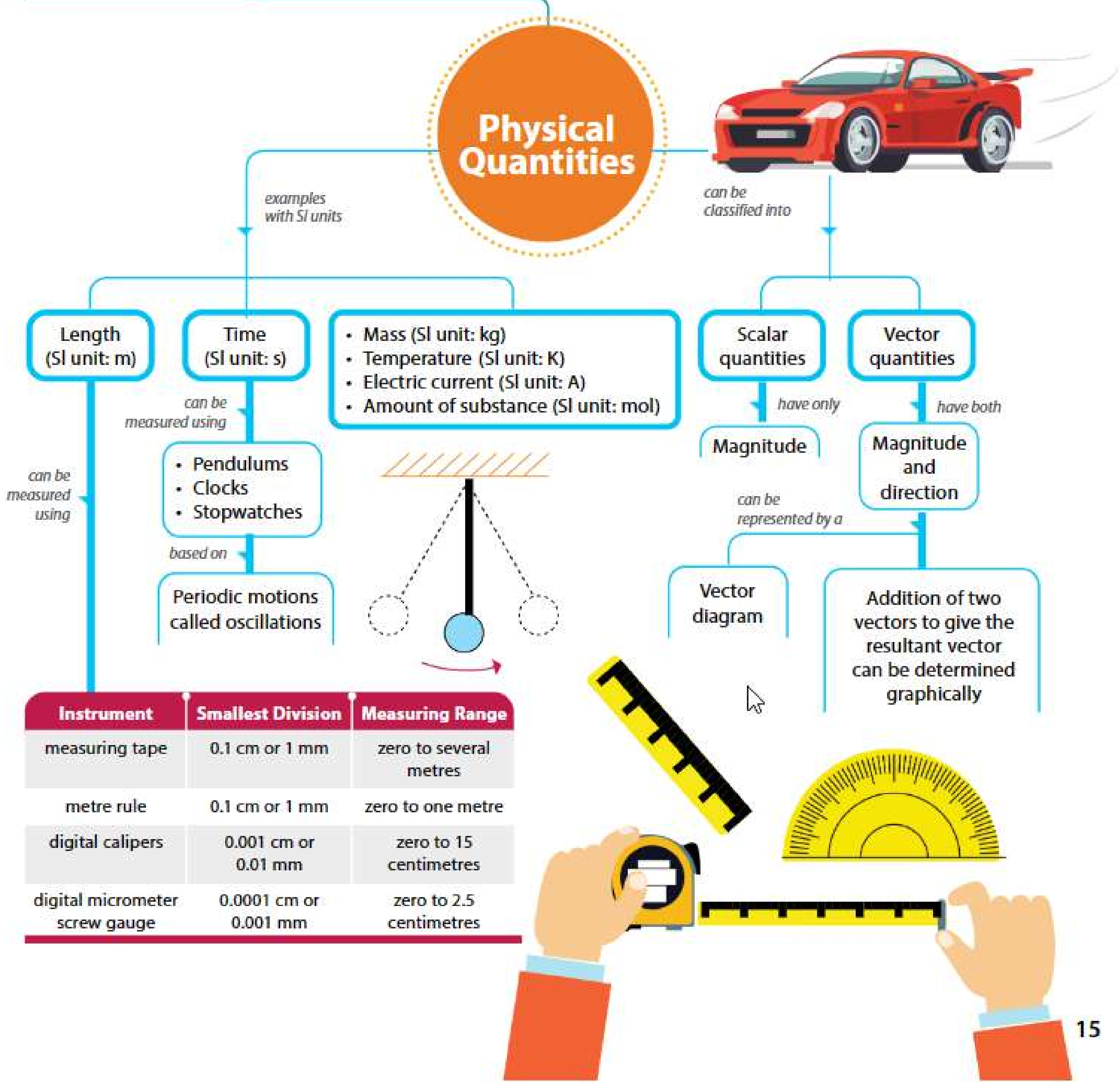
The resultant force when three forces act on a static point mass can also be found by the graphical method. Find out more about this in Chapter 4.

Let's Practise 1.4

1 What are the similarities and differences between scalar and vector quantities?
2 A car travels at 90 km/h due east for an hour and then travels at 60 km/h due west for another hour. Determine the resultant velocity graphically.
3 A man walks 1 km due east and then walks 1 km due north. Determine the resultant displacement graphically.

Link
Theory Workbook
Worksheet 1C
Let's Assess
Let's Reflect

Let's Map It



Physical Quantities

examples with SI units

Length (SI unit: m)

Time (SI unit: s)

- Mass (SI unit: kg)
- Temperature (SI unit: K)
- Electric current (SI unit: A)
- Amount of substance (SI unit: mol)

Time *can be measured using*

- Pendulums
- Clocks
- Stopwatches

based on

Periodic motions called oscillations

can be classified into

Scalar quantities *have only* Magnitude

Vector quantities *have both* Magnitude and direction

can be represented by a

Vector diagram

Addition of two vectors to give the resultant vector can be determined graphically

Length *can be measured using*

Instrument	Smallest Division	Measuring Range
measuring tape	0.1 cm or 1 mm	zero to several metres
metre rule	0.1 cm or 1 mm	zero to one metre
digital calipers	0.001 cm or 0.01 mm	zero to 15 centimetres
digital micrometer screw gauge	0.0001 cm or 0.001 mm	zero to 2.5 centimetres

Let's Review

Section A: Multiple-choice Questions

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

○ A half-metre rule
○ B metre rule
○ C metre rule and digital calipers
○ D ten-metre measuring tape

2 The digital micrometer screw gauge can be used to measure the ________.

○ A circumference of a coin
○ B depth of a test tube
○ C thickness of a coin
○ D thickness of 1000 pieces of A4 paper

3 An object has a width of about 1.5 cm. The reading shown on the digital micrometer screw gauge when it is used to measure the width of the object is ________.

○ A 15 mm
○ B 15.1 mm
○ C 15.01 mm
○ D 15.001 mm

Section B: Structured Questions

1 (a) List **three** examples of base quantities and their corresponding SI units.
(b) The mass of a car is 1 300 000 g. Express the mass of the car in SI unit and standard form.

2 Fill in the blanks with the correct prefixes. The first has been done for you.
(a) 1 k g = 10^3 g
(b) 1 ___ s = 10^{-6} s
(c) 1 mA = ___ A
(d) 1 ___ m = 10^{-2} m
(e) 1 cm^2 = ___ m^2
(f) 1 ___ W = 10^6 W

3 (a) What is a scalar quantity?
(b) Give **two** examples of scalar quantities.
(c) If a car travels 10 km from point A to point B and then another 12 km to point C, what is the total distance travelled by the car?

4 Complete Table 1.6.

Table 1.6

	Length to be Measured	Suitable Instrument	Smallest Division
(a)	several metres		
(b)	between one metre and several metres		
(c)	between 1 cm and 15 cm		
(d)	0.01 cm		
(e)	between 0.001 cm and 0.01 cm		

5 (a) What is a vector quantity?
(b) Give **two** examples of vector quantities.
(c) A car travels 10 km due north and then another 12 km due west. Determine the resultant displacement of the car graphically.

Section C: Free-response Questions

1 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

Given that 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 approach.

2 Define *precision of an instrument*.
State a suitable instrument to measure the diameter of a ten-cent coin. Explain your answer in terms of the precision of the instrument.

Link
Theory Workbook
Revision Worksheet 1

CHAPTER

02 Kinematics

What You Will Learn

- What are speed, velocity and acceleration?
- How do we analyse motion graphically?
- What is acceleration of free fall?

In the August 2016 Rio Olympics, the winner of the men's 100-metre final, Usain Bolt, 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 seconds during the 2009 World Athletics Championship in Berlin.

What an amazing record! How can we analyse his speeds in the different races? Was he always ahead of his competitors throughout the race?

2.1 What Are Speed, Velocity and Acceleration?

Learning Outcomes

- State what is meant by *speed* and *velocity*.
- Calculate average speed using *distance travelled / time taken*.
- State what is meant by *uniform acceleration* and calculate the value of acceleration using *change in velocity / time taken*.
- Interpret given examples of non-uniform acceleration.

Disciplinary Idea

Matter and energy make up the universe.

Kinematics (study of motion) provides us with a vocabulary for describing the motion of matter in the universe such as the 100-m sprint on land or the seasonal migration of humpback whales in the oceans in search of feeding and breeding grounds.

Speed

If Usain Bolt were to race against a cheetah in a 100-metre sprint, who would be the winner (Figure 2.1)?

Figure 2.1 Who is the real king of speed?

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

Speed is the distance travelled per unit time. Its SI unit is metre per second (m/s).

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

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

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

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

Helpful Note

A unit of time can be a second, a minute or an hour.

Figure 2.2 Average speeds of different objects or animals

Average Speed

Table 2.1 shows the results for men's running events at the 2020 Tokyo Olympics.

Table 2.1 Results for men's running events at the 2020 Tokyo Olympics

Athlete	Country	Event / m	Time / s	Average Speed / m/s
Jacobs Lamont Marcell	Italy	100	9.80	10.2
Andre de Grasse	Canada	200	19.62	10.2
Steven Gardiner	Bahamas	400	43.85	9.12
Emmanuel Kipkurui Korir	Kenya	800	105.06	7.61

The speeds shown in Table 2.1 are 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 may be different from the speed at another instant. The speed of an object at a particular **Instant** is known as its *instantaneous* speed.

Word Alert

Instant: a point in time

Worked Example 2A

A car travels 6 km in 5 minutes.

(a) Calculate its average speed in m/s.

(b) Is the average speed of a car higher than the cheetah's speed shown in Figure 2.2?

Answer

(a) Average speed $= \frac{\text{total distance travelled}}{\text{total time taken}} = \frac{6 \times 1000 \text{ m}}{5 \times 60 \text{ s}} = 20 \text{ m/s}$

(b) No. The car's average speed of 20 m/s is lower than the cheetah's average speed of 30 m/s.

Uniform Speed

When the change in the distance travelled by an object for every unit of time is the *same*, the object undergoes constant or uniform speed (Table 2.2).

Table 2.2 Object moving with uniform speed (10 m/s)

Time/ s	Distance/ m	Change in Distance/ m
0	0	0
1	10	10 – 0 = 10
2	20	20 – 10 = 10
3	30	30 – 20 = 10

From Table 2.2, when the speed of the object is constant at 10 m/s, the distance travelled in each one-second interval is always 10 m (Figure 2.3).

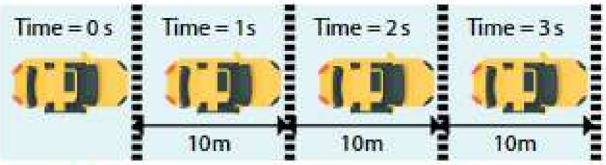
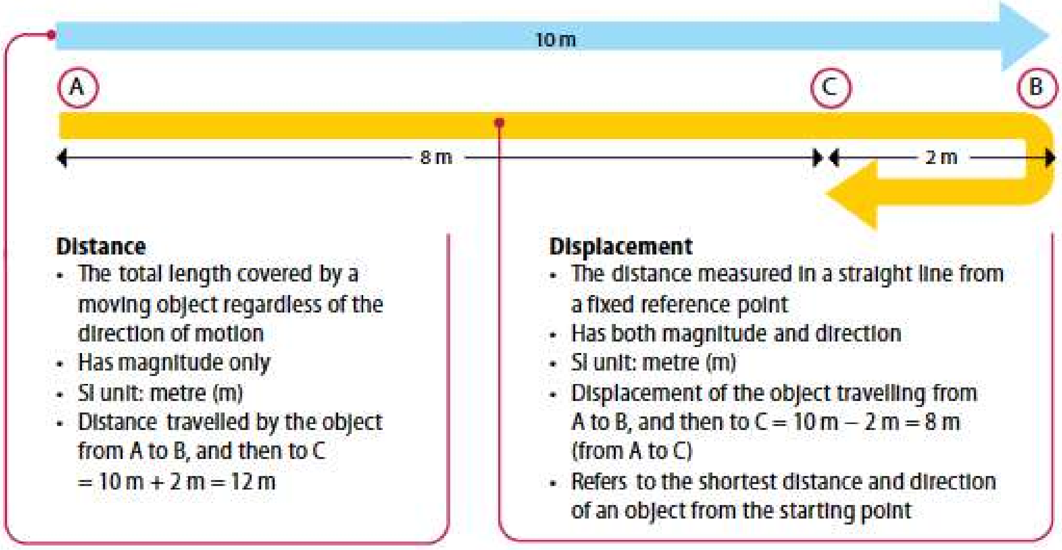


Figure 2.3 For an object with a uniform speed of 10 m/s, the increase in the distance travelled in each one-second interval is a constant value of 10 m.

Differences Between Distance and Displacement

We have learnt about the differences between distance and displacement. Can you recall them?

Figure 2.4 shows the motion of an object from point A to point B and then to point C. We shall use it to illustrate the similarity and differences 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 from a fixed reference point
- 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 2.4 Similarities and differences between distance and displacement

Link

Recall from Chapter 1: There are two types of physical quantities — scalars and vectors.

Helpful Note

For any object moving in a straight line, we can assign a direction from a reference point as positive.

For example in Figure 2.4, we can assign the direction to the right of A as positive. The displacement of the moving object at B is +10 m.

Worked Example 2B

Figure 2.5 shows a car that travels 5.0 km due east from point O and makes a U-turn to travel another 3.0 km to reach the ending point E.

Calculate:
(a) the distance covered; and
(b) its displacement.

Figure 2.5

Answer
(a) Distance covered = 5.0 km + 3.0 km = 8.0 km
(b) Taking the direction due east of point O as positive:
Displacement = 5.0 km – 3.0 km = 2.0 km
The displacement of the car is 2.0 km due east of the starting point O.

Velocity

We have learnt in Chapter 1 that 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 the rate of change in displacement. Its SI unit is metre per second (m/s).

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

To calculate the average velocity, we use the following formula:

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

Worked Example 2C

Figure 2.6 shows a car that travels 5.0 km due east and makes a U-turn to travel another 7.0 km.

Figure 2.6

If the time taken for the whole journey is 0.20 h, calculate the:
(a) average speed; and
(b) average velocity of the car.

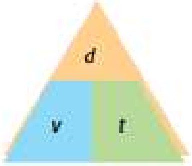
Answer
(a) Average speed $= \frac{\text{total distance travelled}}{\text{total time taken}} = \frac{(5.0 + 7.0)\text{ km}}{0.20\text{ h}} = 60\text{ km/h}$

(b) Taking the direction due east of point O as positive:
Average velocity $= \frac{\text{total displacement}}{\text{total time taken}} = \frac{(5.0 - 7.0)\text{ km}}{0.20\text{ h}} = -10\text{ km/h}$

The car is moving at an average velocity of 10 km/h westwards.

Helpful Note

The "triangle" method can help you to recall the relationship between velocity v, displacement d and time t.



- To find time t, cover t to obtain $t = \frac{d}{v}$.
- To find velocity v, cover v to obtain $v = \frac{d}{t}$ (as shown above).
- To find displacement d, cover d to obtain $d = vt$ (as shown above).

This method can also be applied to other similar formulae, in which variable x is directly proportional to variable y but inversely proportional to variable z:

$x \propto \frac{y}{z}$

$x = \frac{ky}{z}$,

where k = constant

Acceleration

An object accelerates when its velocity changes. Figure 2.7 shows that an object undergoes acceleration when:

- its speed or direction changes; or
- when both its speed and direction change.

Figure 2.7 Three scenarios in which acceleration occurs

▶ **Acceleration** is the rate of change of velocity.

▶ $$\textbf{Acceleration} = \frac{\textbf{change of velocity}}{\textbf{time taken}}$$

Acceleration is a vector quantity. Its SI unit is **metre per second per second (m/s^2)**.

Uniform Acceleration

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 2.3).

Table 2.3 Object moving with uniform acceleration

Time / s	Velocity / m/s			
0	0	+20	100	–20
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 2.3, when the velocity of the object is increasing by 20 m/s every second, the acceleration is 20 m/s^2 (Figure 2.8). The increase in the distance travelled in each one-second interval is of a different magnitude. When the velocity of the object is decreasing by 20 m/s every second, the acceleration is –20 m/s^2 or the deceleration is 20 m/s^2. The decrease in the distance travelled in each one-second interval is of a different magnitude.

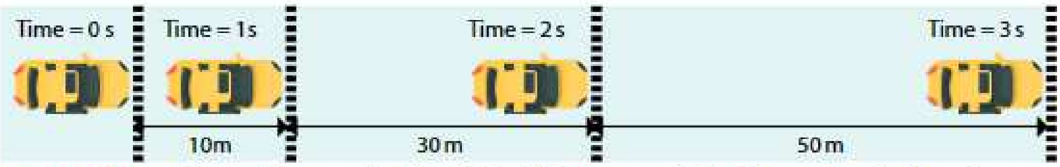


Figure 2.8 For an object with an acceleration of 20 m/s^2, the increase in the distance travelled in each one-second interval is not a constant value.

Disciplinary Idea

Forces help us to understand motion.

Characterising motion with position, displacement, velocity and acceleration provides the basis for formulating and appreciating Newton's laws of motion that provide the link to forces.

► **Uniform acceleration** is a constant rate of change of velocity.

The following equation can be used to determine the uniform acceleration a of an object:

► $$a = \frac{\Delta v}{\Delta t} = \frac{v - u}{t_v - t_u}$$

where Δv = change in velocity (m/s)
Δt = time interval between t_u and t_v (s)
v = final velocity (m/s)
u = initial velocity (m/s)
t_v = time at which an object is at final velocity v (s)
t_u = time at which an object is at initial velocity u (s)

Helpful Note

The delta symbol, Δ, is used to represent change or difference.

For example, in the equation for calculating uniform acceleration, Δv indicates the change in velocity.

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 2.9). What is its acceleration, assuming that it accelerates uniformly?

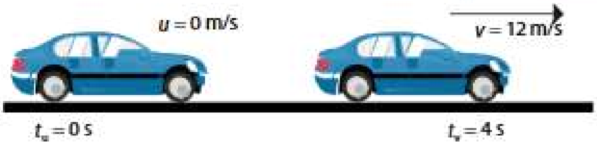


Figure 2.9

Answer
We assign the direction to the right as positive.
Given: initial velocity u = 0 m/s (since the car starts from rest)
final velocity v = 12 m/s
time taken $\Delta t = t_v - t_u$ = 4 s
Since its acceleration is assumed to be uniform,
$a = \frac{v-u}{\Delta t} = \frac{(12-0)\text{ m/s}}{4\text{ s}} = 3.0\text{ m/s}^2$
The acceleration is 3.0 m/s^2.

Physics Connect

Scan the QR code to explore a simulation on the acceleration of a car.

Worked Example 2E

The velocity of a golf ball rolling in a straight line changes from 8 m/s to 2 m/s in 10 s (Figure 2.10). What is its deceleration, assuming that it is decelerating uniformly?

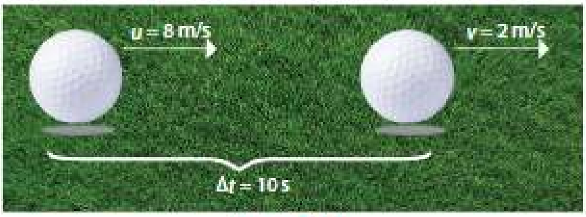


Figure 2.10

Thought Process
When an object is slowing down, it is decelerating. Its final speed (v) is lower than its initial speed (u). Hence, the acceleration of the object ($a = \frac{v-u}{\Delta t}$) is a negative value. The deceleration of an object that is slowing down is the positive value of its acceleration.

Answer
We assign the direction to the right as positive.
Given: initial velocity u = 8 m/s
final velocity v = 2 m/s
time taken Δt = 10 s
Since its acceleration is assumed to be uniform,
$a = \frac{v-u}{\Delta t} = \frac{(2-8)\text{ m/s}}{10\text{ s}} = -0.60\text{ m/s}^2$

The negative calculated value indicates that the ball is slowing down (i.e. decelerating). The deceleration of the ball is the positive value of its acceleration when the ball is slowing down. The deceleration is 0.60 m/s^2.

Non-uniform Acceleration

An object undergoes non-uniform acceleration if the change in its velocity for every unit of time is *not the same* (Table 2.4).

Table 2.4 Object moving with non-uniform acceleration

Time / s	Velocity / m/s	Change in Velocity / m/s
0	0	0
1	10	10 – 0 = 10
2	40	40 – 10 = 30
3	60	60 – 40 = 20
4	70	70 – 60 = 10
5	50	50 – 70 = –20

Note that the change in velocity is not the same for every second. The moving object is undergoing non-uniform acceleration (Figure 2.11).

Figure 2.11 For an object with a non-uniform acceleration, the increase in the distance travelled in each one-second interval increases in a varying manner.

Let's Practise 2.1

1 At the start of a journey, the odometer (i.e. a meter that tracks the total distance a car has travelled) showed an initial reading of 50 780 km. At the end of the journey, the odometer reading was 50 924 km. The journey took two hours. What was the average speed of the journey in:
  (a) km/h; and
  (b) m/s?

2 "Velocity is speed in a specific direction." Is this statement true or false? Explain your answer.

3 (a) What is acceleration?
  (b) Given that the velocity of an object moving in a straight line changes uniformly from u to v in time t, write an expression for the acceleration of the object.

Link
Theory Workbook
Worksheet 2A

2.2 How Do We Analyse Motion Graphically?

Learning Outcomes

- Plot and interpret a displacement–time graph and a velocity–time graph.
- Deduce the motion of a body from the shape of a displacement–time graph.
- Deduce the motion of a body from the shape of a velocity–time graph.
- Calculate the area under a velocity–time graph to determine the displacement, for motion with uniform velocity or uniform acceleration.

Displacement–Time Graphs

The displacement–time graph of an object gives us some information about the motion of the object.

Let us look at the motion of a car as an example. In Figure 2.12, the car is travelling away from the starting point O. It travels along a straight line in one direction.

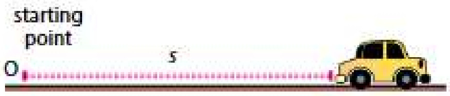


Figure 2.12 Motion of a car

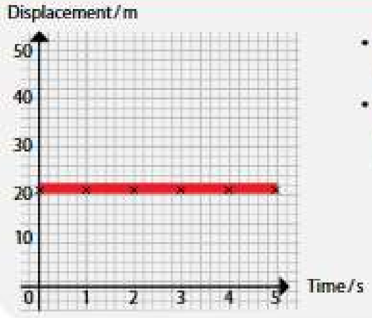
The displacement of the car is measured at every second. The displacement and time are recorded, and a graph is plotted using the data. There are four possible scenarios for the motion of the car.

Figures 2.13 and 2.14 show the displacement–time graphs of the car at rest and travelling at a uniform velocity.

▶ The gradient of a displacement–time graph of an object gives the velocity of the object.

Car at rest

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

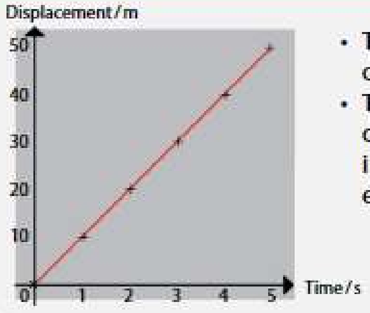


- The graph has zero gradient.
- The displacement of the car is a constant for every second.

Figure 2.13 Displacement–time graph of a car at rest

Car travelling at a uniform velocity of 10 m/s

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



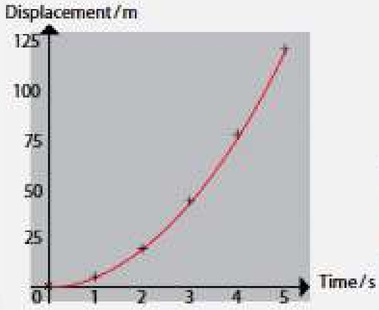
- The graph has a constant gradient.
- The displacement of the car increases 10 m every second.

Figure 2.14 Displacement–time graph of a car travelling at a uniform velocity of 10 m/s

Figures 2.15 and 2.16 show the displacement–time graphs of the car travelling at non-uniform velocity.

Car travelling with increasing velocity (non-uniform velocity)

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



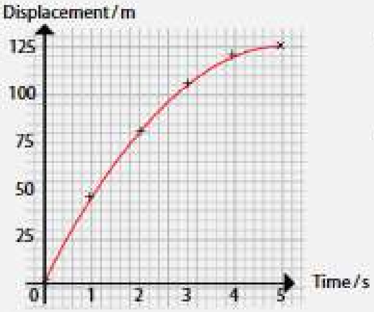
- The graph has an increasing gradient.
- The velocity of the car increases.

The instantaneous velocity of the car at any time *t* is given by the gradient of the tangent at the point.

Figure 2.15 Displacement–time graph of a car travelling with increasing velocity (non-uniform velocity)

Car travelling with decreasing velocity (non-uniform velocity)

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



- The graph has a decreasing gradient.
- The velocity of the car decreases.

Figure 2.16 Displacement–time graph of a car travelling with decreasing velocity (non-uniform velocity)

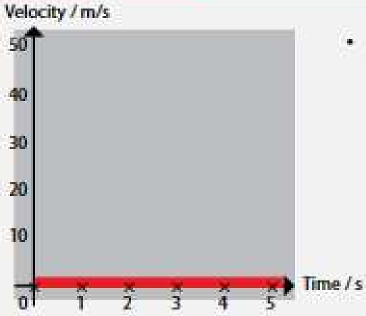
Velocity–Time Graphs

Velocity–time graphs can be used to show uniform and non-uniform acceleration of a car that is travelling along a straight line in one direction. Figures 2.17 and 2.18 show the velocity–time graphs of the car at rest and travelling at a uniform velocity.

▶ The gradient of a velocity–time graph of an object gives the acceleration of the object.

Car at rest

Time / s	0	1	2	3	4	5
Velocity / m/s	0	0	0	0	0	0

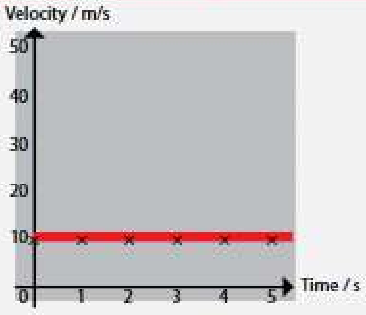


- The velocity of the car remains at 0 m/s so the car has zero acceleration.

Figure 2.17 Velocity–time graph of a car at rest

Car travelling at a uniform velocity of 10 m/s

Time / s	0	1	2	3	4	5
Velocity / m/s	10	10	10	10	10	10



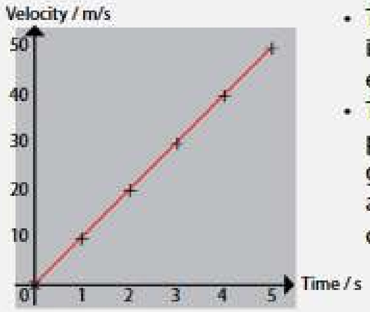
- The velocity of the car remains at 10 m/s so the car has zero acceleration.

Figure 2.18 Velocity–time graph of a car travelling at a uniform velocity of 10 m/s

Figures 2.19 and 2.20 show the velocity–time graphs of the car travelling with uniform acceleration and deceleration.

Car travelling with uniform acceleration

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

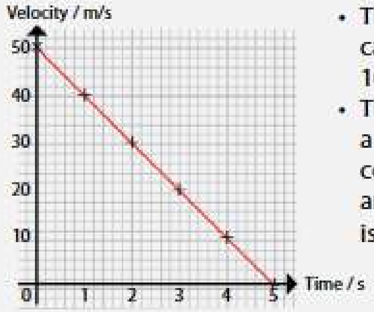


- The velocity of the car increases by 10 m/s every second.
- The graph has a positive and constant gradient, and the acceleration is constant.

Figure 2.19 Velocity–time graph of a car travelling with uniform acceleration

Car travelling with uniform decceleration

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



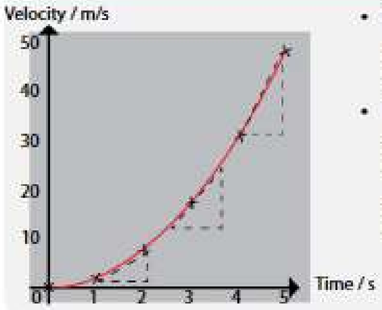
- The velocity of the car decreases by 10 m/s every second.
- The graph has a negative and constant gradient, and the deceleration is constant.

Figure 2.20 Velocity–time graph of a car travelling with uniform deceleration

Figures 2.21 and 2.22 show the velocity–time graphs of the car travelling with non-uniform acceleration.

Car travelling with increasing acceleration (non-uniform acceleration)

Time / s	0	1	2	3	4	5
Velocity / m/s	0	2	8	18	32	50

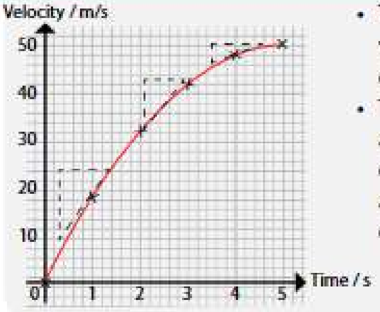


- The increase in velocity of the car is increasing with time.
- The graph has a positive and increasing gradient, and the acceleration increases.

Figure 2.21 Velocity–time graph of a car travelling with increasing acceleration (non-uniform acceleration)

Car travelling with decreasing acceleration (non-uniform acceleration)

Time / s	0	1	2	3	4	5
Velocity / m/s	0	18	32	42	48	50



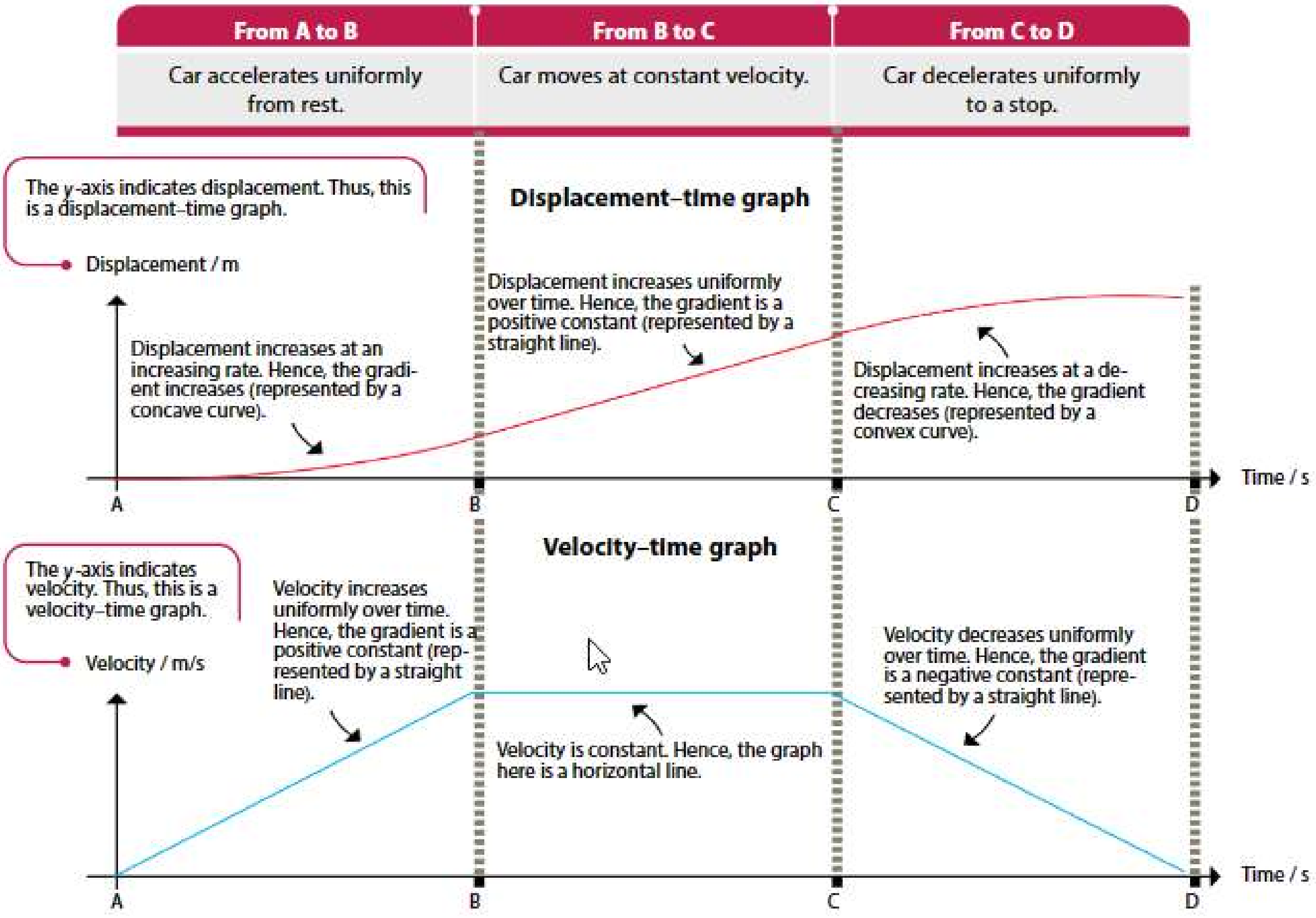
- The increase in velocity of the car is decreasing with time.
- The graph has a positive and decreasing gradient, and the acceleration decreases.

Figure 2.22 Velocity–time graph of a car travelling with decreasing acceleration (non-uniform acceleration)

Comparisons Between Displacement–Time and Velocity–Time Graphs

Displacement–time graphs and velocity–time graphs look very similar, but they give different information. We can differentiate the graphs by looking at the labels on the y-axes.

Assume that a car starts from rest and accelerates uniformly in one direction to a constant velocity. The car then slows down and comes to a stop at a red light. Figure 2.23 shows the displacement–time and velocity–time graphs of the car and how they are related.



From A to B	From B to C	From C to D
Car accelerates uniformly from rest.	Car moves at constant velocity.	Car decelerates uniformly to a stop.

The y-axis indicates displacement. Thus, this is a displacement–time graph.

Displacement increases at an increasing rate. Hence, the gradient increases (represented by a concave curve).

Displacement increases uniformly over time. Hence, the gradient is a positive constant (represented by a straight line).

Displacement increases at a decreasing rate. Hence, the gradient decreases (represented by a convex curve).

The y-axis indicates velocity. Thus, this is a velocity–time graph.

Velocity increases uniformly over time. Hence, the gradient is a positive constant (represented by a straight line).

Velocity is constant. Hence, the graph here is a horizontal line.

Velocity decreases uniformly over time. Hence, the gradient is a negative constant (represented by a straight line).

Figure 2.23 Displacement–time and velocity–time graphs

Worked Example 2F

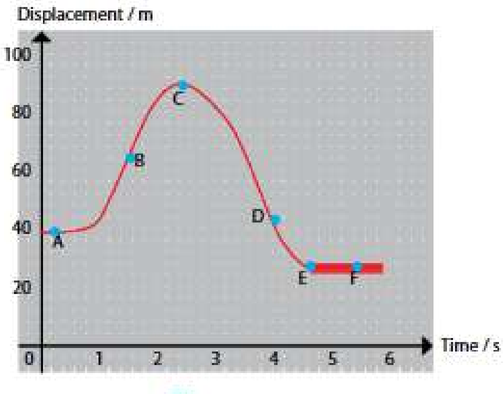


Figure 2.24

Figure 2.24 shows the displacement–time graph of a car. Assume that the direction of the car moving away from origin O is positive.

Describe the motion of the car at each stage: (a) A; (b) B; (c) C; (d) D to E; (e) E to F.

Answer

Stage		Motion of the Car
(a)	A	• Displacement is 40 m from O. • Velocity is zero.
(b)	B	• Displacement is 66 m from O. • Velocity is uniform.
(c)	C	• Displacement is 90 m from O. • Velocity is zero.
(d)	D to E	• Car travels in the opposite direction back towards O. • Displacement decreases at a decreasing rate. • Velocity is non-uniform and decreasing.
(e)	E to F	• Displacement remains at 28 m from O. • Velocity is zero.

Helpful Note

When interpreting the motion of the car in a displacement–time graph, include the displacement and velocity of the car in each interval.

Worked Example 2G

The velocity–time graph of a car is shown in Figure 2.25. Describe the motion of the car.

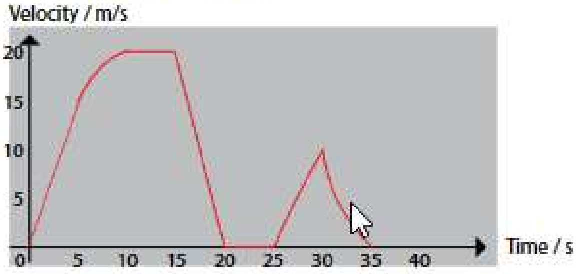


Figure 2.25

Answer

Time	Motion of the Car
0 – 5 s	• Velocity increases uniformly from 0 m/s to 15 m/s. • Acceleration is uniform at $a = \frac{(15 - 0)\text{ m/s}}{5\text{ s}} = 3.0\text{ m/s}^2$.
5 – 10 s	• Velocity increases from 15 m/s to 20 m/s at a decreasing rate. • Acceleration is non-uniform and decreasing.
10 – 15 s	• Velocity is uniform and is at a maximum. • Acceleration is zero.
15 – 20 s	• Velocity decreases uniformly from 20 m/s to 0 m/s. • Acceleration is uniform at $a = \frac{(0 - 20)\text{ m/s}}{5\text{ s}} = -4.0\text{ m/s}^2$.
20 – 25 s	• Both velocity and acceleration are zero. • The car is stationary.
25 – 30 s	• Velocity increases uniformly from 0 m/s to 10 m/s. • Acceleration is uniform at $a = \frac{(10 - 0)\text{ m/s}}{5\text{ s}} = 2.0\text{ m/s}^2$.
30 – 35 s	• Velocity deceases from 10 m/s to 0 m/s at a decreasing rate. • Acceleration is non-uniform and negative.

Helpful Note

When interpreting the motion of the car in a velocity–time graph, explain what is happening interval by interval.

Area Under Velocity–Time Graph

Figure 2.26 shows the velocity–time graph for an object moving with a uniform velocity.

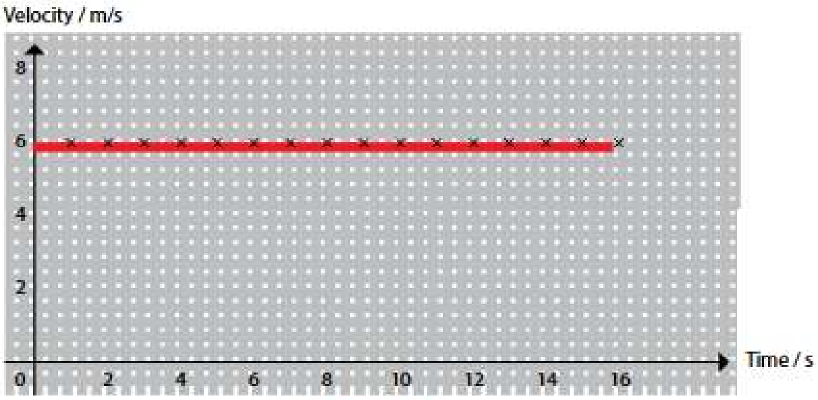


Figure 2.26

The velocity is 6 m/s from time $t = 0$ s to $t = 16$ s. What is the total displacement from $t = 0$ s to $t = 10$ s?

We can calculate it as follows:

$v = 6$ m/s, $t = 10$ s

$v = \frac{d}{t}$

$\therefore d = v \times t = 6 \text{ m/s} \times 10 \text{ s} = 60 \text{ m}$

The product of velocity and time gives the displacement. From Figure 2.27, you can see that the product of 6 m/s and 10 s is the area of the shaded rectangle.

Helpful Note

- Only the area under a velocity–time graph gives the displacement. The area under a displacement–time graph does not give displacement.
- We can derive the total displacement from a displacement–time graph by reading the values directly off the y-axis.

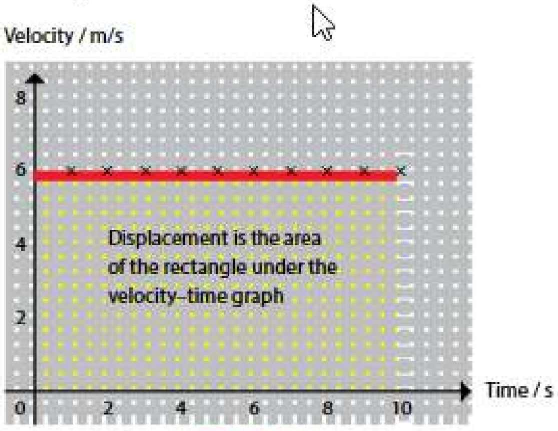
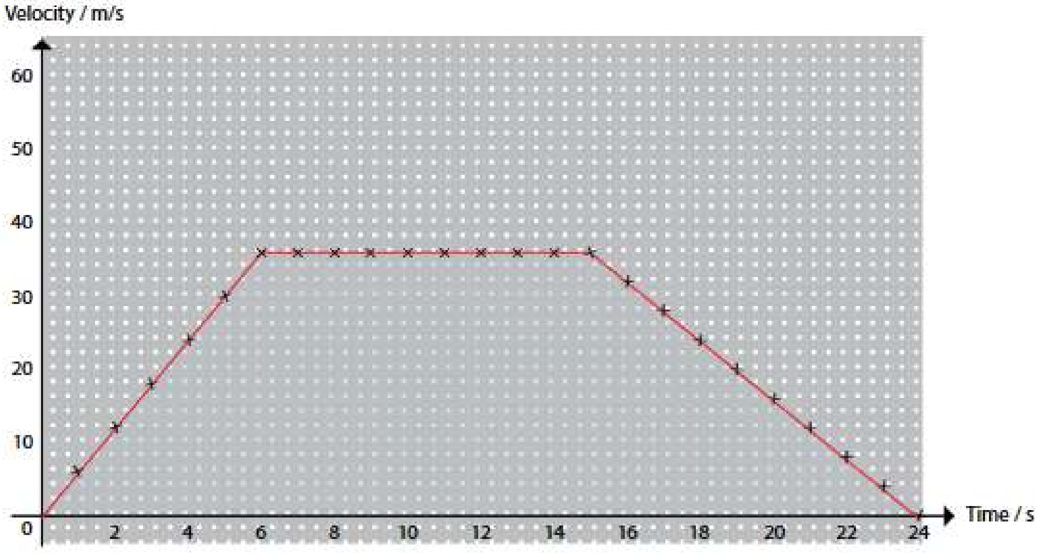


Figure 2.27

▶ The area under the velocity–time graph gives the displacement of the object.

Now, consider the following velocity–time graph for an object that accelerates, moves with a uniform velocity, and then decelerates (Figure 2.28).



From time $t = 0$ s to $t = 6$ s,
- Velocity increases uniformly from 0 m/s to 36 m/s.
- Acceleration $= \frac{(36 - 0)\text{ m/s}}{(6 - 0)\text{ s}}$
  $= 6.0\text{ m/s}^2$

From time $t = 6$ s to $t = 15$ s,
- Velocity remains constant at 36 m/s.
- Acceleration $= 0\text{ m/s}^2$

From time $t = 15$ s to $t = 24$ s,
- Velocity decreases uniformly from 36 m/s to 0 m/s.
- Acceleration $= \frac{(0 - 36)\text{ m/s}}{(24 - 15)\text{ s}}$
  $= -4.0\text{ m/s}^2$

Figure 2.28 Velocity–time graph for an object that accelerates, moves with a uniform velocity, and then decelerates, and the description of its motion

Calculation of Total Displacement

Total displacement of the object
= total area under the velocity–time graph
= area of the trapezium
$= \frac{1}{2} \times$ sum of parallel sides $\times$ height
$= \frac{1}{2} \times (9\text{ s} + 24\text{ s}) \times 36\text{ m/s}$
$= 594$ m

Calculation of Average Speed

Average speed of object
$= \frac{\text{total distance travelled}}{\text{total time taken}}$
$= \frac{594\text{ m}}{24\text{ s}}$
$= 24.8$ m/s

Worked Example 2H

An MRT train moves off from Aljunied station and travels along a straight track towards Paya Lebar station. Figure 2.29 shows how the velocity of the train varies with time over the whole journey.

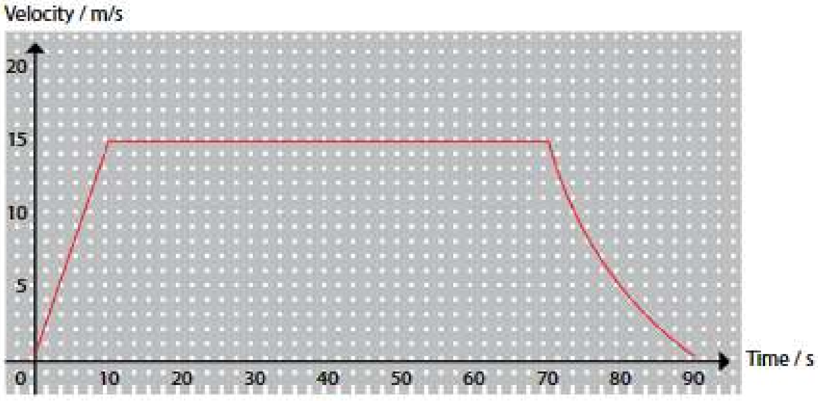


Figure 2.29

(a) Determine the average speed of the train between $t = 0$ s and $t = 70$ s.

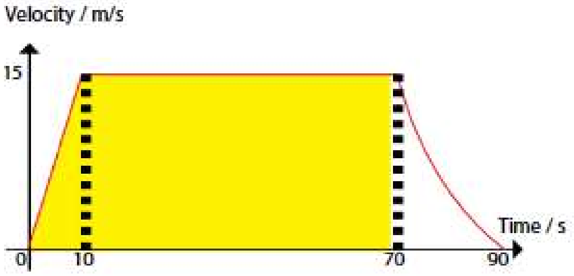
(b) Describe the motion of the train between:

- (I) $t = 0$ s and $t = 10$ s;
- (II) $t = 10$ s and $t = 70$ s; and
- (III) $t = 70$ s and $t = 90$ s.

Answer

(a) Displacement between $t = 0$ s and $t = 70$ s
= area under velocity–time graph between $t = 0$ s and $t = 70$ s
= area of shaded trapezium (Figure 2.29)
$= \frac{1}{2} \times (60 \text{ s} + 70 \text{ s}) \times 15 \text{ m/s} = 975 \text{ m}$

$$\text{Average speed} = \frac{\text{total distance travelled}}{\text{total time taken}} = \frac{975 \text{ m}}{70 \text{ s}} = 13.9 \text{ m/s}$$



(b) (I) The velocity–time graph of the train has a gradient that is positive and constant between $t = 0$ s and $t = 10$ s. This means that the train is undergoing uniform acceleration.

(II) The velocity–time graph of the train is a horizontal line between $t = 10$ s and $t = 70$ s. That is, its gradient is zero. This means that the acceleration of the train is zero.

(III) The velocity–time graph of the train has a negative and decreasing gradient between $t = 70$ s and $t = 90$ s. This means that the velocity of the train decreases at a decreasing rate. The train is undergoing decreasing deceleration.

Helpful Note

Instead of using the formula for finding the area of a trapezium, we can also find the same shaded area under the velocity–time graph by adding the area of the small shaded triangle and area of the shaded rectangle.

Try computing the total displacement using the method above. Check if it gives the same answer as in Worked Example 2H.

Worked Example 2I

A motorist approaches a traffic light junction at 54 km/h. The traffic light turns red when he is 30 m from the junction. If he takes 0.4 s before applying the brakes, and his car slows down at a rate of 3.75 m/s^2, determine whether the motorist can stop his car in time.

The assumptions are:

- The car travels at a uniform velocity of 54 km/h until the brakes are applied.
- Its deceleration of 3.75 m/s^2 is uniform.

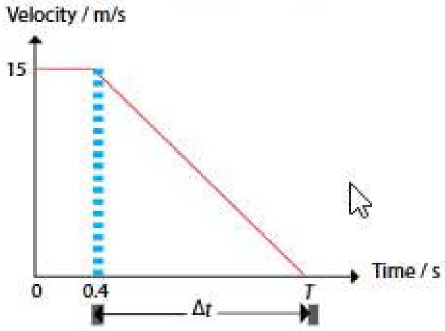
Thought Process
We need to understand the problem before planning the problem-solving approach.
For the car to stop in time, it needs to stop within 30 m. Thus, we need to find the displacement of the car from the junction.

Answer
Step 1: The displacement of the car can be determined by finding the area under its velocity–time graph.

Note: First, convert 54 km/h into a speed in m/s.

$$54\text{ km/h} = \frac{54\text{ km}}{1\text{ h}} = \frac{54\,000\text{ m}}{3600\text{ s}} = 15\text{ m/s}$$

Velocity–time graph of vehicle:



Step 2: To find the area under the velocity–time graph, we need to find Δt.

Find: time interval Δt between the point at which the motorist applies the brakes and the point at which the car stops

Given: uniform deceleration = 3.75 m/s^2
(i.e. acceleration $a = -3.75$ m/s^2)
change in velocity Δv = final velocity – initial velocity = –15 m/s

$$a = \frac{\Delta v}{\Delta t}$$

$$-3.75\text{ m/s}^2 = \frac{-15\text{ m/s}}{\Delta t}$$

$$\Delta t = 4\text{ s}$$

Displacement
= area under velocity–time graph
= area of trapezium
$= \frac{1}{2} \times (0.4\text{ s} + 4.4\text{ s}) \times 15\text{ m/s}$
= 36 m

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

Speed–Time Graph Against Velocity–Time Graph

Consider a volleyball that is tossed vertically upwards and allowed to fall freely with negligible air resistance (Figure 2.30). We assign the upward direction from the ground as positive.

The speed and velocity of the volleyball changes during its journey. The changes in its speed and velocity are shown in Figures 2.31 and 2.32. What do you notice about the areas under the two graphs?

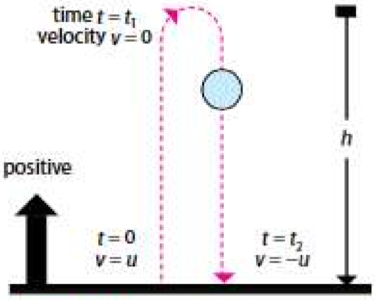


Figure 2.30 Upward and downward journey of a volleyball

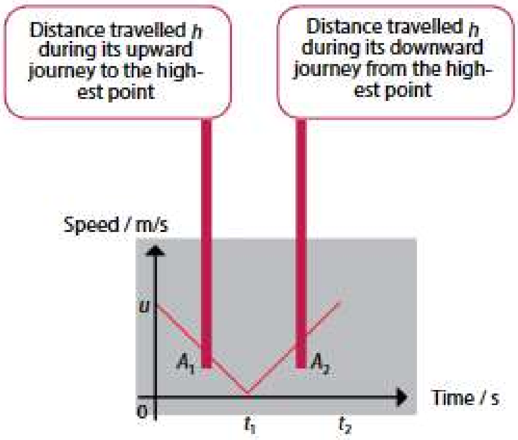


Figure 2.31 Speed–time graph of the volleyball

For the speed–time graph,
total distance travelled by the volleyball
= total area under the speed–time graph
$= A_1 + A_2 = h + h = 2h$ m

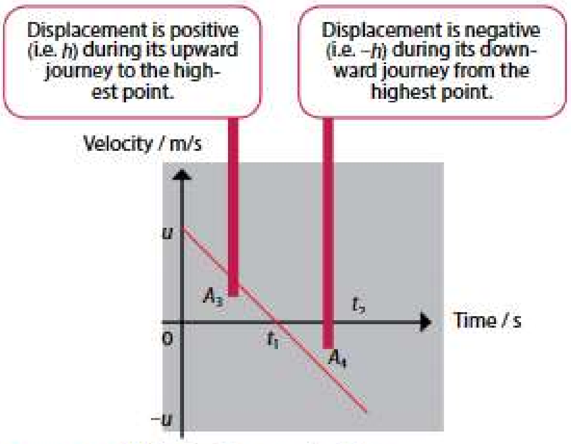


Figure 2.32 Velocity–time graph of the volleyball

For the velocity–time graph,
total displacement of the volleyball
= total area under the velocity–time graph
$= A_3 + A_4 = h + (-h) = 0$ m

Let's Practise 2.2

1 How do we tell whether an object is stationary from its displacement–time graph?
2 How do we determine the velocity of an object using its displacement–time graph?
3 Figures 2.33 and 2.34 show the displacement–time and velocity–time graph of a car.

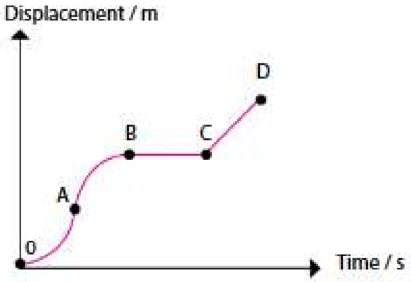


Figure 2.33 Displacement–time graph of a car

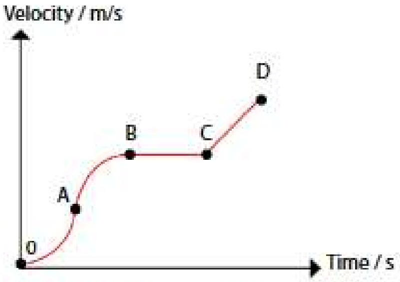


Figure 2.34 Velocity–time graph of a car

For both graphs, describe the motion of the car between points:
(a) OA; (b) AB; (c) BC; and (d) CD.

Link

Theory Workbook
Worksheet 2B

2.3 What Is Acceleration of Free Fall?

Learning Outcome

- State that the acceleration of free fall for a body near to Earth is constant and is approximately 10 m/s^2.

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 past, Aristotle claimed that a heavier object fell faster than a lighter object. His claim was widely accepted. However, in the 17th century, Galileo Galilei had a different finding after conducting a series of experiments. He discovered that all objects, regardless of mass or size, fell at the same acceleration due to the Earth's gravity.

Figure 2.35 shows the difference between Aristotle's claim and Galileo's finding.

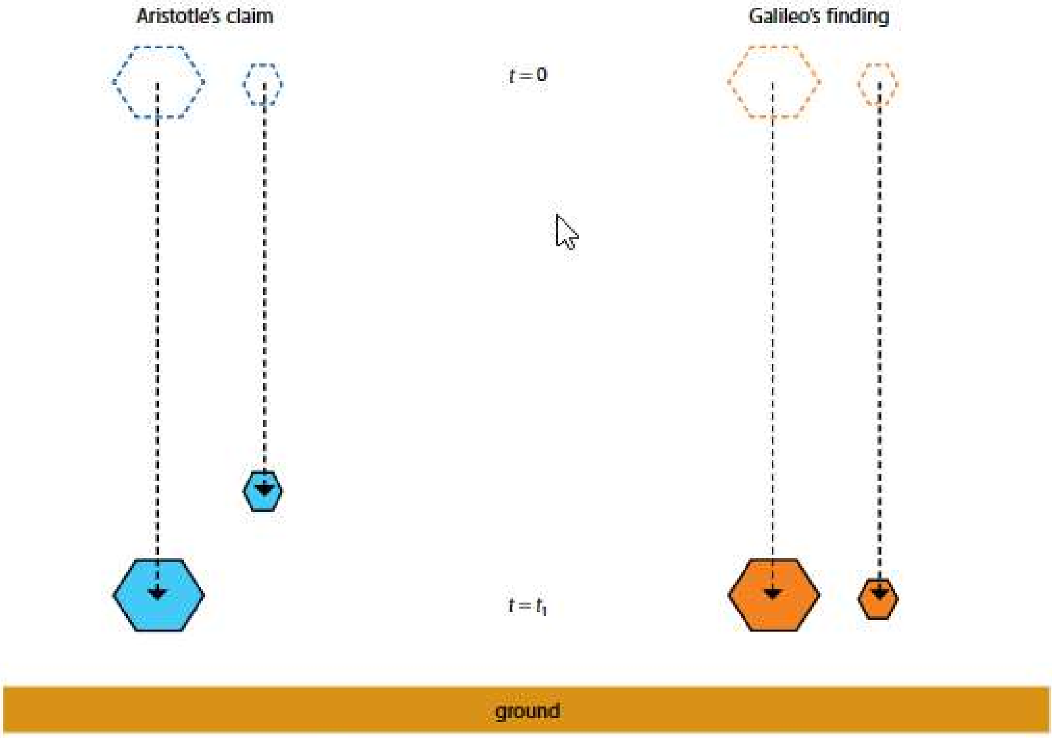


Figure 2.35 If you were a scientist in the 17th century, would you have accepted Galileo's finding? Why?

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

Past to Present

Galileo's willingness to challenge Aristotle's claim using experiments and observations is a good example that science is an evidence-based, model-building enterprise to understand the real-world. He also showed that he had an open mind, and was willing to consider alternatives. This is a value that all scientists should possess.

Link

Practical Workbook
Experiment 2A

Look at Figure 2.36. Based on what you have learnt, which observer(s) is/are correct?

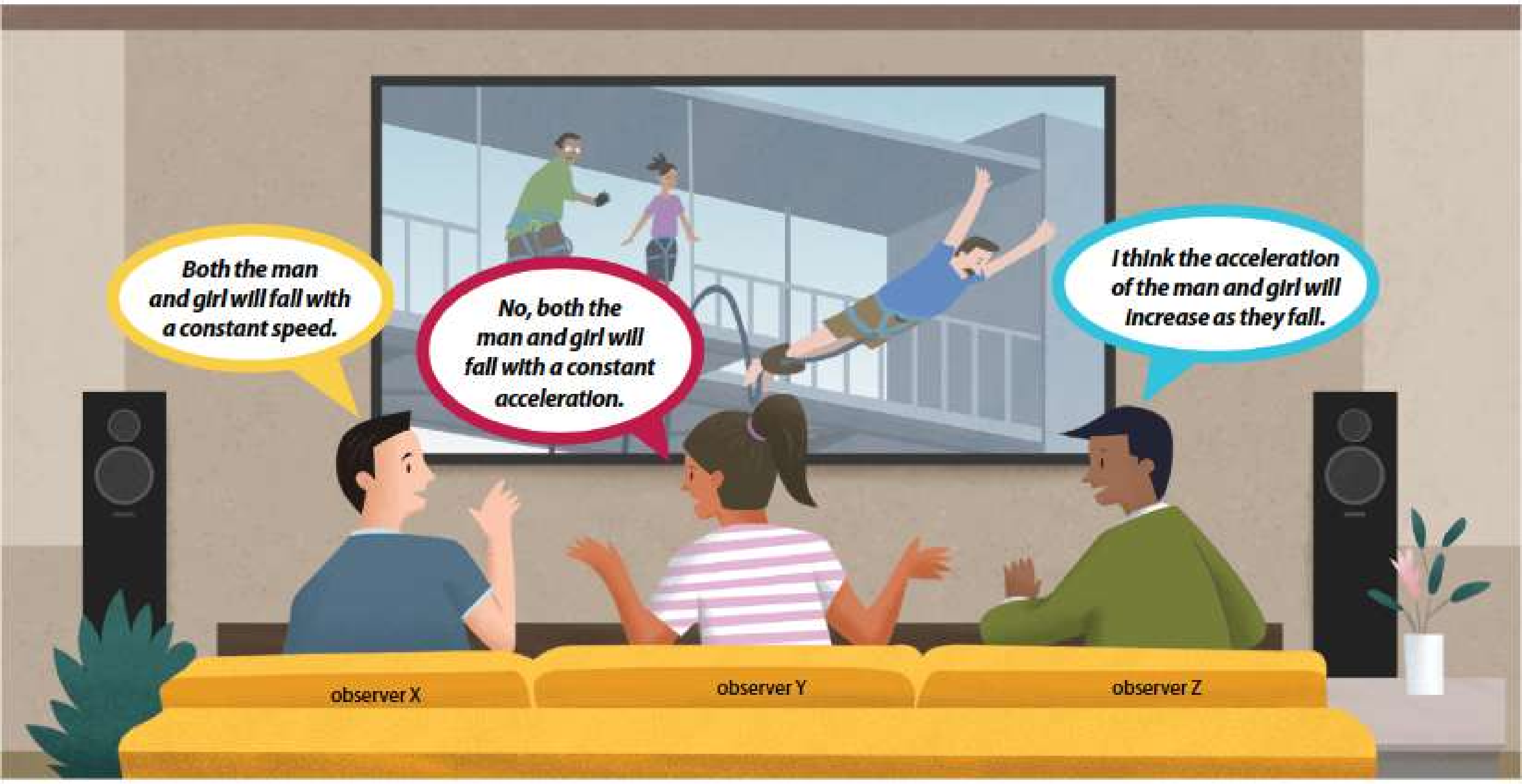


Figure 2.36 Which observer is correct about the man and the girl?

Observer X and observer Z are incorrect as both the man and girl are undergoing constant acceleration of approximately 10 m/s² due to their weights.
Observer Y is correct as from the time they jump to the time just before the bungee cord becomes stretched and pulls on them, they are undergoing constant acceleration.

Worked Example 2J

A sandal fell off a bamboo pole from the third floor while it was being put out to dry. The time taken for the sandal to reach the ground was 1.34 s (Figure 2.37). If air resistance was negligible:

(a) find the velocity of the sandal just before it hit the ground;

(b) find the height of the third floor from the ground; and

(c) do you expect any change in the velocity–time graph if a sock fell off instead?

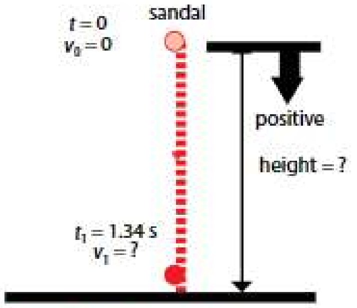


Figure 2.37 Path of the free-falling sandal

Thought Process
Since the air resistance is negligible, the sandal is in free fall (i.e. accelerating at 10 m/s²).

Given: time taken t to reach the ground is $t_1 = 1.34$ s

To visualise the problem, we sketch the velocity–time graph of the free-falling sandal (Figure 2.38).

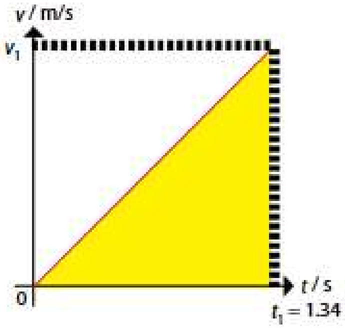


Figure 2.38 Velocity–time graph of the free-falling sandal

Answer

(a) Gradient of v–t graph = constant acceleration due to gravity

$$\frac{(v_1 - 0)\text{ m/s}}{(1.34 - 0)\text{ s}} = 10\text{ m/s}^2$$

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

The velocity of the sandal just before it hit the ground was 13.4 m/s.

(b) Displacement = area under v–t graph
Height of third floor from the ground

$= \frac{1}{2}v_1t_1$

$= \frac{1}{2} \times 13.4\text{ m/s} \times 1.34\text{ s}$

$= 9.0$ m

(c) No. Both the sandal and sock would give the same velocity–time graph, since acceleration is constant at 10 m/s² and air resistance is negligible.

Link
You will learn about weight as a non-contact force and tension as a contact force in Chapter 3.

Let's Practise 2.3

1 Two objects of different masses were released from rest near to Earth's surface. Assuming negligible air resistance, are the gradients of the velocity–time graphs for both of the objects the same or different? Explain your answer.

2 An object is released from an unknown height and falls freely for 5 s before it hits the ground.
   (a) Sketch the velocity–time graph for a time interval of 5 s, assuming there is negligible air resistance.
   (b) What is the velocity of the object just before it hits the ground?
   (c) What is the unknown height?

Link
Theory Workbook
Worksheet 2C
Let's Assess
Let's Reflect

Problem-based Learning Activity

You are an engineer in the Land Transport Authority (LTA) committee in charge of planning the transport system in Singapore. Your team receives a news report on the rise in the number of traffic accidents especially those involving elderly pedestrians.

From the report, your team realises that many of the accidents happened as the pedestrians were not observing traffic rules. Some elderly pedestrians got into accidents when they jaywalked or crossed the road when the green man was blinking as they overestimated their walking speed.

To reduce the number of traffic accidents, your team is tasked to propose how pedestrian crossings can be improved.

Use the following questions to guide you in coming up with your proposal. You may do a search on the Internet to find the answers.

- Besides elderly pedestrians, what are some other groups that take a longer time to cross roads?
- What are some technologies currently used at pedestrian crossings?
- How can we improve these technologies?

Link

Theory Workbook
Problem-based Learning: Application

Practical Workbook
Problem-based Learning: STEM Project

Cool Career

Sports Engineer

If you are someone who loves sports and technology, a career in sports engineering may be worth exploring. A sports engineer designs apparel for athletes that improves fluid (air or liquid) flow across the athletes' body to increase the speed of the athletes (Figure 2.39).

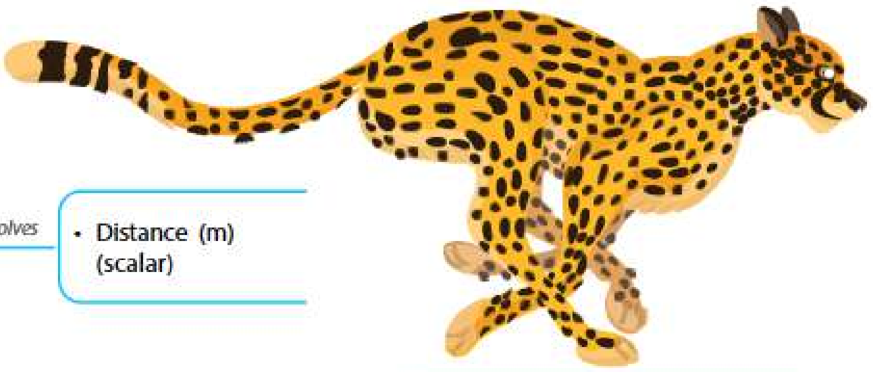
As speed is a major factor in sports such as running, skating and swimming, a sports engineer will need a good understanding of kinematics, fluid dynamics and material science. This will help them develop sports apparel that will minimise resistive forces during movement.

Besides apparel, a sports engineer also does research on other equipment, such as helmets and goggles. They also research on the postures that athletes need to be mindful of to achieve minimal drag (resistance) and therefore complete the race in the best possible times.

Figure 2.39 A sports engineer works closely with an athlete to improve his or her performance.

Let's Map It

Kinematics



can be described in terms of

- Speed (m/s) (scalar)

involves

- Distance (m) (scalar)

can be found by

- Speed = $\frac{\text{distance}}{\text{time taken}}$
- Average speed = $\frac{\text{total distance}}{\text{total time taken}}$
- Gradient of distance–time graph

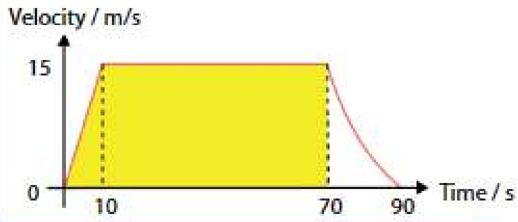
- Velocity (m/s) (vector)

involves

- Displacement (m) (vector)

can be found by

Area under velocity–time graph



can be found by

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

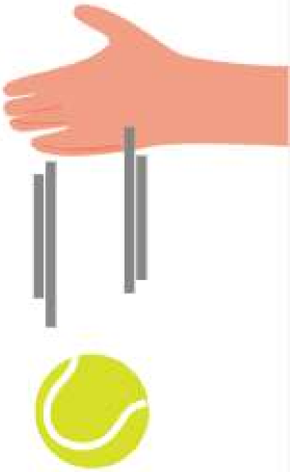
- Acceleration (m/s²) (vector)

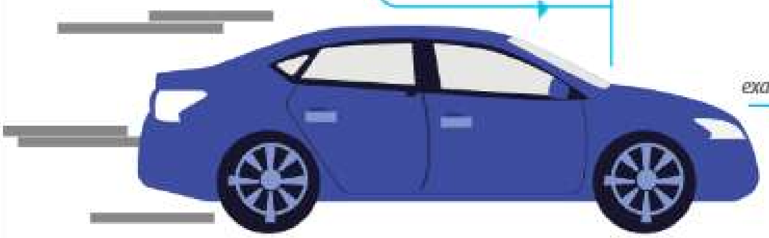
can be found by

- Acceleration = $\frac{\text{change in velocity}}{\text{time taken}}$
- Gradient of velocity–time graph

example

Acceleration of free fall for a body near Earth is constant and is approximately 10 m/s²





Let's Review

Section A: Multiple-choice Questions

1 The average speed of a car is 35 km/h. How far can it travel in 45 minutes?

○ A 0.78 km
○ B 26.25 km
○ C 129 km
○ D 467 km

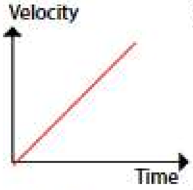
2 A car accelerates uniformly from 5 m/s to 13 m/s in 4.0 s. What is the acceleration of the car?

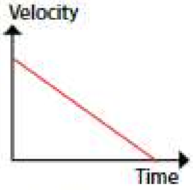
○ A 0.50 m/s²
○ B 0.80 m/s²
○ C 1.25 m/s²
○ D 2.00 m/s²

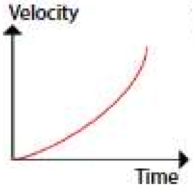
3 A ball that is thrown vertically upwards at 1.2 m/s decelerates uniformly at 10 m/s². How long will it take to reach zero velocity?

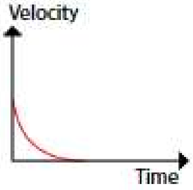
○ A 0.12 s
○ B 2.4 s
○ C 6.0 s
○ D 12.0 s

4 Which of the following velocity–time graphs represents the motion of an object slowing down at a non-uniform deceleration?

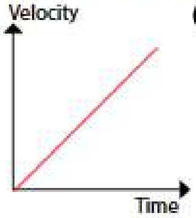
○ A


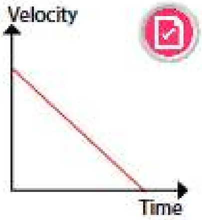
○ B


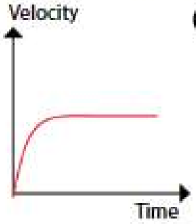
○ C


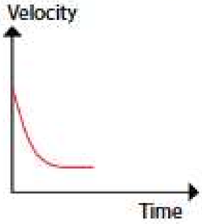
○ D


5 Which of the following velocity–time graphs represents the motion of an object falling to the ground in the absence of air resistance?

○ A


○ B


○ C


○ D


Section B: Structured Questions

1 (a) Define *average speed*.

(b) Figure 2.40 shows a cyclist's route. He started from point A at 6 am and went past three other points B, C and D, before returning to point A at 6 pm.

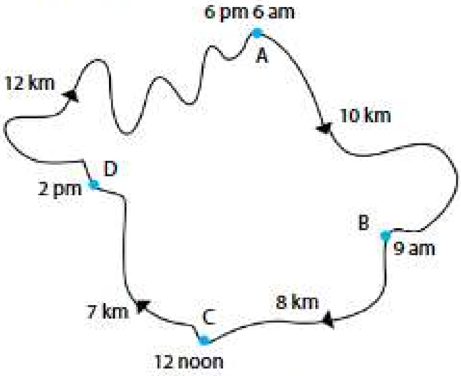


Figure 2.40

Calculate the average speed of the cyclist:

(i) from A to B;
(ii) from B to C; and
(iii) for the whole journey.

2 Figure 2.41 shows the velocity–time graphs for four particles A, B, C and D.

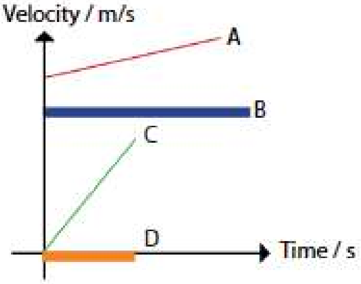


Figure 2.41

Describe the motion of these four particles.

3 A train travels along a straight track from one station to another. Figure 2.42 shows how the velocity of the train varies with time over the whole journey.

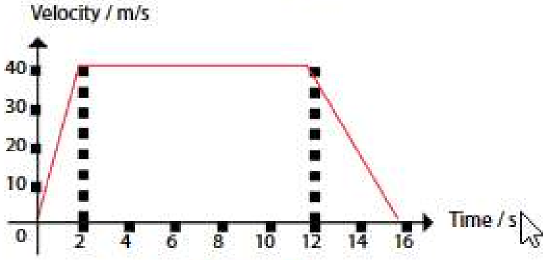


Figure 2.42

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

(b) Determine the acceleration of the train during the first two seconds of the journey.

(c) Determine the:

- **(i)** displacement between the two stations; and
- **(ii)** average speed of the train.

4 Figure 2.43 shows how the velocity of a moving body varies with time t.

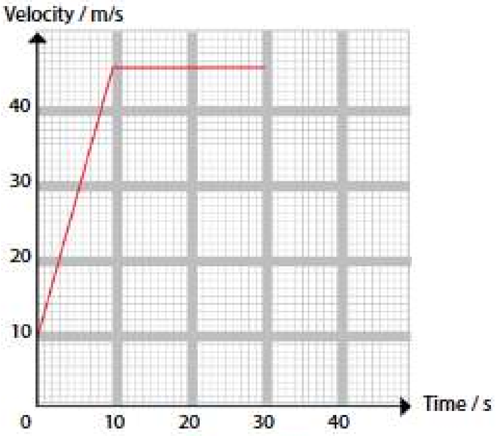


Figure 2.43

(a) Determine the acceleration of the body during the first 10 s.

(b) Between $t = 30$ s and $t = 45$ s, the body decelerates uniformly to rest.

- **(i)** Complete the graph for this time interval.
- **(ii)** From the graph drawn in **(b)(i)**, obtain the velocity of the body when $t = 37.5$ s.

(c) Determine the displacement of the body between $t = 30$ s and $t = 45$ s.

5 Figure 2.44 shows how the velocity of a car varies with time t.

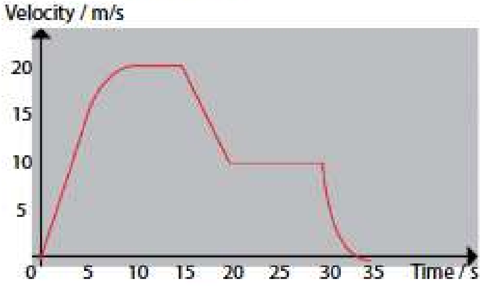


Figure 2.44

Describe the motion of the car between:

(a) $t = 0$ s and $t = 5$ s;
(b) $t = 5$ s and $t = 10$ s;
(c) $t = 10$ s and $t = 15$ s;
(d) $t = 15$ s and $t = 20$ s;
(e) $t = 20$ s and $t = 30$ s; and
(f) $t = 30$ s and $t = 35$ s.

Section C: Free-response Questions

1 Figure 2.45 shows a smooth track ABCD. The track has a horizontal section BC calibrated in metres. A smooth, steel ball bearing of mass 0.3 kg was released from a point on the slope AB.

Figure 2.45

A stopwatch was used to time how long it took the ball bearing to go past the various calibration marks. The times were recorded in the Table 2.5. The timing on the stopwatch started some time after the ball bearing went past B.

Table 2.5

Displacement from B / m	Time / s
2.0	3.5
3.0	6.0
4.0	8.5
5.0	11.0

(a) Using graph paper, plot a displacement–time graph for the steel ball bearing.
(b) Calculate the average speed of the ball bearing between the 3.0 m and 4.0 m marks.
(c) Assuming that there was negligible friction between the ball bearing and the track, calculate the displacement of the ball bearing from B just before the timing started on the stopwatch.
(d) What was the acceleration of the ball bearing as it rolled along BC? Explain your answer.
(e) The ball bearing slowed down on its way up slope CD and stopped momentarily at point T before rolling back down the slope. Given that at T the reading on the stopwatch was 13 s, calculate the deceleration of the ball bearing as it rolled up slope CD.

2 A feather was released from rest in a vacuum, and then in air. In both situations, the feather was released from a significant height.

(a) Compare and comment on the motion of the feather in a vacuum and in air.
(b) Sketch the velocity–time graphs of the motion of the feather in a vacuum and in air.

CHAPTER

03 Dynamics I: Mass and Weight

What You Will Learn

- What are the types of forces?
- Is mass the same as weight?

Have you watched a video on the launch of a satellite before? A lot of fuel is burnt to launch the rocket carrying the satellite from Earth towards space. Once in space, the satellite is separated from the rocket and the satellite orbits around Earth.

On 18 January 2019, a satellite that was built by scientists from Nanyang Technological University (NTU) and Kyushu Institute of Technology (Kyutech) was successfully launched into space. This was the ninth satellite that was successfully deployed by NTU.

What can we say about the mass and weight of the satellite as it is launched from Earth into space?

3.1 What Are the Types of Forces?

Learning Outcome

- Identify and distinguish between contact forces and non-contact forces.

Forces

To move our luggage from one point to another, we can either push it or pull it (Figure 3.1).

Intuitively, a force can be thought of as a push or a pull due to interaction between objects to explain changes in motion. When a force is exerted on an object, the object can start or stop moving, slow down or speed up. It can also change the direction of motion of the object.

Figure 3.1 Our hands exert either a push or a pull on our luggage to move it.

Disciplinary Idea

Matter interacts through forces and fields.

Bodies can interact with and exert forces on each other by physical contact or across a distance without physical contact.

Types of Forces

Forces are produced by the interaction between objects. Forces can be classified into two types:

- non-contact forces, which do not require objects to be in contact to exist; and
- contact forces, which exist between objects that are in contact.

Figure 3.2 lists some non-contact forces.

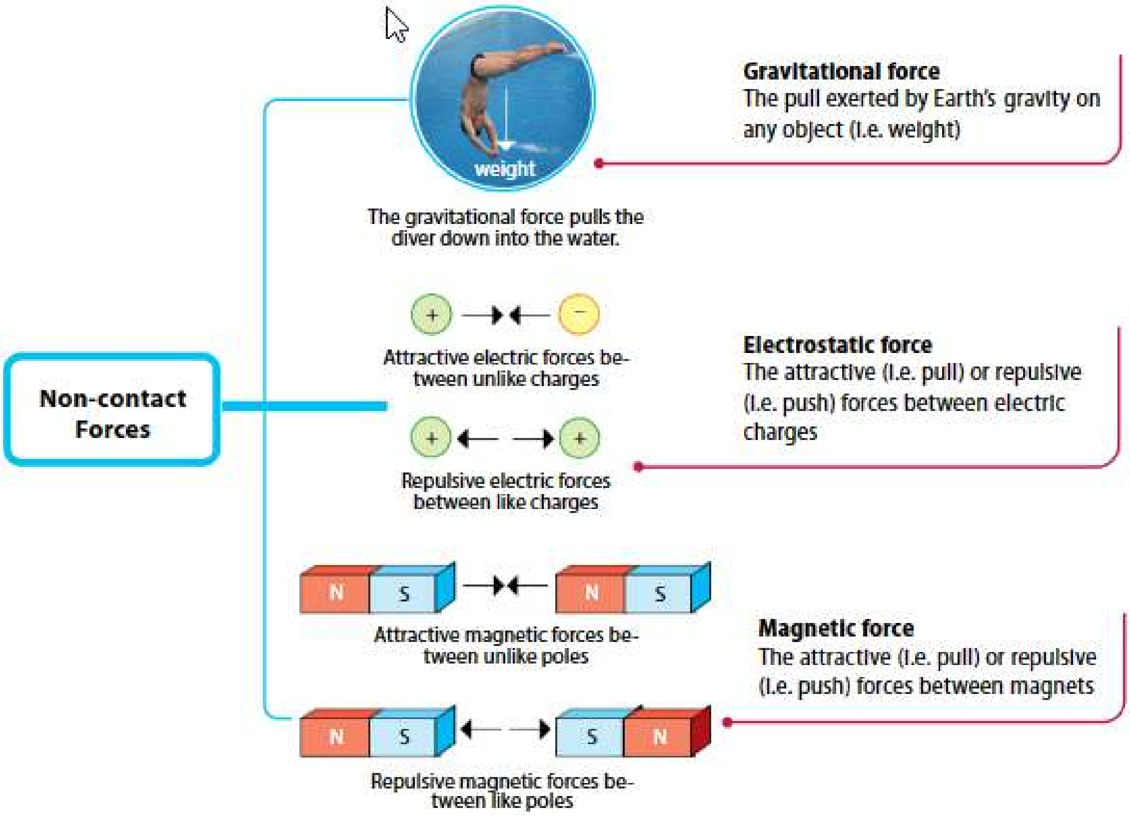
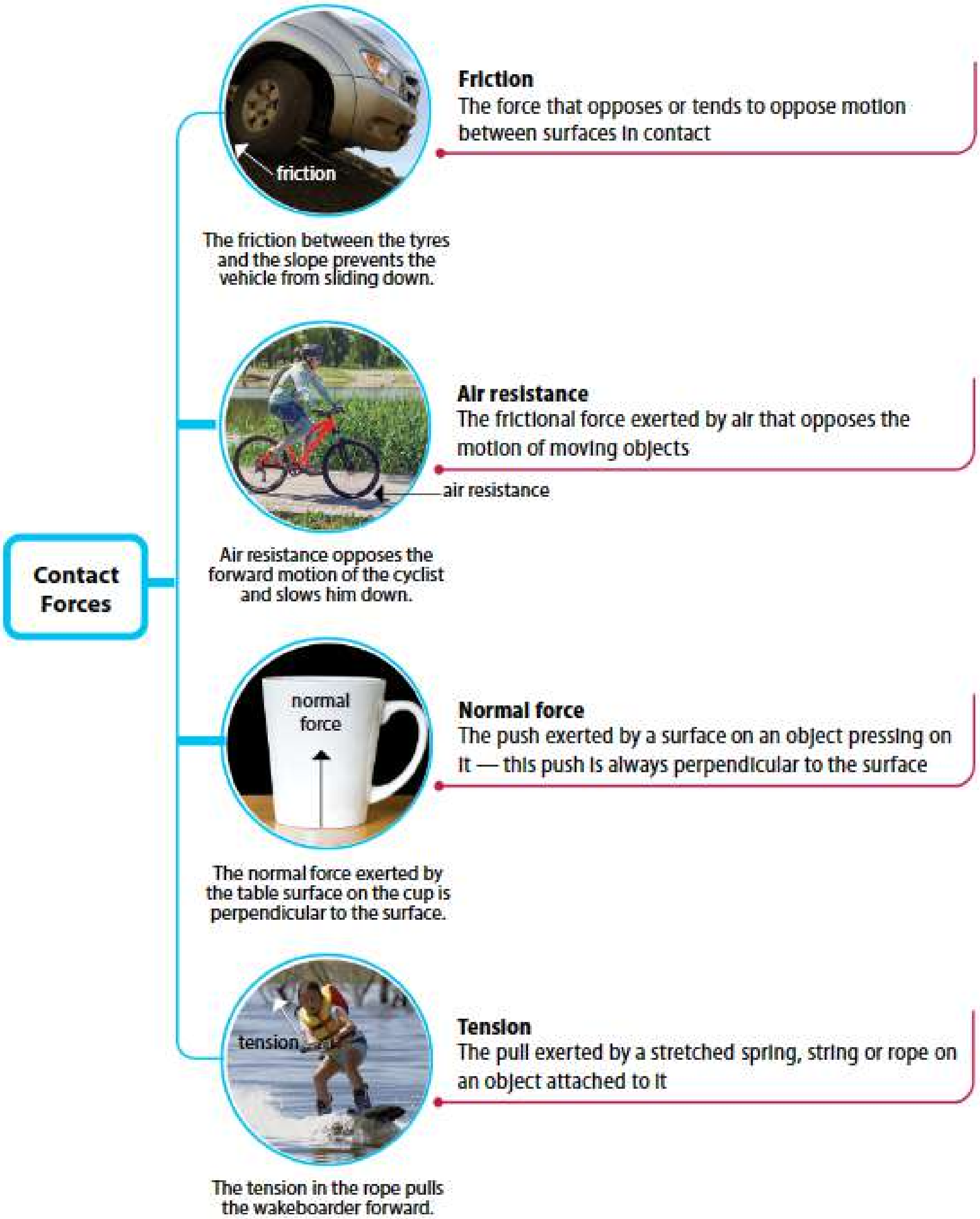


Figure 3.2 Types of non-contact forces and their nature

Figure 3.3 lists some contact forces.



Friction
The force that opposes or tends to oppose motion between surfaces in contact

The friction between the tyres and the slope prevents the vehicle from sliding down.

Air resistance
The frictional force exerted by air that opposes the motion of moving objects

Air resistance opposes the forward motion of the cyclist and slows him down.

Normal force
The push exerted by a surface on an object pressing on it — this push is always perpendicular to the surface

The normal force exerted by the table surface on the cup is perpendicular to the surface.

Tension
The pull exerted by a stretched spring, string or rope on an object attached to it

The tension in the rope pulls the wakeboarder forward.

Figure 3.3 Types of contact forces and their nature

Let's Practise 3.1

1 (a) What is a *force*?
(b) What can a force do?
2 (a) Name **three** types of forces in our daily lives.
(b) Are the forces in (a) contact forces or non-contact forces?

Link
Theory Workbook
Worksheet 3A

3.2 Is Mass the Same as Weight?

Learning Outcomes

- State that mass is a measure of the amount of matter in a body.
- State that a gravitational field is a region in which a mass experiences a force due to gravitational attraction.
- Define *gravitational field strength g*.
- Recall and apply the relationship *weight = mass × gravitational field strength* to new situations or to solve related problems.
- Distinguish between mass and 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?

Mass

▶ **Mass** is a measure of the amount of matter in a body.

Its SI unit is the **kilogram (kg)**.

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.

Helpful Note

The body or object has to be at rest when the observer measures the amount of matter in it.

Scientists have found that when an observer looks at an object moving at very high speeds (near to the speed of light), he or she 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.

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 Earth. This force is the gravitational pull (gravitational force or gravity) exerted by Earth.

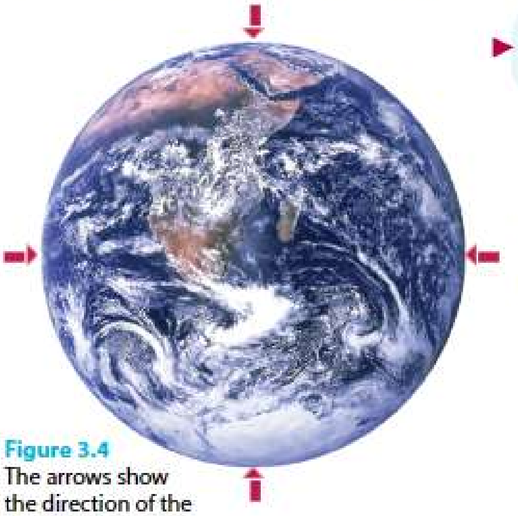


Figure 3.4
The arrows show the direction of the gravitational force.

▶ **Weight** is the gravitational force acting 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 Earth (Figure 3.4).

Helpful Note

The SI unit of force is newton (N), which is named after a famous physicist, Sir Isaac Newton.

Gravitational Field

We 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 in which a mass experiences a force due to gravitational attraction.

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

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 Earth. This is because the moon's gravitational field strength is weaker than Earth's gravitational field strength.

▶ **Gravitational field strength g** is defined as the gravitational force per unit mass placed at that point.

In equation form:

▶ $$g = \frac{W}{m}$$

where g = gravitational field strength (N/kg)
W = weight (N)
m = mass of the object (kg)

On Earth, the gravitational field strength g is approximately 10 N/kg. This means that a 1 kg mass on Earth's surface experiences a force of 10 N due to 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 Earth's surface and the moon's surface (Figure 3.5). The elephant would weigh much more on Earth's surface than on the moon's surface even though its mass remains unchanged.

Disciplinary Idea

Matter interacts through forces and fields.

To explain the non-contact forces between two bodies, we say that the interaction between them is mediated through fields such as gravitational field, electric field and magnetic field.

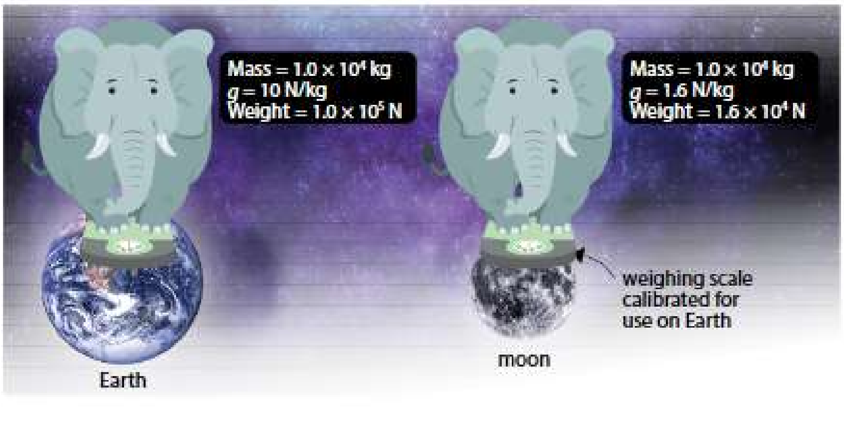


Figure 3.5 The elephant has a smaller weight when it is on the moon.

Relation Between Mass and Weight

From the equation $g = \frac{W}{m}$, we have $\mathbf{W = mg}$.

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 also doubles.

Word Alert

Directly proportional: 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.

Answer

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 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:

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

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

Link

When unbalanced forces act on an object of mass m, the object will accelerate in the direction of the resultant force. You will learn more about this in Chapter 4.

▶ $\mathbf{F = ma}$ where F = resultant force (N)
m = mass (kg)
a = acceleration (m/s^2)

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).

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

By comparing equations (1) and (2), we can see that gravitational field strength near the Earth's surface ($g = \frac{W}{m} = 10$ N/kg) is equivalent to the acceleration of free fall ($g = \frac{W}{m} = 10 \text{ m/s}^2$).

Common Weighing Instruments

Common weighing instruments like the spring balance, bathroom scale and electronic balance measure the weight of an object, not its mass (Figure 3.6). These machines, however, are calibrated to give readings in grams (g) or kilograms (kg).

Figure 3.6 The electronic balance is a commonly used weighing instrument for measuring mass. In fact, electronic balances measure weight, but they are calibrated to give readings for mass.

Using these weighing 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 Earth. This is because the gravitational field strength on the moon (1.6 N/kg) is less than that on Earth (10 N/kg).

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

Figure 3.7 A beam balance is used to measure mass.

Measurement of Mass

To avoid having to calibrate weighing scales for different gravitational field strengths, the mass of an object can be measured using a beam balance (Figure 3.7).

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 Earth or on the moon, will be the same.

Table 3.1 shows how mass is different from weight.

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/s². The acceleration of free fall on Earth is 10 m/s². A rock has a mass of 10 kg on Earth. Calculate the weight of the rock on:

(a) Earth; and

(b) the moon.

Thought Process

We know that:

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

Answer

(a) Weight of the rock on Earth = $10\ \text{kg} \times 10\ \text{m/s}^2 = 100\ \text{N}$

(b) Weight of the rock on the moon = $10\ \text{kg} \times 1.6\ \text{m/s}^2 = 16\ \text{N}$

(Note: $1\ \text{kg m/s}^2 = 1\ \text{N}$)

Past to Present

An interesting age-old device that is used for measuring mass is the traditional Chinese weighing device commonly used to measure herbs (Figure 3.8). Have you ever wondered how it works?

The herbs of unknown mass *m* are placed on a circular pan at one end of a copper bar. This creates a downward force at the pan. The bar is not balanced. By shifting a suspended piece of bronze weight of known mass along the bar, the copper bar can be balanced. The user then reads the markings on the bar to know the mass of the herbs on the pan.

This device is not as accurate as the electronic balance that is more commonly used today.

Figure 3.8 Traditional weighing scale

We can show the difference between mass and weight using a simple experiment. Look at Figure 3.9. Do you know whose guess is correct? Can you explain why?

Figure 3.9 Simple experiment to show the difference between mass and weight

The string above the ball will break when the string is pulled with a gradual increase in force.

The tension in the string above the ball balances the weight of the ball. When the string is pulled with a gradual increase in force, both the pull (downward force) and the weight of the ball acts on the string above the ball. Thus, the string breaks.

When there is a sudden pull on the string, the pull exerted is not transmitted to the string above the ball. The string below the ball breaks as the mass of the ball has a tendency to remain stationary and resists the sudden change in motion. This concept of inertia will be covered in Chapter 4.

Link

Theory Workbook
Worksheet 3B
Let's Assess
Let's Reflect

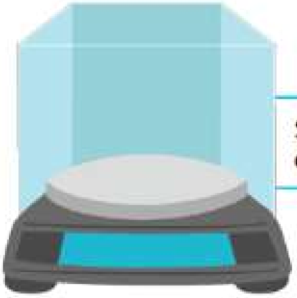
Let's Practise 3.2

1 List **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 Earth's. If a person has a mass of 60 kg on Earth, how much will he weigh on the moon?

Let's Map It

Mass *m* (SI unit: kg)

- *is defined as* A measure of the amount of matter in a body
- *is a* Scalar quantity
- *values may be compared using*
  - Electronic balance
  - Beam balance
- *is related to* Weight *W*



Weight *W* (SI unit: N)

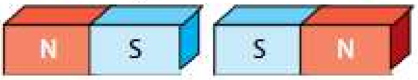
- *values may be compared using*
  - Spring balance
- *is a* Vector quantity
- *is related to* Types of Forces
- *is defined as* Gravitational force acting on an object that has mass

Types of Forces

examples

Contact forces
- Friction
- Air resistance
- Tension
- Normal force

Non-contact forces
- Gravitational force
- Electrostatic force
- Magnetic force



Gravitational force acting on an object that has mass

- *due to* The effect of a gravitational field, which is a region in which a mass experiences a force due to gravitational attraction

$W = mg$

where

Gravitational field strength g is the gravitational force per unit mass placed at that point.

which is equivalent to

Acceleration of free fall g for a body near to Earth

Let's Review

Section A: Multiple-choice Questions

1 Which of the following is a non-contact force?

○ A Attractive magnetic forces between unlike poles of two magnets
○ B Frictional force between the shoes of a person walking on a pavement
○ C Force exerted by the wall on the person leaning on it
○ D Force exerted by the water on a boat floating in a lake

2 Which of the following is a contact force?

○ A Attractive electric forces between two unlike charges
○ B Frictional force between the tyres of a moving car and the road
○ C Pull exerted by Earth's gravity on an apple in a tree
○ D Repulsive magnetic forces between like poles of two magnets

3 Which of these statements is correct?

○ A The mass of an object can be measured with a spring balance.
○ B The mass of an object does not change with location.
○ C The weight of an object can be measured with a beam balance.
○ D The weight of an object can never change.

4 An astronaut of weight 700 N on Earth landed on the moon's surface where the gravitational field strength is 1.6 N/kg. If the gravitational field strength on Earth is 10 N/kg, what is the weight of the astronaut on the moon?

○ A 112 N ○ B 160 N
○ C 438 N ○ D 700 N

Section B: Structured Questions

1 A breakfast cereal packet carries the 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; and
(b) weight of the contents.

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

3 What happens to the (a) mass and (b) weight of a satellite as it is launched from Earth into space?

4 We have learnt that Earth's gravitational field strength g (10 N/kg) is the same as the acceleration due to free fall, a_g (10 m/s^2). They are said to be dimensionally the same even though their units are different. Prove that N/kg is the same as m/s^2.

5 Look at Figure 3.10.

Figure 3.10

Identify the contact and non-contact forces acting on:

(a) the boy standing on the beach; and
(b) the boat floating in the sea.

Section C: Free-response Question

1 Explain the following observations.

(a) The mass of a piece of rock measured using a beam balance is the same on Earth and on the moon.
(b) The weight of the same piece of rock measured using a spring balance, is different on Earth and on the moon.

CHAPTER

04 Dynamics II: Forces

What You Will Learn

- What are Newton's Laws of Motion?
- What are free-body and vector diagrams?
- What are some effects of resistive forces on motion?

Jumping off an aircraft at an altitude of 4000 metres is definitely not for the faint hearted. Is it possible for someone to experience the thrill of skydiving without the need to jump from such a great height?

Yes! One can experience this at the world's largest skydiving simulator in Singapore. It is an indoor skydiving wind tunnel with a height of 17.2 metres and a diameter of 5.03 metres. What an amazing invention to make the skydiving dream come true for anyone young or old!

How do the skydivers stay suspended in the simulator?

Physics Connect

Scan the QR code to find out more about the forces acting on a skydiver.

4.1 What Are Newton's Laws of Motion?

Learning Outcomes

- Apply Newton's Laws to:
  - (i) describe the ways in which a force may change the motion of a body;
  - (ii) describe the effect of balanced and unbalanced forces on a body; and
  - (iii) identify action-reaction pairs acting on two interacting bodies.
- Recall and apply the relationship *resultant force = mass × acceleration* to new situations or to solve related problems.
- Show an understanding that mass is the property of a body which resists change in motion (inertia).

Link

Recall from Chapter 3: There are different types of forces around us. Some are contact forces while others are non-contact forces.

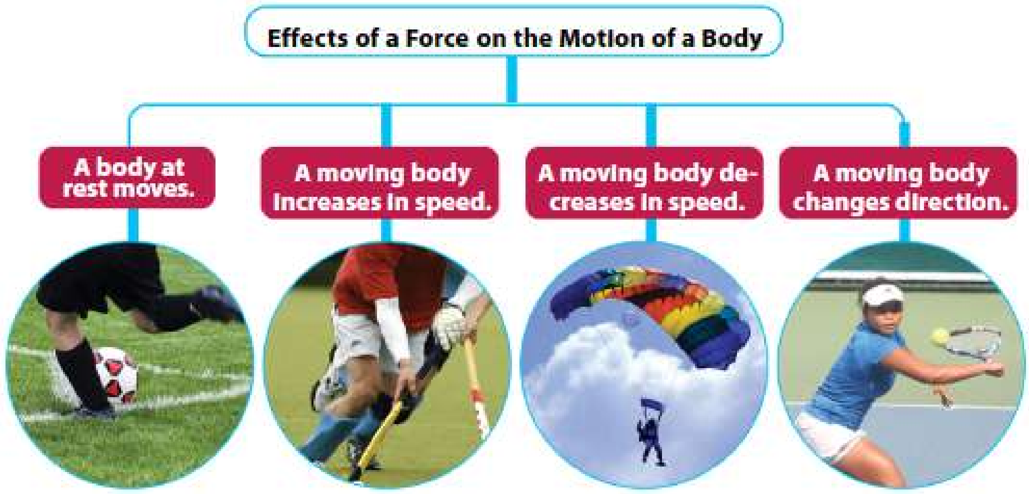
Effects of a Force on the Motion of a Body

We can observe how forces affect the motion of objects in sports (Figure 4.1).

Disciplinary Idea

Forces help us understand motion.

Dynamics describes the relationship between the motion of bodies found in our universe and the forces acting on them.



A stationary football moves when it is kicked. There is a change in speed.

A moving hockey ball moves faster when it is pushed. There is an increase in speed.

A descending parachutist slows down due to air resistance. There is a decrease in speed.

A moving tennis ball is returned when it is hit. There is a change in direction.

Figure 4.1 Effects of forces on the motion of a body in sports

Link

A force acting on an object can cause the object to turn. This is known as the turning effect of a force. You will learn more about this in Chapter 5.

In each of the four sports in Figure 4.1, when a force is applied on an object, there is a change in speed and/or direction over time. In other words, there is a change in velocity. This means that there is acceleration (or deceleration). Thus, a force can cause an object to accelerate (or decelerate).

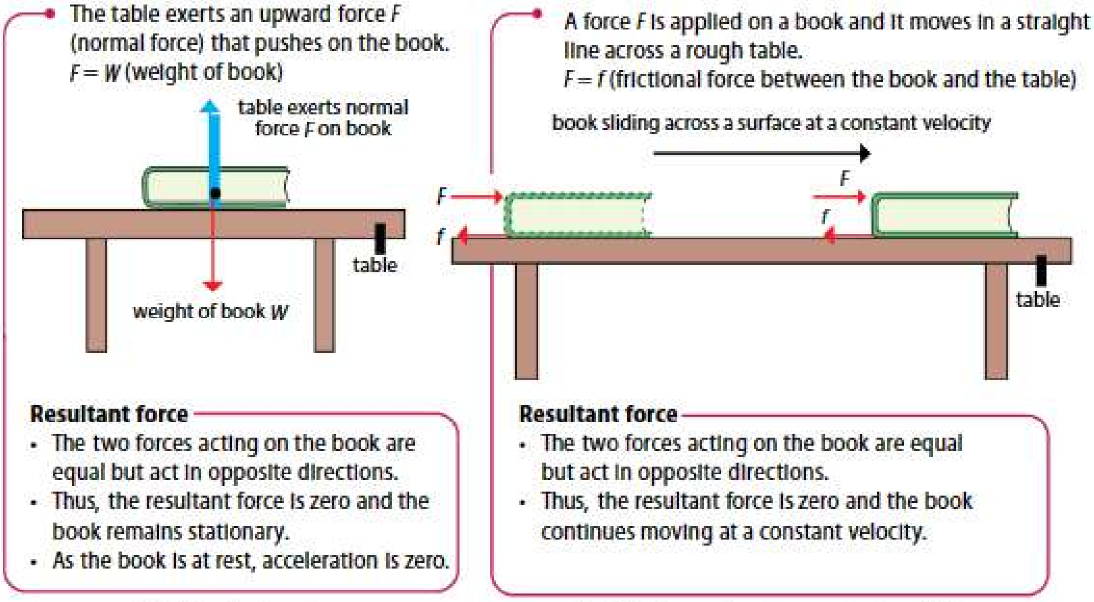
Does this mean there are no forces acting on an object when its acceleration is zero?

Zero acceleration implies that the object can be stationary or moving with constant velocity (Figure 4.2). However, even though acceleration is zero, it does not mean there are no forces acting on it. It means that the resultant of these forces is zero.

Figure 4.2 Even when we are motionless on a weighing scale, it still measures a force that acts on us — our weight.

Balanced Forces and Newton's First Law

If the resultant force acting on an object is zero, we say the forces acting on the object are **balanced** (Figure 4.3).



The table exerts an upward force F (normal force) that pushes on the book. $F = W$ (weight of book)

Resultant force

- The two forces acting on the book are equal but act in opposite directions.
- Thus, the resultant force is zero and the book remains stationary.
- As the book is at rest, acceleration is zero.

A force F is applied on a book and it moves in a straight line across a rough table. $F = f$ (frictional force between the book and the table)

Resultant force

- The two forces acting on the book are equal but act in opposite directions.
- Thus, the resultant force is zero and the book continues moving at a constant velocity.

(a) A book at rest (b) A book moving at a constant velocity

Figure 4.3 Forces on an object at rest or moving at a constant velocity are balanced. The resultant force on each object is zero.

The two examples in Figure 4.3 illustrate Newton's First Law of Motion (i.e. the Law of Inertia).

▶ **Newton's First Law of Motion** states that every object will continue in its state of rest or uniform motion in a straight line unless a resultant force acts on it.

We now know how an object behaves if the resultant force acting on it is zero. What if the resultant force is not zero?

Past to Present

In the past, it was thought that a force needs to constantly act on a moving body to keep it in motion. However, in the 17th century, Galileo Galilei overturned this widely accepted theory through experiments. He discovered that a body in motion would remain in motion unless a force acts on it.

Sir Isaac Newton built on Galileo's work and came up with the laws of motion. This shows the spirit of collaboration where scientists build on scientific knowledge in light of new evidence from experiments.

Disciplinary Idea

Forces help us understand motion.

Based on Newton's First Law of Motion, when the resultant force acting on a body is zero, the body is at rest or is moving at a constant velocity.

Inertia

Imagine you are on a safari in Africa when a big elephant suddenly comes charging at you. To escape the charging elephant, should you run in a straight line or in a zigzag manner (Figure 4.4)?

The answer may seem obvious, but what is the reasoning behind it? To explain it, we need to understand *inertia* and how it is related to mass.

Figure 4.4
How would you escape a charging elephant?

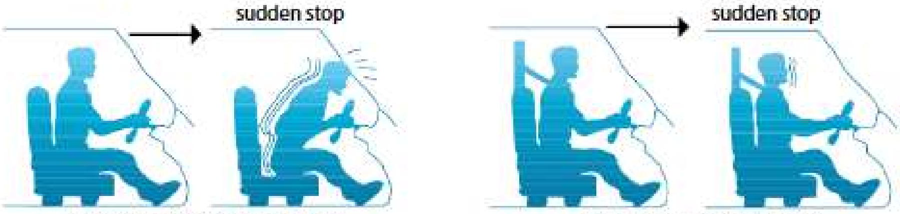
The **inertia** of an object refers to the reluctance of the object to change its state of rest or motion, due to its mass.

Mass is the property that resists the change in motion (inertia). An object with a greater mass will have greater inertia. In other words, the larger the mass of an object, the harder it will be for the object to:

- start moving;
- slow down;
- move faster; or
- change direction.

This explains why it is harder for an elephant to chase you in a zigzag manner. In fact, if the elephant tries to do that, it will probably trip and fall!

Inertia also explains why people should wear seat belts. If the driver suddenly applies the brakes, he will continue to move forward due to his inertia. Without a seat belt holding him back, he would crash into the windscreen (Figure 4.5(a)). A seat belt provides the necessary opposing force that stops him (Figure 4.5(b)).



(a) Driver not wearing seat belt (b) Driver wearing seat belt

Figure 4.5 Seat belts are designed to help prevent injury.

Disciplinary Idea
Matter and energy make up the universe.

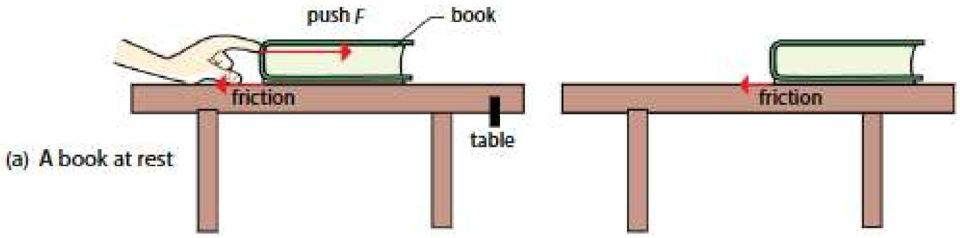
Inertia is due to the mass of a body.

Unbalanced Forces and Newton's Second Law

If the resultant force acting on an object is not zero, we say the forces acting on the object are **unbalanced**.

In Figure 4.3(b), the forces acting on the book are balanced and it moves at a constant velocity. If the applied force F is now increased, the forces that act on the book are no longer balanced and the book accelerates (Figure 4.6(a)).

If the applied force F is now removed while the book is still in motion (Figure 4.6(b)), friction is the resultant force. The resultant force causes the book to decelerate and eventually stop.



(a) If the push is larger than the friction, the book will accelerate.

(b) When the pushing force is removed, the only force acting on the book is friction. This will cause the book to decelerate to a stop.

Figure 4.6 Friction causes a book to decelerate.

When there is a resultant force acting on an object, the object will accelerate in the direction of the resultant force. The relationship between resultant force, mass and acceleration is described by Newton's Second Law of Motion.

Link

Practical Workbook
Experiment 4A

Newton's Second Law of Motion states that when a resultant force acts on an object of a constant mass, the object will accelerate in the direction of the resultant force.

The product of the mass and acceleration of the object gives the resultant force.
Newton's Second Law of Motion in symbols:

$F = ma$ where F = resultant force (N)
m = mass of object (kg)
a = acceleration of object (in m/s^2)

Newton's Second Law of Motion tells us that:

- a resultant force F on an object produces an acceleration a;
- doubling the resultant force F on an object doubles its acceleration a; and
- with the same resultant force F, doubling the mass m halves the acceleration a.

One newton is defined as the force that produces an acceleration of 1.0 m/s^2 on a mass of 1.0 kg.
If m = 1.0 kg and a = 1.0 m/s^2, by $F = ma$,
F = 1.0 kg × 1.0 m/s^2 = 1.0 kg m/s^2 = 1.0 N

Disciplinary Idea

Forces help us understand motion.

Based on Newton's Second Law of Motion, when the resultant force acting on a body is zero, the body is at rest or is moving at a constant velocity.

Worked Example 4A

A boy pushes a stationary box of mass 20 kg with a force of 50 N. Calculate the acceleration of the box. (Assume that there is no friction.)

Answer

Given: mass $m = 20$ kg
force $F = 50$ N

From Newton's Second Law:

$F = ma$, where a = acceleration of the box

$a = \frac{F}{m} = \frac{50\text{ N}}{20\text{ kg}} = 2.5\text{ m/s}^2$ in the direction of the applied force

Worked Example 4B

(a) A shipping container of mass 1000 kg rests on a frictionless floor. A rope pulls the container to the right, causing it to increase its speed to 20 m/s in 5 s. Calculate the tension force in the rope.

(b) Subsequently, the same container is pulled by an additional leftward tension force of 5000 N. Find the resultant acceleration and state its direction.

Thought Process

(a) From Newton's Second Law, tension force $T = ma$, where a = acceleration produced.

(b) The direction of the additional tension force is towards the left. This is opposite to the direction of the tension force of 4000 N in (a). Hence, the additional tension force is –5000 N.

Answer

Given: mass $m = 1000$ kg
initial speed $u = 0$ m/s
final speed $v = 20$ m/s
time $\Delta t = 5$ s

(a)
$$a = \frac{v - u}{t} = \frac{20\text{ m/s} - 0\text{ m/s}}{5\text{ s}} = 4\text{ m/s}^2$$

$$\therefore T = ma = 1000\text{ kg} \times 4\text{ m/s}^2 = 4000\text{ N}$$

(b) Resultant force $F = 4000\text{ N} + (-5000\text{ N}) = -1000$ N

$$a = \frac{F}{m} = \frac{-1000}{1000} = -1.0\text{ m/s}^2$$

The resultant acceleration is 1.0 m/s² to the left.

Helpful Note

The relationship $a = \frac{v - u}{t}$ only applies to motion of uniform acceleration.

Newton's Third Law

When you swim in a pool, do you sometimes push your feet against the wall to push yourself forward? When you do this, you are applying Newton's Third Law of Motion (Figure 4.7). This law indicates that forces occur in pairs.

▶ **Newton's Third Law of Motion** states that if body A exerts a force F_{AB} on body B, then body B will exert an equal and opposite force F_{BA} on body A.

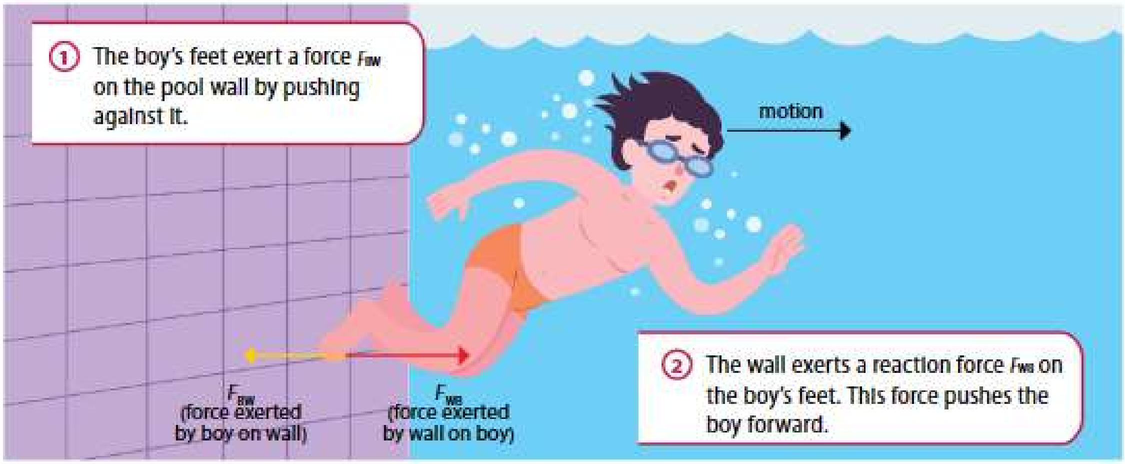
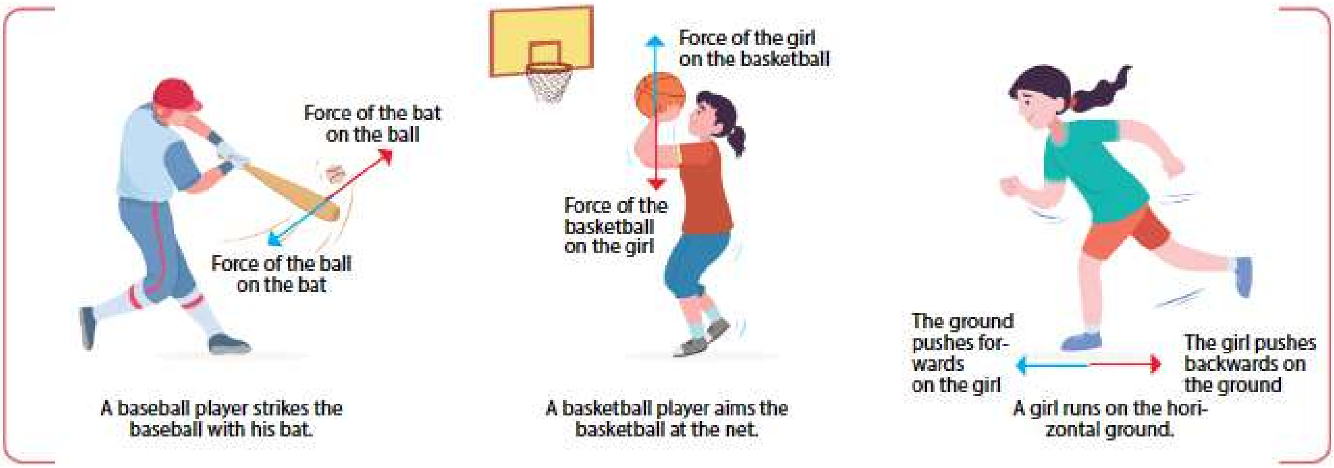


Figure 4.7 Newton's Third Law of Motion at work

In Figure 4.7, F_{BW} and F_{WB} occur as a pair. They are equal in magnitude, but act in opposite directions. F_{BW} acts on the wall, while F_{WB} acts on the boy. Thus, for every action, there is an equal and opposite reaction.

Figure 4.8 shows some examples of action–reaction pairs.



A baseball player strikes the baseball with his bat.

A basketball player aims the basketball at the net.

A girl runs on the horizontal ground.

Figure 4.8 Some examples of action and reaction forces

Weight is a force exerted by gravity on every object. Consider a book that is placed on a table. Does the force of the table on the book form an action–reaction pair with the weight of the book?

Disciplinary Idea

Matter interacts through forces and fields.

Based on Figure 4.9, we can conclude that if a field (e.g. gravitational field of Earth) exerts a force on a body, the body exerts an equal and opposite force on the source of the field.

In Figure 4.9, we examine the forces acting on:
- the book; and
- the table with the book.

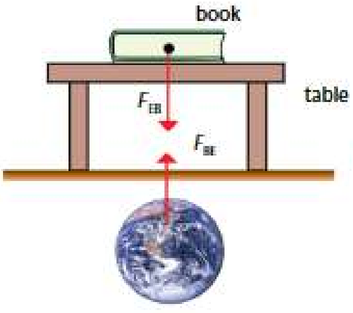


Figure 4.9(a) Forces between the book and Earth

F_{EB} is the gravitational force of Earth on the book.
F_{BE} is the gravitational force of the book on Earth.

F_{TB} is the normal force by the table on the book.
F_{BT} is the normal force by the book on the table.

Note: F_{BT} is not the weight of the book.

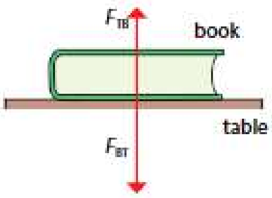


Figure 4.9(b) Forces between the book and the table

The pair of action and reaction forces are as shown.
- The gravitational force F_{EB} exerted by Earth on the book, and the upward force F_{BE} exerted by the book on Earth (Figure 4.9(a)).
- The normal force F_{TB} by the table on the book, and the normal force F_{BT} by the book on the table (Figure 4.9(b)).

Each action–reaction pair are equal in magnitude but act in opposite directions.

Disciplinary Idea

Forces help us understand motion.

Based on Newton's Third Law of Motion, forces are produced in pairs.

Hence, the force of the table on the book does not form an action–reaction pair with the weight of the book.

Newton's Third Law of Motion tells us four characteristics of forces:
1. Forces always occur in pairs. Each pair is made up of an action and a reaction forces.
2. Action and reaction forces are equal in magnitude.
3. Action and reaction forces act in opposite directions.
4. Action and reaction forces act on different bodies.

Let's Practise 4.1

1 What can you deduce about the resultant force acting on an object that is:
  (a) moving at a constant speed in a straight line; and
  (b) accelerating?

2 An unloaded van has an acceleration of 5 m/s^2. A fully loaded van has a mass, twice that of the unloaded van. If the forward thrust on both vans is the same, what is the acceleration of the fully loaded van?

3 The AIM-9 Sidewinder air-to-air missile, which the Singapore Air Force uses, has a mass of 86.5 kg. If the missile can accelerate from 300 m/s to 700 m/s in 6 s, what is the average resultant force on the missile? (Assume that the loss in mass of the missile is negligible after it is launched.)

4 Two groups of people get into two identical cars. One group consists of five sumo wrestlers, while the other group consists of five marathon runners. Assuming both drivers step on the accelerator such that the driving force for both cars is equal, state and explain which car:
  (a) takes off faster from rest; and
  (b) will need a longer braking distance, once in motion.

Link

Theory Workbook
Worksheet 4A

4.2 What Are Free-body and Vector Diagrams?

Learning Outcomes

- Identify forces acting on a body and draw free-body diagram(s) representing the forces acting on the body.
- Solve problems for a static point mass under the action of three forces for two-dimensional cases by a graphical method.

Free-body Diagrams

In Section 4.1, we have been using arrows to represent forces acting on individual objects. These diagrams are called **free-body diagrams**.

When we solve problems about forces, we need to identify the forces acting on individual objects or systems. Drawing a free-body diagram of an object helps us identify and visualise the forces and their effects on the object.

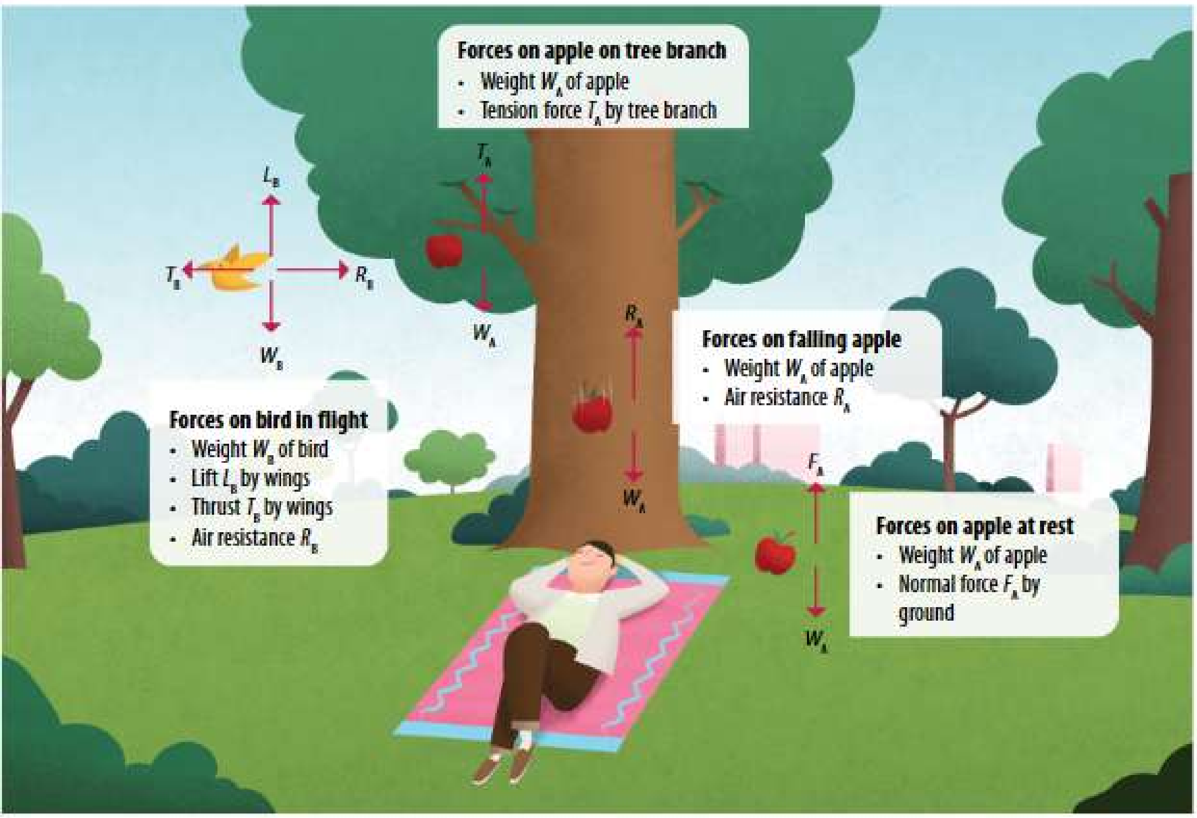
Figure 4.10 shows some examples of free-body diagrams. These examples will give you an idea of how to identify forces when solving a problem.

Disciplinary Idea

Conservation laws constrain the changes in systems.

A system can comprise of a single body or a collection of bodies. It can range from something as large as the solar system to something as small as a particle.

It is important to identify the system involved to analyse and understand its behaviour or motion under the interactions of forces.



Forces on apple on tree branch
- Weight W_A of apple
- Tension force T_A by tree branch

Forces on bird in flight
- Weight W_B of bird
- Lift L_B by wings
- Thrust T_B by wings
- Air resistance R_B

Forces on falling apple
- Weight W_A of apple
- Air resistance R_A

Forces on apple at rest
- Weight W_A of apple
- Normal force F_A by ground

Figure 4.10 Examples of free-body diagrams

Worked Example 4C

A truck engine of mass 5000 kg pulls a trailer of mass 1000 kg along a level track at an acceleration of 0.10 m/s² (Figure 4.11). The resistive force acting on the truck engine is 10 N per 1000 kg. The resistive force acting on the trailer is 5 N per 1000 kg.

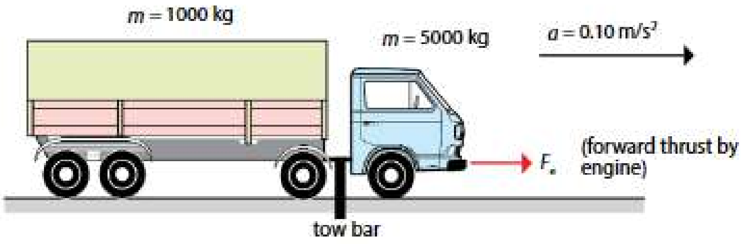


Figure 4.11

(a) Draw the free-body diagrams of the trailer and the engine (omit the vertical forces).

(b) Calculate the:

- **(I)** tension in the connecting tow bar between the engine and the trailer; and
- **(II)** forward thrust exerted by the engine.

Answer

(a)

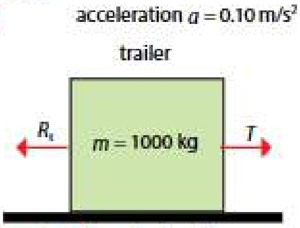


Figure 4.12 Free-body diagram of the trailer

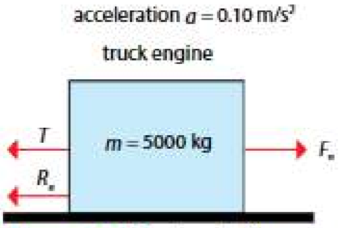


Figure 4.13 Free-body diagram of the engine

(b) Let us assign the rightward direction as positive.

(I) Note: Examine all the forces acting on the trailer only. Referring to Figure 4.12, two forces are acting on the trailer — tension T and the resistance R_t to the trailer.

For the trailer, using $F = ma$, where F is the resultant force on the trailer,

$$F = ma$$
$$T - R_t = ma$$
$$T = ma + R_t$$
$$= 1000 \text{ kg} \times 0.10 \text{ m/s}^2 + 5 \text{ N}$$
$$= 105 \text{ N}$$

(II) Note: Examine all the forces acting on the engine only. Referring to Figure 4.13, three forces are acting on the engine — the forward thrust F_e exerted by the engine, tension T, and the resistance R_e on the engine.

For the engine, using $F = ma$,

$$F_e - T - R_e = ma$$
$$F_e = ma + T + R_e$$
$$= 5000 \text{ kg} \times 0.10 \text{ m/s}^2 + 105 \text{ N} + 5 \times 10 \text{ N}$$
$$= 655 \text{ N}$$

Vector Diagrams

In Chapter 1, we have learnt how to add two vectors by the graphical method. We can apply what we have learnt to find the resultant force when three forces act on an object in two dimensions.

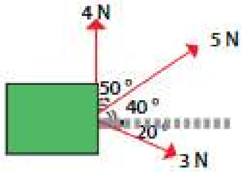
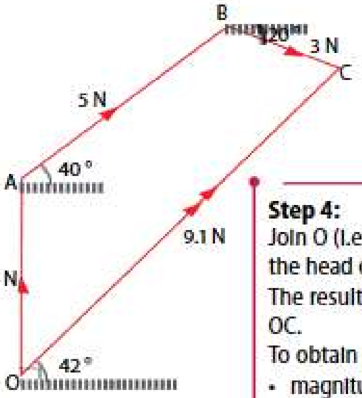


Figure 4.14 Three forces acting on a block

Consider three forces acting on a block (Figure 4.14).

Figure 4.15 describes how we can obtain the resultant force acting on the block.

Scale: 1 cm : 1 N



Step 1:
Choose an appropriate scale. Draw an arrow to represent one of the forces. Here, we draw OA to represent the 4 N force first.

Step 2:
From A, draw arrow AB to represent the 5 N force. The head of the arrow OA is joined to the tail of arrow AB.

Step 3:
From B, draw arrow BC to represent the 3 N force. The head of the arrow AB is joined to the tail of arrow BC.

Step 4:
Join O (i.e. the tail of the 4 N force) to C (i.e. the head of the 3 N force).
The resultant force is represented by arrow OC.
To obtain its:

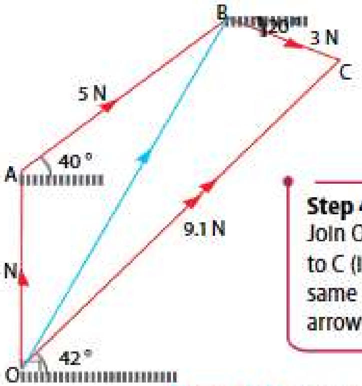
- magnitude, measure the length of OC; and
- direction, measure the angle of OC and the horizontal baseline.

Figure 4.15 Addition of three forces acting on an object in two dimensions

The resultant force on the block has a magnitude of 9.1 N, and acts at an angle of 42 ° to the horizontal.

Alternatively, the resultant force (OC) can also be found by first finding the resultant of the 4 N force (OA) and 5 N force (AB) as an intermediate step (Figure 4.16).

Scale: 1 cm : 1 N



Step 1:
Choose the appropriate scale. Draw OA and AB to represent the 4 N and 5 N forces, respectively.

Step 2:
Join O to B to form arrow OB. OB represents 8.17 N, the intermediate resultant force of OA and AB.

Step 3:
From B, draw an arrow BC to represent the 3 N force. The head of the arrow OB is joined to the tail of arrow BC.

Step 4:
Join O (i.e. the tail of the 8.17 N force) to C (i.e. the head of the 3 N force). The same resultant force represented by arrow OC is obtained.

Figure 4.16 Addition of three forces acting on an object by finding the intermediate force of two of the forces

Link

Recall from Chapter 1:
A vector diagram can be used to add up two vectors. In a vector diagram, a vector quantity is represented by an arrow.

Helpful Note

If arrows representing the forces result in a closed triangle, we say that the forces are in equilibrium (i.e. the resultant force is zero) (Figure 4.17).

If the arrows do not result in a closed triangle, there is a resultant force acting on the object. It is represented by the arrow from the tail of the first arrow to the head of the last arrow (Figure 4.18).

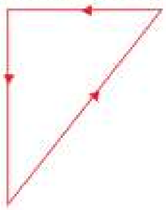


Figure 4.17 Forces acting on an object form a closed triangle if they are in equilibrium.

Figure 4.18 Forces acting on an object do not form a closed triangle if they are not in equilibrium.

Worked Example 4D

An object O weighing 6.0 N hangs from the end of a string OC that is pulled sideways by a force F. The string OC makes an angle of 30 ° with the vertical, as shown in Figure 4.19. The tension T has a magnitude of 7.0 N. Given that the resultant force is zero, determine the magnitude of the force F.

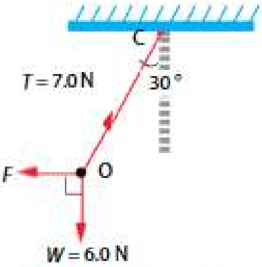


Figure 4.19 (Not drawn to scale)

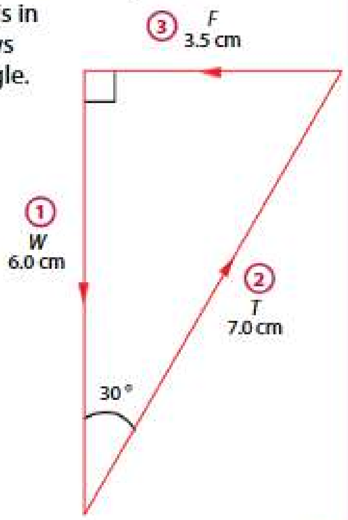
Thought Process
Since the resultant force is zero, the object is in equilibrium. In other words, the three arrows representing the forces form a closed triangle.

Answer

① Using a scale of 1 cm : 1 N, draw force vector W.

② Draw force vector T, with a 30 ° angle between the vectors W and T.

③ Since the object is in equilibrium (resultant force is zero), the arrows representing the forces W, F and T result in a closed triangle. Draw force vector F to complete the triangle.



By measurement, the length of F is 3.5 cm, so force F has a magnitude of 3.5 N.

Let's Practise 4.2

1 Draw a free-body diagram representing the four forces acting on a helicopter that is moving at a constant velocity (Figure 4.20).

Figure 4.20

2 An object O of weight W is supported by two strings (Figure 4.21). The tension in each string is 10 N. Using a vector diagram, find the value of W.

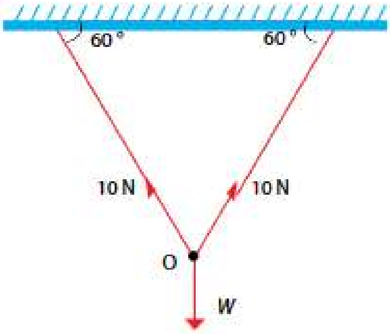


Figure 4.21

Link

Theory Workbook
Worksheet 4B

Practical Workbook
Experiment 4B

4.3 What Are Some Effects of Resistive Forces on Motion?

Learning Outcomes

- Explain the effects of friction on the motion of a body.
- Describe the motion of bodies with constant mass falling in uniform gravitational field with or without air resistance, including reference to terminal velocity.

Friction and Its Effects

Friction is the contact force that opposes or tends to oppose motion between surfaces in contact.

Friction opposes motion between surfaces in contact. It is the result of **irregularities** of the surfaces (Figure 4.22).

Word Alert

Irregularities: unevenness; not regular in shape

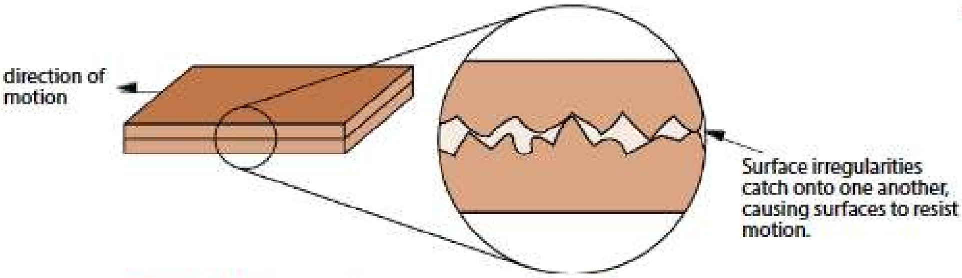


Figure 4.22 Microscopic view of two surfaces in contact

For example, if a force is applied to move a book across a table towards the right, friction will act towards the left. If the applied force is removed, friction will cause the book to slow down and come to a stop eventually.

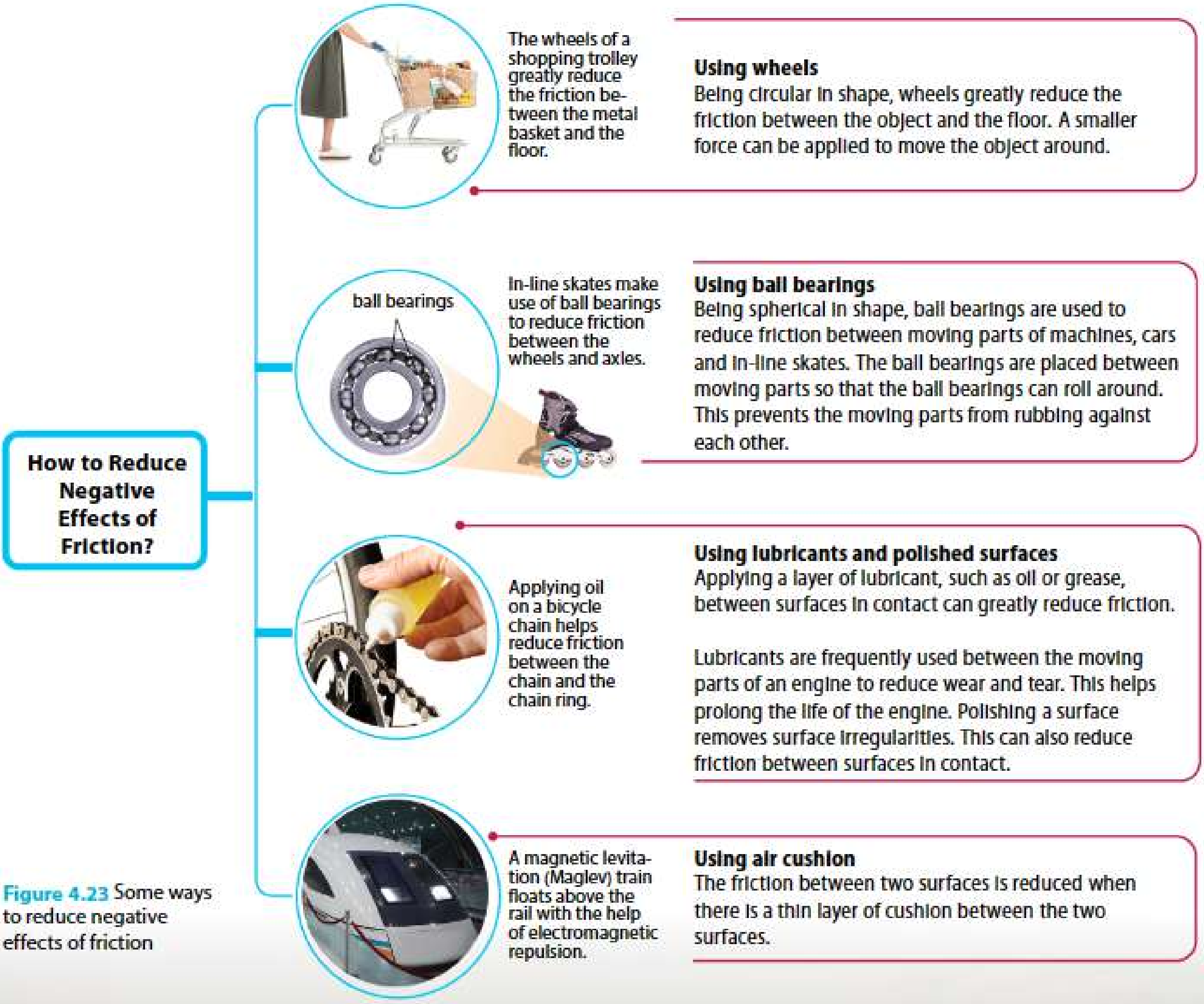
The effects of friction can be positive or negative. Table 4.1 lists some of these effects. Can you think of other effects of friction?

Table 4.1 Some positive and negative effects of friction

Positive Effects of Friction	Negative Effects of Friction
We can walk without slipping.	Cars are less efficient by up to 20%.
Moving objects are able to slow down when needed.	Moving parts in engines, motors and machines suffer wear and tear.

Reducing Negative Effects of Friction

Friction can result in wear and tear. There are different ways to reduce the negative effects of friction (Figure 4.23).



How to Reduce Negative Effects of Friction?

The wheels of a shopping trolley greatly reduce the friction between the metal basket and the floor.

Using wheels
Being circular in shape, wheels greatly reduce the friction between the object and the floor. A smaller force can be applied to move the object around.

In-line skates make use of ball bearings to reduce friction between the wheels and axles.

Using ball bearings
Being spherical in shape, ball bearings are used to reduce friction between moving parts of machines, cars and in-line skates. The ball bearings are placed between moving parts so that the ball bearings can roll around. This prevents the moving parts from rubbing against each other.

Applying oil on a bicycle chain helps reduce friction between the chain and the chain ring.

Using lubricants and polished surfaces
Applying a layer of lubricant, such as oil or grease, between surfaces in contact can greatly reduce friction.

Lubricants are frequently used between the moving parts of an engine to reduce wear and tear. This helps prolong the life of the engine. Polishing a surface removes surface irregularities. This can also reduce friction between surfaces in contact.

A magnetic levitation (Maglev) train floats above the rail with the help of electromagnetic repulsion.

Using air cushion
The friction between two surfaces is reduced when there is a thin layer of cushion between the two surfaces.

Figure 4.23 Some ways to reduce negative effects of friction

Do you know why high-pressure air is ejected from the underside of a hovercraft (Figure 4.24)?

Figure 4.24 A hovercraft ejects high-pressure air from its underside.

Enhancing Positive Effects of Friction

Despite the negative effects of friction, friction can be a useful force. There are different ways in which we make use of friction (Figure 4.25).

How to Enhance Positive Effects of Friction?

Treads on a car tyre increase the amount of friction between the tyre and the road. This reduces the chance of skidding on rainy days.

Using treads

Friction is important to the motion of vehicles. Without friction, a vehicle cannot move as its tyres will just spin at the same spot. Friction enables the tyres to grip the road surface and roll without slipping.

On a rainy day, a moving vehicle may skid on wet roads. Its tyres need to have more grip on the road to prevent skidding. Thus, tyres are designed with treads — grooves that quickly channel water out from underneath the tyres. This improves the grip of the tyres on wet roads, thus preventing skidding.

Parachute increases air resistance and helps the skydiver to fall slowly and land safely.

Using parachute

Air resistance is a type of friction in air. A skydiver in midair varies air resistance to change his speed.

- To speed up, he reduces air resistance by reducing the surface area in contact with the air (head-first position).
- To slow down, he increases air resistance by increasing the surface area in contact with the air (spread-eagle position).
- To achieve a safe landing, he increases air resistance significantly. He does this by making use of the much larger surface area of an open parachute.

Rock climbers carry a bag of chalk powder with them to improve their grip.

Using chalk

Rock climbers need to have a firm grip on the rock surface with their hands and feet. They usually use chalk powder on their hands to absorb perspiration and improve their grip.

Figure 4.25 Some ways to enhance positive effects of friction

Let us look at a positive effect of friction.

Let's Investigate 4A

Aim

To use friction to move an object

Procedure

1 Cut a piece of drinking straw into two pieces of equal length (4 cm each).
2 Stick the two pieces of drinking straw onto a piece of cardboard (Figure 4.26).
3 Pass a string through the two straws.
4 Hang the string on a nail or retort stand.
5 Hold both ends of the string. Make the string taut.
6 Pull each end of the string alternately so that the card will move up the string.

Discussion

When the string moves downwards from our pull on it, there is an opposing force acting in the opposing direction (i.e. friction acts upwards). Thus, the card moves up the string due to the friction between the string and the inside of the pieces of straw.

Question

1 Suggest a change to Figure 4.26 so that the card can move up faster when the amount of downward force exerted on the string remains the same.

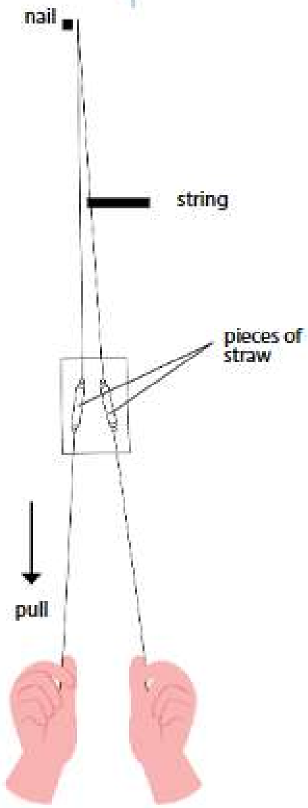


Figure 4.26

Cool Career

Indoor skydiving Instructor

Being an indoor skydiving instructor to bring the joy of skydiving to people of all ages is certainly an unusual and cool career.

Before certification by the International Bodyflight Association, the instructors need to demonstrate that they are physically fit and patient in coaching the students to ensure a safe and enjoyable skydiving experience for all. They also need to be knowledgeable in the resistive force that acts on the body when in different positions to guide their students accordingly (Figure 4.27).

Figure 4.27 An indoor skydiving instructor takes note of the resistive force on the body of the skydiver as he guides the student into different positions.

Objects Falling Without Air Resistance

An object can only be in free fall if the only force acting on it is its own weight. Figure 4.28 shows the path taken by a feather and by a hammer falling in a **vacuum** (i.e. in free fall).

Word Alert

Vacuum: a space where there is no matter (i.e. no air)

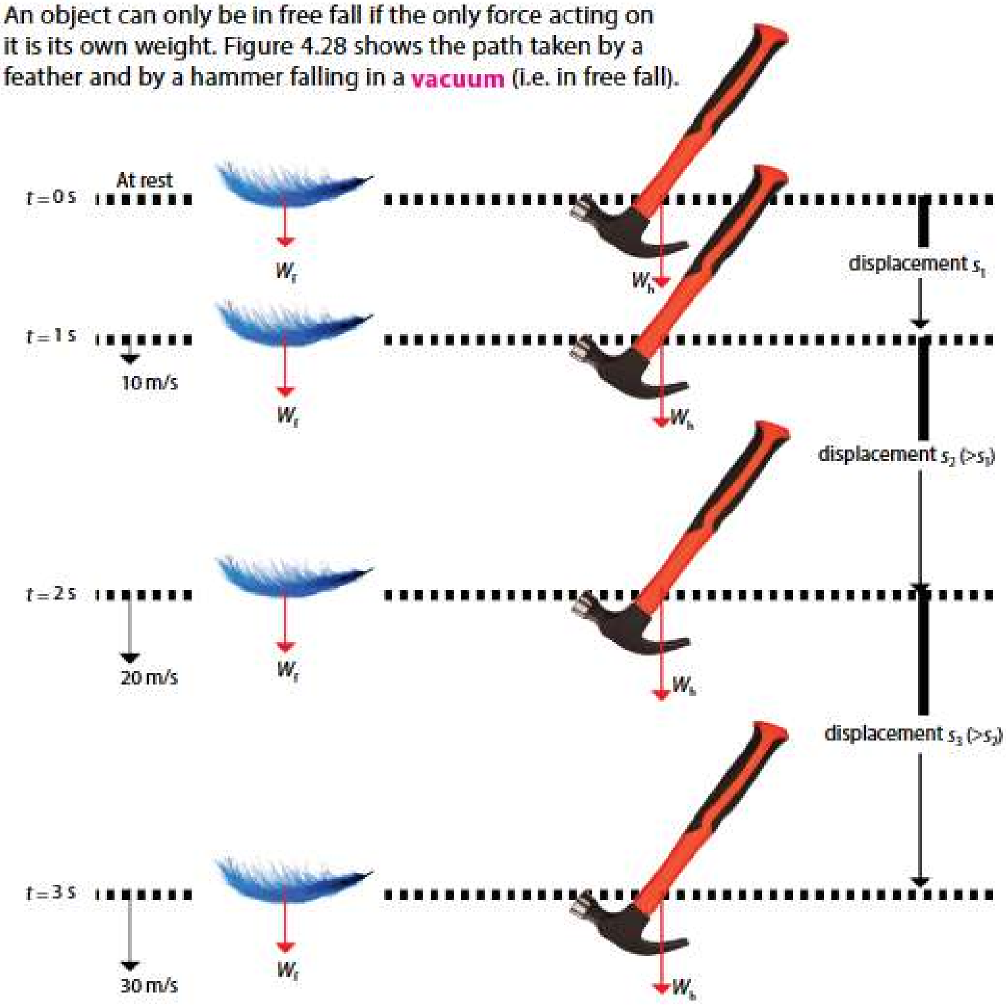


Figure 4.28 A feather and a hammer in free fall

From Figure 4.28, we can make the following deductions:

- The velocity of the two objects under gravity increases by 10 m/s every second. That is, both objects undergo a constant acceleration of 10 m/s².
- The direction of their motion is downward (i.e. towards the centre of Earth).
- The acceleration of the free-falling objects does not depend on their mass or size. In other words, all objects fall freely at a constant acceleration of 10 m/s². Figure 4.29 shows the velocity–time graph that describes the motion of the two free-falling objects.

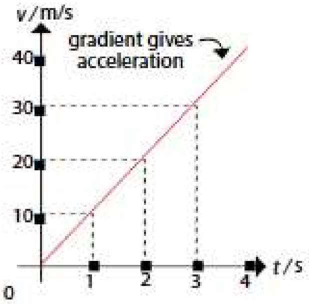


Figure 4.29 Velocity–time graph of free-falling motion

Link

Recall from Chapter 2: The acceleration of free fall for an object near to Earth is constant and is approximately 10 m/s².

Objects Falling with Air Resistance

When you run fast, do you feel air brushing against you? You are experiencing air resistance. It has the following characteristics:

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

Figures 4.30 and 4.31 show the velocity–time graph and the motion of a piece of paper falling through air respectively.

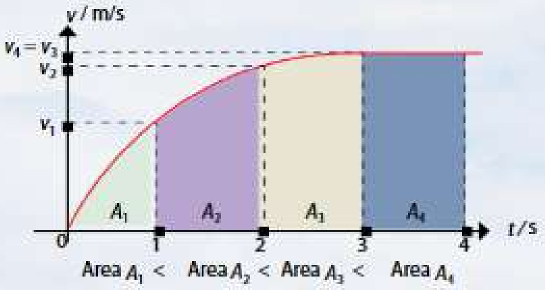


Figure 4.30 Velocity–time graph of a piece of paper falling through air

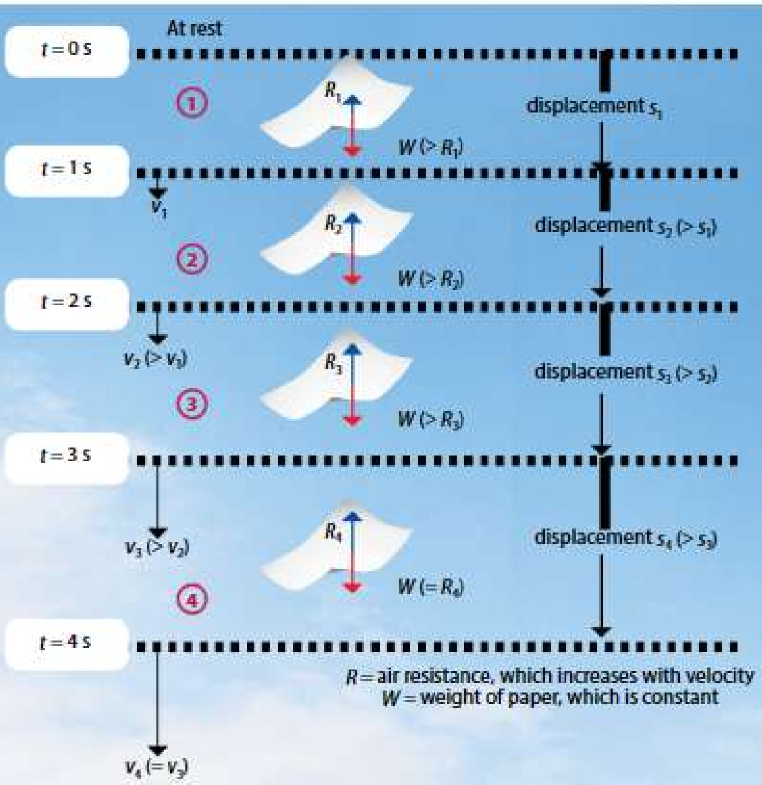


Figure 4.31 How the velocity of a falling piece of paper and air resistance acting on it change over time

Table 4.2 summarises the forces involved, the changes in velocity and acceleration, and the displacement of the piece of paper at different time intervals.

Table 4.2 Summary of the forces involved, changes in velocity and acceleration, and displacement of the piece of paper as it falls through the air

Time Interval	Forces Involved	Changes in Velocity and Acceleration	Displacement
①	$W > R_1$	• Velocity increases from zero to v_1. • There is acceleration.	$s_1 = A_1$
②	$W > R_2$ $R_2 > R_1$	• Velocity increases from v_1 to v_2. • Δv smaller i.e. $(v_2 - v_1) < (v_1 - v_0)$ • Acceleration is lower than that in ①.	$s_2 = A_2$ $s_2 > s_1$
③	$W > R_3$ $R_3 > R_2$	• Velocity increases from v_2 to v_3. • Δv smaller i.e., $(v_3 - v_2) < (v_2 - v_1)$ • Acceleration is lower than that in ②.	$s_3 = A_3$ $s_3 > s_2$
④	$W = R_4$	• Velocity stays constant. • $\Delta v = 0$, i.e. $v_3 = v_4$ = terminal velocity • Acceleration is zero.	$s_4 = A_4$ $s_4 > s_3$

Small dense objects, such as steel balls, fall through air at the same acceleration and hit the ground at the same time. This is because they experience low air resistance. In comparison, a piece of paper is light and has a large surface area. It experiences greater air resistance. The paper falls at a lower acceleration.

Objects experience higher air resistance when their speed increases.

▶ When the air resistance acting against an object equals its weight, the object starts to travel at a constant speed known as **terminal velocity**. This means that the object has zero acceleration.

If an object falls through a short distance, it may not reach terminal velocity before hitting the ground.

Worked Example 4E

A window cleaner drops a sponge from a window at time $t = 0$ s. Figure 4.32 shows the velocity–time graph for the motion of the sponge.

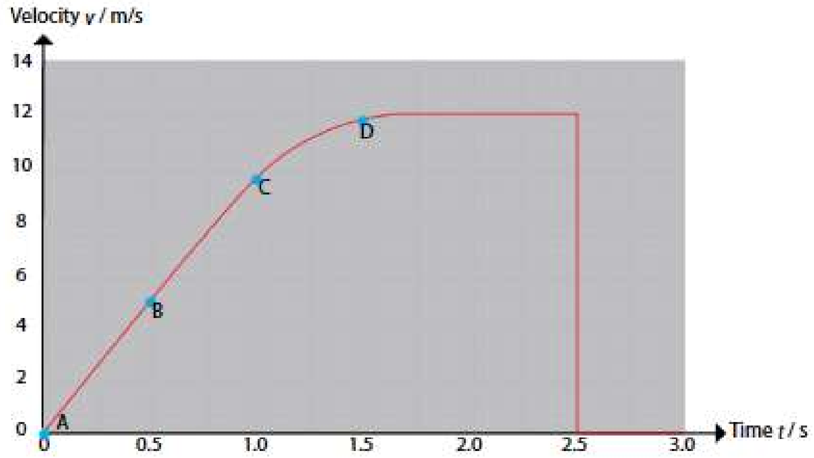


Figure 4.32

(a) Describe the motion of the sponge between A and D.
(b) Find the displacement of the sponge between $t = 0$ s and $t = 0.6$ s.

Answer

(a) From A to B, the velocity of the sponge increases uniformly and the acceleration is constant at 10 m/s². From B to D, the velocity is still increasing but at a decreasing rate. The acceleration decreases. After D, the acceleration soon becomes zero and terminal velocity of 12 m/s is reached.

(b) Displacement
= area under velocity–time graph
$= \frac{1}{2} \times (0.6 \text{ s}) \times (6.0 \text{ m/s})$
= 1.8 m

Worked Example 4F

A box is dropped from a helicopter (Figure 4.33). The mass m of the box is 5.0 kg.

(a) Determine the resultant force on the box when the total force opposing the motion of the box at a particular instant during its fall is 20 N.

(b) Determine the resultant force acting on the box when the box reaches terminal velocity.

(c) Sketch a velocity–time graph to show the motion of the box through air until it reaches terminal velocity.

(d) Describe the motion of the box, in terms of the forces involved. (Take gravitational field strength $g = 10$ N/kg)

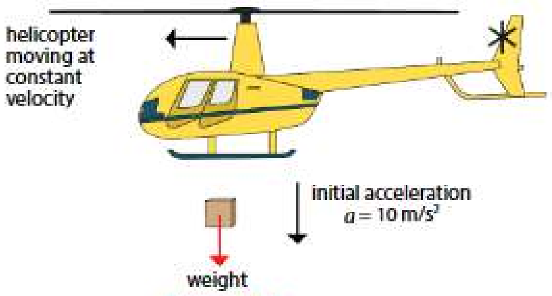


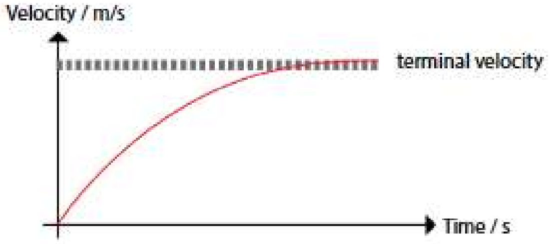
Figure 4.33

Let us assign the downward direction as positive.

(a) Given: mass m of the box = 5 kg
Let F = resultant force of the box at the instant when the total opposing force is 20 N.
Resultant force $F = 50 \text{ N} + (-20 \text{ N}) = 30 \text{ N}$

(b) When the box reaches terminal velocity, the acceleration becomes zero and the resultant force is 0 N.

(c)



(d)

- When the box is released from rest, the only initial force acting on the box is the weight of the box. Thus, the box accelerates downwards at 10 m/s².
- As the box falls, the air resistance it experiences increases. The resultant force is now less than the weight of the box. The box still accelerates, but the acceleration is less than 10 m/s².
- Air resistance increases with the increase in velocity. Eventually, the air resistance balances the weight of the box. The resultant force decreases to 0 N, and the box falls at terminal velocity (i.e. zero acceleration).

Figure 4.34 shows two skydivers of equal mass, A and B, who leaped off a plane at the same time. Three observers have different views on why skydiver A is above skydiver B. Whose view is scientifically correct?

Figure 4.34 Why is skydiver A above skydiver B?

There are two forces acting on the skydivers (Figure 4.35). The amount of air resistance each skydiver experiences depends on the surface area. Air resistance increases when the surface area is larger.

Skydiver A is in the spread-eagle position (larger surface area), while skydiver B is falling in the head first position (smaller surface area). Thus, skydiver A experiences a higher air resistance than skydiver B.

The resultant forces acting downwards on the skydivers are their respective weights minus the respective air resistances acting upwards on them. Since the weights of both skydivers are the same, the resultant force acting downwards on skydiver A will be smaller than that acting on skydiver B. A smaller resultant force means a smaller acceleration for the same mass and thus, a smaller rate of increase in velocity. Hence, skydiver A is above skydiver B.

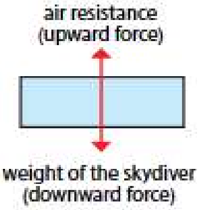


Figure 4.35 Forces acting on each skydiver

Let's Practise 4.3

1. A force of 50 N is needed to keep a trolley of mass 60 kg moving at a uniform velocity of 2 m/s. What is the frictional force on the trolley?
2. A feather and a stone are released simultaneously from the same height. Explain why the feather will hit the ground much later than the stone, even though the acceleration of free fall is the same for both objects.
3. The effects of friction can be both positive and negative. Give **one** real-world example for each effect.

Link

Theory Workbook
Worksheet 4C
Let's Assess
Let's Reflect

Let's Map It

Forces (SI unit: N)

affects

Motion of objects

is governed by

Newton's First Law of Motion

Every object will continue in its state of rest or uniform motion in a straight line unless a resultant force acts on it.

is related to the

Inertia

which is

The property of a body which resists change in motion

and is quantified by

Mass of the object (i.e. greater the mass of the object, greater the inertia)

applies to

Balanced forces

Newton's Second Law of Motion

When a resultant force acts on an object of constant mass, the object will accelerate in the direction of the resultant force.

$F = ma$

where

F = resultant force (N)

m = mass (kg)

a = acceleration (m/s^2)

applies to

$F = 0$ N

Balanced forces

for a body

- At rest
- Moving at a constant velocity

$F \neq 0$ N

Unbalanced forces

for a body

- Accelerating
- Decelerating

Newton's Third Law of Motion

If body A exerts a force F_{AB} on body B, then body B will exert an equal and opposite force F_{BA} on body A.

describes

Action–reaction pairs

Without air resistance, an object falls with constant acceleration.

With air resistance, an object falls with decreasing acceleration and may reach terminal velocity.

Let's Review

Section A: Multiple-choice Questions

1 When a force is applied to an object, several effects are possible. Which of the following effects **cannot** occur?

○ A The mass of the object decreases.
○ B The object remains still.
○ C The object slows down.
○ D The object speeds up.

2 Figure 4.36 shows four forces acting on a block.

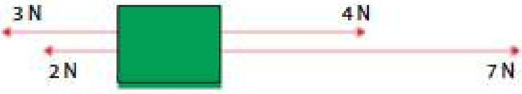


Figure 4.36

What is the resultant force?

○ A 5 N to the left
○ B 6 N to the right
○ C 11 N to the right
○ D No resultant force

3 In Figure 4.37, object A and object B are stacked one on top of the other. Given that the masses of objects A and B are 3.0 kg and 2.0 kg respectively, what is the horizontal acceleration of object A when object B is pulled by a horizontal force of 10 N? (Assume all the surfaces are frictionless.)

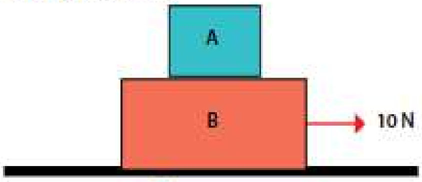


Figure 4.37

○ A 0 m/s^2
○ B 2.0 m/s^2
○ C 3.0 m/s^2
○ D 5.0 m/s^2

4 Two persons X and Y were standing in a bus travelling at a constant velocity. To avoid hitting a child running across the road, the bus driver stepped on the brakes to stop the bus. If the mass of X is larger than that of Y, which of the following statements is correct?

○ A Both X and Y were thrown backward in the opposite direction of the bus's initial velocity.
○ B Both X and Y were thrown forward in the same direction as the bus's initial velocity.
○ C Only X was thrown backwards in the opposite direction of the bus's initial velocity.
○ D Only X was thrown forward in the same direction as the bus's initial velocity.

5 A parachutist of weight 700 N falls at terminal velocity. Which combination gives the weight, air resistance and resultant force acting on him?

		Weight	Air Resistance	Resultant Force
○	A	700 N downwards	700 N downwards	Zero
○	B	700 N downwards	Zero	700 N downwards
○	C	700 N downwards	700 N upwards	Zero
○	D	700 N downwards	700 N upwards	700 N downwards

Section B: Structured Questions

1 (a) Name the SI unit of force and state the symbol for the SI unit.

(b) Complete the following table using Newton's Second Law of Motion, $F = ma$.

	Mass	Force	Acceleration
(i)	8 kg	80 N	
(ii)		200 N	2.0 m/s^2
(iii)	2 g		10 cm/s^2

2 A turbofan engine is able to provide a maximum thrust of 2.49 × 10^5 N. An airliner has four of these engines. If its mass is 2.72 × 10^5 kg, what is the acceleration at take-off?

3 A tow truck of mass 1500 kg is towing a small car of mass 1000 kg. The horizontal force exerted on the car by the truck is 1000 N, and the system of the tow truck and the car has an acceleration of 0.50 m/s^2.

(a) Draw a free-body diagram of the:
  (I) tow truck; and
  (II) car.

(b) Calculate:
  (I) the friction between the car on tow and the road;
  (II) the forward tractive force of the tow truck, given that the friction on the tow truck is 750 N; and
  (III) the resultant force acting on the system of the tow truck and the car.

4 A student was standing in the middle section of a moving bus when the bus came to a sudden stop. A wooden box hit the student's legs. The student claimed that the box came from the front section of the bus. Is the claim true? Explain your answer.

5 A shopper pushes a trolley of mass 40 kg with a force of 100 N along a horizontal surface. The friction between the four wheels of the trolley and the surface is 20 N. What is the acceleration of the trolley?

Section C: Free-response Questions

1 Figure 4.38 shows a light, smooth pulley with masses m_1 and m_2 on opposite sides connected by a light, inextensible string hung over the pulley.
Find the acceleration a and the tension T in the string in terms of m_1, m_2, and the acceleration due to gravity g.

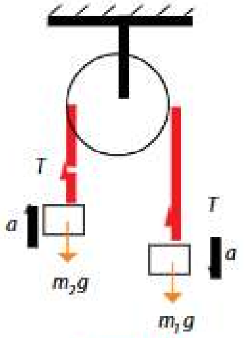


Figure 4.38

2 Figure 4.39 shows cords supporting an object of weight 100 N. Using the graphical method, find the tensions T_1 and T_2.

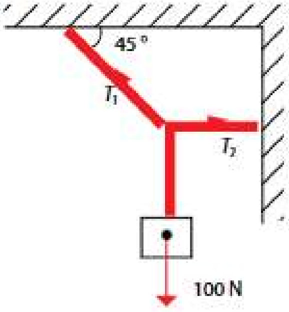
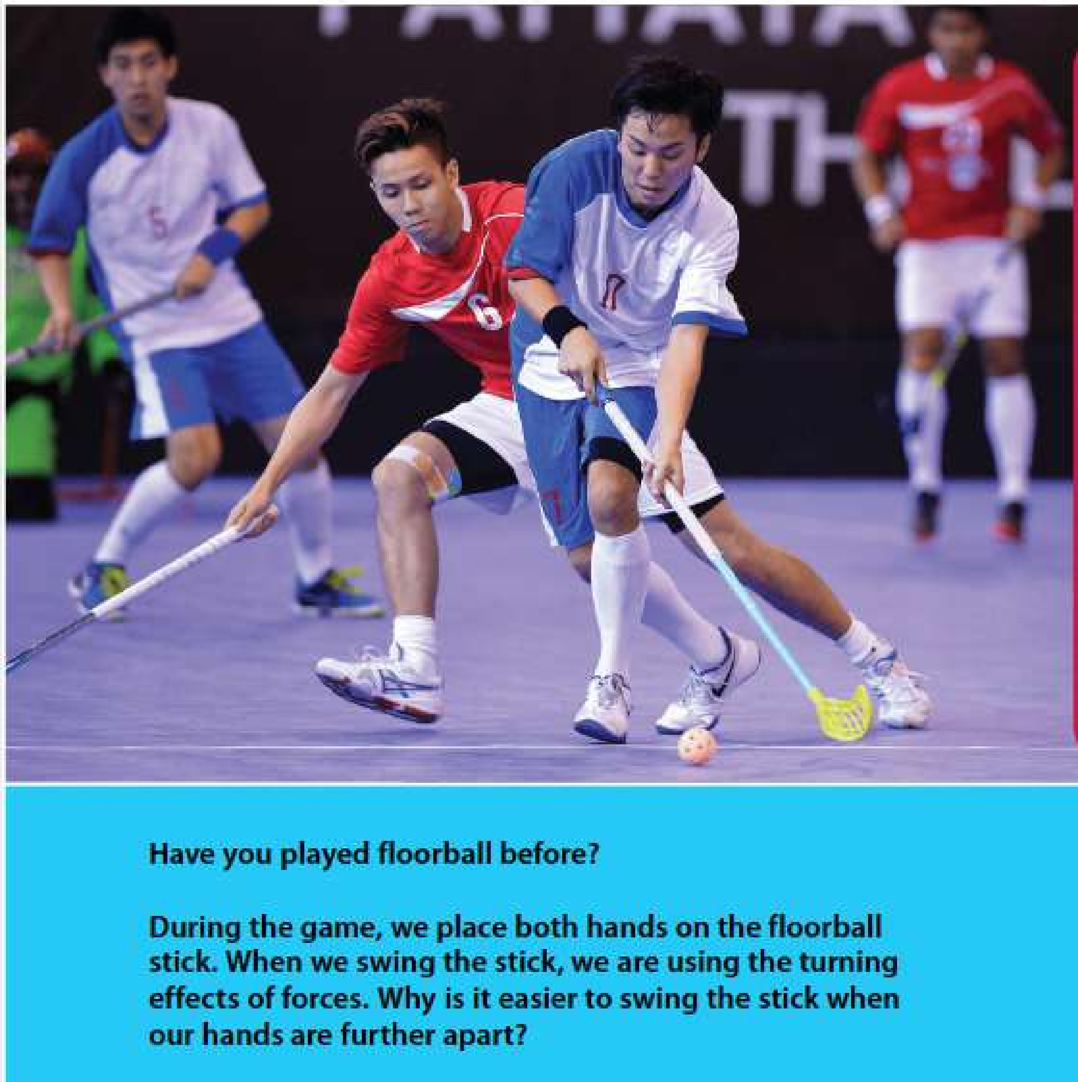


Figure 4.39

CHAPTER

05 Turning Effects of Forces



What You Will Learn

- When does a force cause something to turn?
- How can we prevent objects from toppling?

Have you played floorball before?

During the game, we place both hands on the floorball stick. When we swing the stick, we are using the turning effects of forces. Why is it easier to swing the stick when our hands are further apart?

We encounter turning effects of forces in our everyday lives. Activities such as turning the cap of a water bottle, opening a door and keeping our balance involve the turning effects of forces. Turning effects of forces are also used in everyday tools. A spanner, screwdriver, nail cutter and scissors are examples of tools that make use of the turning effects of forces. How does a force cause something to turn?

5.1 When Does a Force Cause Something to Turn?

Learning Outcomes

- Describe the moment of a force about a pivot in terms of its turning effect and relate this to everyday examples.
- Recall and apply the relationship *moment of a force (or torque) = force × perpendicular distance from the pivot* to new situations or solve related problems.
- State the principle of moments for a body in equilibrium.
- Apply the principle of moments to new situations or to solve related problems.

Moment

It is easier to lift the lid of a tightly closed tin of cereal with a longer spoon instead of a shorter spoon. Have you wondered why?

To answer the question, we need to understand what the turning effect of a force is. When we use a spoon to lift the lid, the force applied on the spoon exerts a turning effect. The turning effect of a force is called its **moment**.

The concept of moment is best shown using a simple **lever** (Figure 5.1). A **lever** is a rigid bar resting on a **pivot** or **fulcrum**. It is used to move a load when a force is applied.

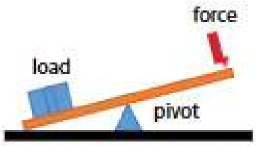


Figure 5.1 A simple lever

Using a spoon to lift the lid of a tin is an example of using a lever. In Figure 5.2:

- the spoon is the rigid bar;
- the edge of the tin at which the spoon is at is the pivot; and
- the lid is the load.

When a force is applied, the load experiences a turning force. This is because the rigid bar is hinged at the pivot and can make a sweeping movement only.

Figure 5.2 Lifting the lid of a tin using a spoon

The turning effect of the force is **proportional** to:

- the perpendicular distance from the pivot where the force is applied; and
- the magnitude of the force applied.

This turning effect of the force is also known as a **torque**.

In Figure 5.2, the perpendicular distance from the edge of the lid to the end of a longer spoon is longer than that of a shorter spoon. Thus, using a longer spoon creates a greater turning effect. That is why it is easier to lift the lid with a longer spoon.

Helpful Note

The word *moment* means *turning effect*. Instead of saying "turning effect of a force ", we say "moment of a force".

Disciplinary Idea

Matter interacts through forces and fields.

A force exerted on an extended body can cause a turning effect.

Word Alert

Lever: a bar that moves around a fixed point

Proportional: having a constant ratio to another quantity

The **moment of a force** M, or torque, about a pivot is the product of the force F and the perpendicular distance d from the pivot to the line of action of the force.

$M = Fd$ where F = force applied (N)
d = perpendicular distance from the pivot to the line of action of the force (m)

The SI unit of moment of a force is **newton metre (N m)** and is a vector quantity. The moment of a force has a direction (Figure 5.3). A **clockwise rotation** about a pivot is a **clockwise moment**. An **anticlockwise rotation** about the pivot is an **anticlockwise moment**.

It is important to note that in order to create a moment, the line of action of the force must not pass through the pivot.

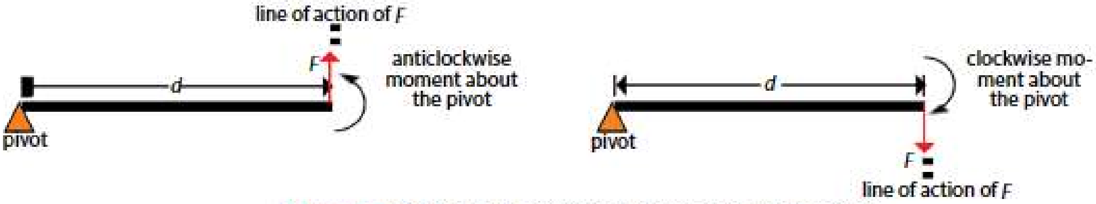


Figure 5.3 Clockwise or anticlockwise moment about a pivot.

Worked Example 5A

Figure 5.4 shows a teaspoon being used to lift the lid of a coffee tin.

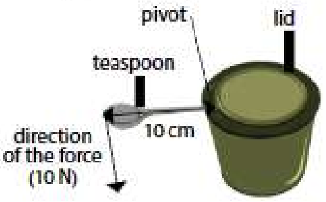


Figure 5.4 A spoon is used to lift the lid.

(a) Calculate the magnitude of the moment that is generated.
(b) What is the direction of the moment?
(c) The teaspoon is replaced by a tablespoon such that the perpendicular distance between the applied force and pivot is now 20 cm. Calculate the force required to generate the same moment in (a).

Answer

(a) Magnitude of the moment $M = Fd$

$$= (10\text{ N}) \times (10 \times 10^{-2}\text{ m})$$
$$= 1.0\text{ N m}$$

(b) The moment has an anticlockwise direction.

(c) To generate the same moment, the applied force

$$F = \frac{M}{d}$$
$$= \frac{1}{20 \times 10^{-2}}$$
$$= 5.0\text{ N}$$

By using a longer tablespoon, the amount of effort or the applied force is reduced.

Disciplinary Idea

Forces help us understand motion.

A body may tend to turn about a pivot point when the line of action of an applied force has a non-zero distance from the pivot.

Principle of Moments

In our discussion so far, we have considered only the moment of the applied force, but not that of the load. As the load has mass and hence, weight, it exerts a turning effect as well.

In Figure 5.5, we can see that the load exerts a moment that is opposite to that of the applied force *F*. If the lever does not rotate, then the clockwise and anticlockwise moments are equal.

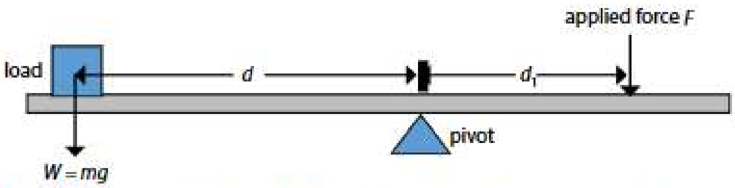


Figure 5.5 The forces acting on both sides of a pivot of a balanced lever

We say that the lever is balanced or in **equilibrium**. This is the principle of moments.

The **principle of moments** states that when a body is in equilibrium, the sum of clockwise moments about a pivot is equal to the sum of anticlockwise moments about the same pivot.

Sum of clockwise moments about any pivot = Sum of anticlockwise moments about the same pivot

Worked Example 5B

Figure 5.6 shows a beam with negligible mass. If $F_1 = 20$ N, determine the force F_2 if the beam is balanced.

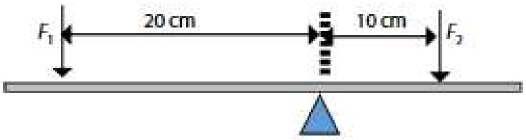


Figure 5.6

Thought Process
The key word is "balanced". This implies that we can apply the principle of moments. The clockwise moment about the pivot is created by force F_2. The mass of the beam is negligible and does not have to be considered in our working.

Answer
By the principle of moments, taking moments about the pivot:

Sum of clockwise moments = Sum of anticlockwise moments

$$F_2 \times 10\text{ cm} = F_1 \times 20\text{ cm}$$
$$F_2 \times 10\text{ cm} = 20\text{ N} \times 20\text{ cm}$$
$$F_2 = 40\text{ N}$$

Word Alert
Equilibrium: state of balance

Disciplinary Idea
Forces help us understand motion.

In Chapter 4, bodies are represented using a point for simplicity.

For an extended body (matter), forces can cause a turning effect when the line of action of the force is at different positions on the body.

Helpful Note
There is no need to convert to SI units (e.g. metres) as long as the units on both sides of the equation are the same.

Worked Example 5C

Figure 5.7(a) shows a uniform beam that is 1 m long and has a mass of 2 kg. If $F_1 = F_2 = 10$ N, determine the force F_3 if the beam is balanced. Use gravitational field strength $g = 10$ N/kg.

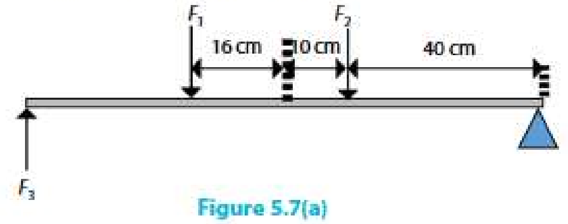


Figure 5.7(a)

Thought Process

As the beam is balanced, we can apply the principle of moments. The mass of the beam is not negligible. Since the beam is uniform, the weight is evenly distributed and can be represented by a single point acting through the centre of the beam, also known as the centroid. More explanation on this will be given in Section 5.2.

Even though all the forces are on the same side of the pivot, they do not generate the same moments. The anticlockwise moment is created by forces F_1, F_2 and the weight of the beam W about the pivot (Figure 5.7(b)). The clockwise moment is created by force F_3.

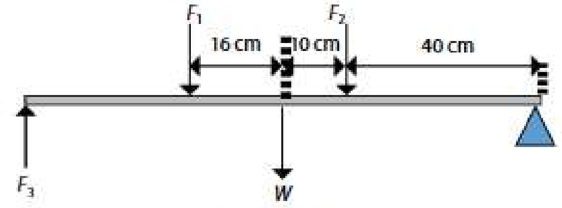


Figure 5.7(b)

Answer

Weight W of the beam = 2 kg × 10 N/kg = 20 N

By the principle of moments, taking moments about the pivot:

Sum of clockwise moments = Sum of anticlockwise moments

$$F_3 \times 100 \text{ cm} = F_1 \times 66 \text{ cm} + F_2 \times 40 \text{ cm} + W \times 50 \text{ cm}$$
$$F_3 \times 100 \text{ cm} = 10 \text{ N} \times 66 \text{ cm} + 10 \text{ N} \times 40 \text{ cm} + 20 \text{ N} \times 50 \text{ cm}$$
$$F_3 = 20.6 \text{ N}$$

Worked Example 5D

Figure 5.8 shows an L-shaped beam of negligible mass with a pivot at A. If the load has a weight W of 100 N and F_2 is 40 N, determine the force F_1 required to keep the beam in balance.

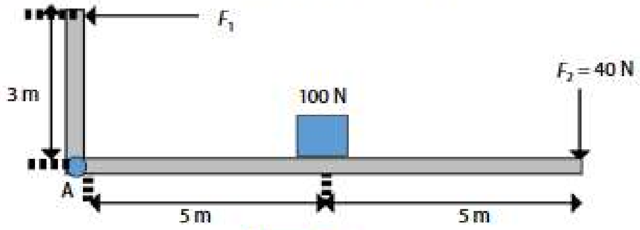


Figure 5.8

Thought Process
As the beam is balanced, we can apply the principle of moments. The clockwise moment is created by F_2 and the load. The anticlockwise moment is created by F_1.

When calculating the moment, we will need to identify the perpendicular distance from the force to the pivot. The weight of the load can be represented as a single point through the centre of the load. The mass of the L-shaped beam is negligible and does not have to be considered in our working.

Answer
By the principle of moments, taking moments about the pivot:

Sum of clockwise moments = Sum of anticlockwise moments

$$W \times 5\text{ m} + F_2 \times 10\text{ m} = F_1 \times 3\text{ m}$$
$$100\text{ N} \times 5\text{ m} + 40 \times 10\text{ m} = F_1 \times 3\text{ m}$$
$$F_1 = 300\text{ N}$$

Conditions for Equilibrium

As seen in the Worked Examples, for a body or an object to be stationary or in equilibrium, it must not have any rotational or **translational motion**. In other words, there should be no resultant moments and no resultant force acting on the body. Thus, the conditions for a body in equilibrium are:
- The resultant moment on the body is zero.
- The resultant force on the body is also zero.

Word Alert
Translational motion: motion by which a body shifts from one point in space to another

Physics Connect
Scan the QR code to explore a simulation to balance a rule.

Let's Practise 5.1

1 Figure 5.9 shows a beam with negligible mass. If F_1 = 50 N and F_2 = 20 N, determine the force F_3 if the beam is balanced.

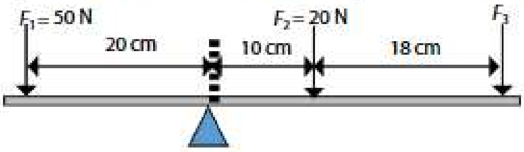


Figure 5.9

2 Albert and Ben are seated at opposite ends of a 4 m long seesaw (Figure 5.10). The pivot of the seesaw is at the centre of the seesaw. If Albert weighs twice as much as Ben, how much nearer to the pivot should Albert move so that the seesaw is balanced?

Figure 5.10

Link

Theory Workbook
Worksheet 5A

Practical Workbook
Experiment 5A

Tech Connect

3D printers can print 3D objects such as a cup, a figurine, or even a house. The printer head and printing bed can move in three directions, that is, in the x, y and z axes (Figure 5.11). Movements along these axes are created through a wheel and belt system. The wheels are driven by motors, which produce a torque or moment of a force.

Can you think of any other simple machines that generate a moment using wheels?

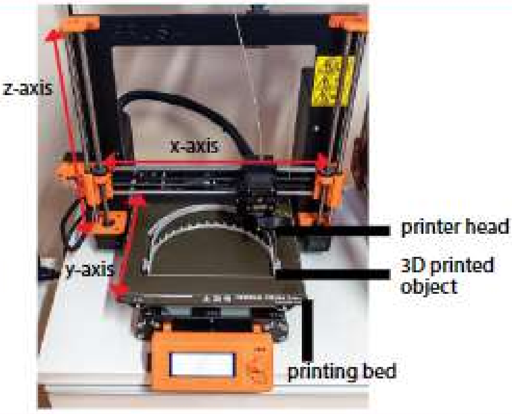


Figure 5.11 The printer head and printing bed of the 3D printer can move in three directions in order to print a 3D object.

Past to Present

The mechanical calculator was invented in the 17th century. The device was used for addition and subtraction.

Figure 5.12 shows a mechanical calculator from the 1950s. The device makes use of the turning effects of forces to work. The crank handle is turned to create a turning force that rotates the pin-wheels and other components to perform the basic mathematical functions. Today, we have electronic calculators that are smaller, lighter and easier to use.

Figure 5.12 A mechanical calculator makes use of the turning effect of forces.

5.2 How Can We Prevent Objects from Toppling?

Learning Outcomes

- Show an understanding that the weight of a body may be taken as acting at a single point known as its centre of gravity.
- Describe qualitatively the effect of the position of the centre of gravity on the stability of objects.

Disciplinary Idea

Forces help us to understand motion.

The line of action of the force at different positions on a body can cause a turning effect, i.e. a moment. The body may tend to turn about its pivot of an applied force has a non-zero distance from the pivot.

If the body is in balance, then its centre of gravity is either directly below or above the pivot point. The net moment due to gravity acting on the body about the pivot point will be zero.

Centre of Gravity

All objects are made up of many particles. When gravity acts on a body, every particle of the body is attracted towards Earth. The total weight of the particles can be represented by a single weight acting on a single point. This single point is the centre of gravity.

The **centre of gravity** of an object is an imaginary point where the entire weight of the object seems to act.

To understand why the total weight of a body can be replaced by a single weight acting on a single point, consider a body that is hung freely from a string (Figure 5.13).

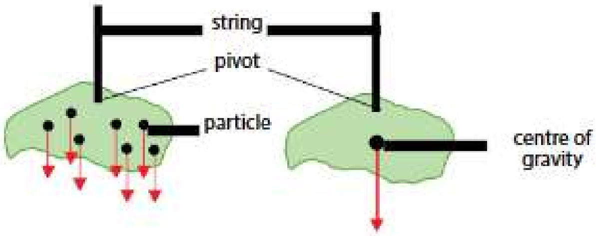


Figure 5.13 The individual particles of a body create a moment which, in balance, can be represented by a force acting through a single point below the pivot.

For the body to be in balance, the sum of clockwise moments due to individual particles must be equal to the sum of anticlockwise moments. This is equivalent to having a force acting through a point below the pivot, since the net turning effect is zero.

We can also represent the sum of all the individual particles' weight by a resultant force acting through this point. This resultant force is the weight of the body.

The centre of gravity for an object that has a regular shape and uniform density is at the centroid or centre of the object. Figure 5.14 shows the positions of the centre of gravity of some regular-shaped objects with uniform density. It is important to note that the centre of gravity can be outside the object.

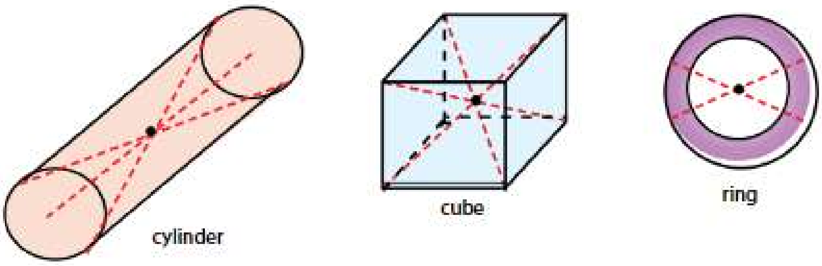


Figure 5.14 The centre of gravity of regular-shaped objects with uniform density is at the centroid of the objects (indicated by the black dot).

Let's Investigate 5A

Aim
To find the centre of gravity of an irregularly shaped plane lamina

Procedure

1. Draw and cut out an irregularly shaped plane lamina from a piece of cardboard or a vanguard sheet using a pair of scissors.
2. Make three small holes near the edge of the lamina. The holes should be as far apart from one another as possible.
3. Suspend the lamina freely from a pin. The lamina will come to a rest when the centre of gravity is below the pin.
4. Hang a **plumb line** from the pin in front of the lamina (Figure 5.15).
5. Mark the top and bottom of the plumb line on the lamina using a fine marker pen.
6. Repeat steps 3 to 5 for the other two holes.
7. Place the lamina on the table and join the markings with straight dashed lines using a long rule (Figure 5.16).

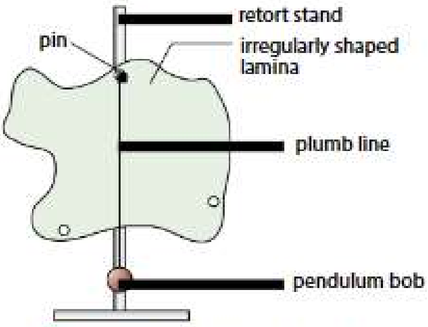


Figure 5.15 The plumb line cuts through the centre of gravity of the lamina.

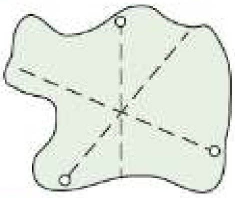


Figure 5.16 Determining the centre of gravity of the lamina

Precautions

- Switch off the fans. Wind may affect the equilibrium position of the lamina.
- Use a thin thread for the plumb line.
- Ensure plumb line is not swinging when marking the points.
- Ensure that the holes on the lamina are small but still allow the lamina to swing freely. Frictional force between the pin and lamina may affect the equilibrium position.

Observation
The centre of gravity of the lamina is the point of intersection of the three dashed lines.
(For some irregularly shaped lamina, the point of intersection could be lying outside the shape itself.)

Questions

1. Define the *centre of gravity* of an object.
2. Would having two holes be sufficient to find the centre of gravity of an irregularly shaped plane lamina? Explain your answer.

Word Alert
Plumb line: weight suspended from a string

Link
Practical Workbook
Experiment 5B

Stability

Consider a block of wood shown in Figure 5.17. Why does the block:

- return to its original position in Figure 5.17(a); and
- topple in Figure 5.17(b)?

(a) The block will return to its original position after it is pushed slightly.

(b) The block topples after it is pushed more strongly.

Figure 5.17 What happens to a block when it is displaced

We can answer the questions by looking at the position of the centre of gravity CG of the block. The position of the centre of gravity of an object affects its stability (Figure 5.18).

▶ The **stability** of an object is a measure of its ability to return its original position.

If the block is tilted slightly, it can return to its original position (Figure 5.18(a)).

The vertical line through its centre of gravity still falls within its base. The block's weight creates an anticlockwise moment about the pivot that helps the block return to its original position.

If the block is tilted a little more, it will reach a point where its centre of gravity is in line with the pivot and the block would balance on its edge (Figure 5.18(b)).

If the block is tilted even further, the block will topple (Figure 5.18(c)).

The vertical line through its centre of gravity falls outside its base. The centre of gravity of the block will generate a clockwise moment and cause the block to topple.

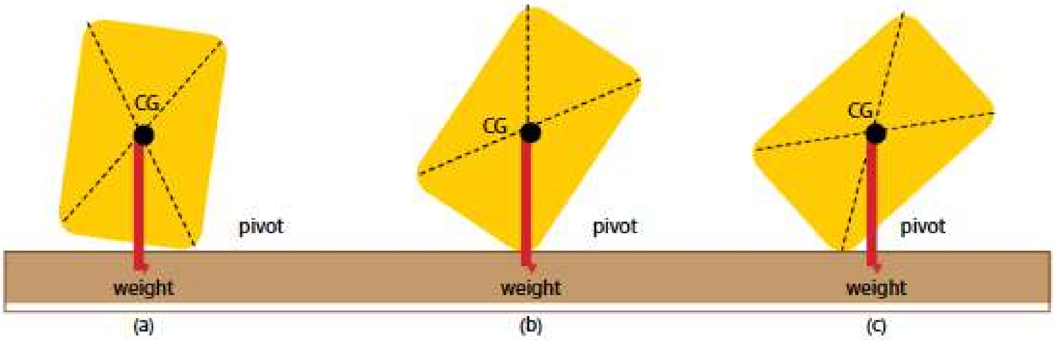


Figure 5.18 How the centre of gravity affects the stability of the block

The stability of an object can be affected in two ways — the position of the centre of gravity and the area of the base of the object.

The lower the centre of gravity of an object, the more stable it is. Let us compare two blocks, A and B, with the same base area but of different heights (Figure 5.19). The centre of gravity of each block is indicated by the label, CG. When slowly tilted through the same angle, block A will topple first. This is because block A has a higher centre of gravity. The vertical line through the centre of gravity of block A falls outside its base at a smaller tilt angle.

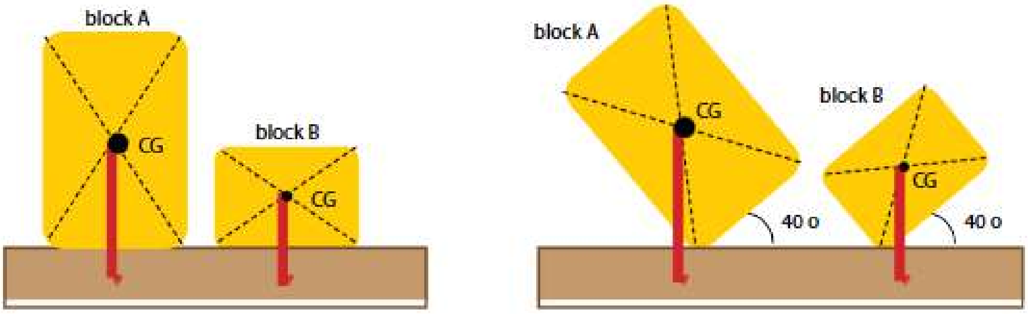


Figure 5.19 The lower the centre of gravity, the more stable the object.

Similarly, the larger the base area of an object, the more stable it is. Let us consider two stools, Y and Z, with different base areas but of the same height (Figure 5.20). The centre of gravity of each stool is indicated by the label, CG. When slowly tilted through the same angle, stool Z will topple first. This is because stool Z has a smaller base area. The vertical line through the centre of gravity of stool Z falls outside its base at a smaller tilt angle.

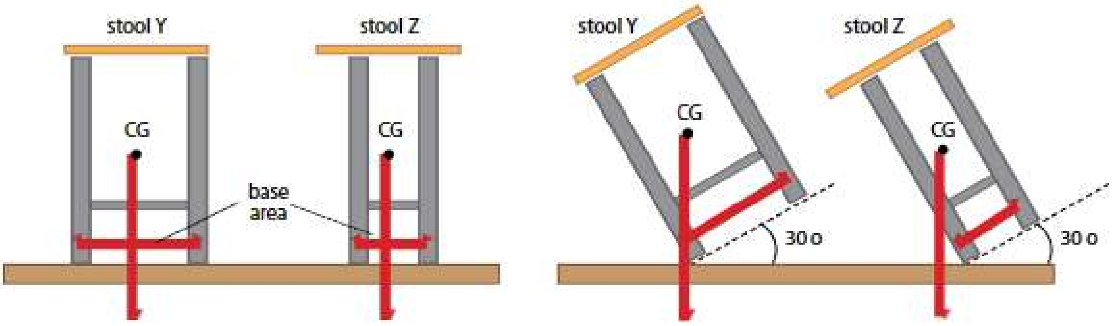


Figure 5.20 The bigger the base area, the more stable the object.

Worked Example 5E

Figure 5.21 shows a family portrait with a weight of 50 N hanging on the wall. If string B snaps:

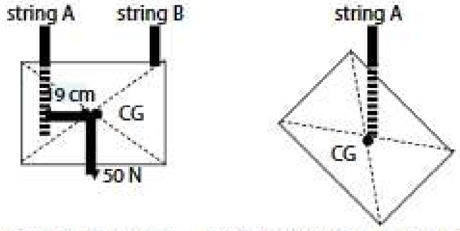
(a) what is the moment created by the family portrait; and

(b) what is the new equilibrium position? You may assume that the mass of the family portrait is evenly distributed.

Figure 5.21

Thought Process

Since the mass of the family portrait is evenly distributed, its centre of gravity (CG) is at its geometric centre (Figure 5.22(a)). When string B snaps, the point that string A holds on to the portrait becomes a pivot. Therefore, the moment generated is a clockwise moment.



(a) Simplified diagram of the system (b) Simplified diagram of the system after string B is cut

Figure 5.22

Answer

(a) Clockwise moment = 50 N × 19 × 10^{-2} m = 9.5 N m

(b) The new equilibrium position is one where the centre of gravity is directly below the pivot (Figure 5.22(b)).

From the discussion, we know that a lower position of the centre of gravity and a greater base area increase the stability of an object. Look at Figure 5.23. Three students are discussing how the toy dragonfly can balance on its tip.

Figure 5.23 Why is the toy dragonfly able to balance on its tip?

The toy is able to balance on its tip as its centre of gravity is in line with the pivot (point at which the tip rests on the stand). Since the centre of gravity (line of action of weight) is directly below the pivot, no moment is generated in any given direction. Hence, the toy will not topple.

Let's Practise 5.2

1. A composite block made of iron and wood is resting on the floor (Figure 5.24). The centre of gravity of the composite block is labelled as CG. State **two** ways to make this block more stable by changing the orientations of the block.

Figure 5.24 Composite block made of iron and wood

2. A trap door that weighs 50 N has a handle that is 60 cm from the hinge (Figure 5.25). If the centre of gravity (CG) of the trap door is 30 cm from the hinge, what is the force required to open the trap door?

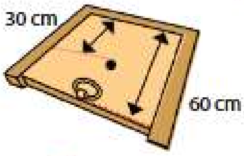


Figure 5.25

Link

Theory Workbook
Worksheet 5B
Let's Assess
Let's Reflect

Cool Career

Industrial Designer

An industrial designer applies the knowledge of the turning effects of forces, centre of gravity and stability of objects in the design of automobiles and personal mobility devices. Industrial designers of such products research the various ways in which these products are used. They also work with other designers and engineers to combine art and engineering practices to improve the product's appearance, functionality and safety (Figure 5.26).

Figure 5.26 Industrial designers work closely with others when designing a product.

Let's Map It

Turning Effect of a Force

is also known as

Moment of a Force or Torque (SI unit: N m)

is related to

Centre of gravity

affects the

Stability of a body

can be increased by

- Lowering the centre of gravity
- Increasing the base area

can be found using this formula

$M = Fd$

where

M = moment (N m)

F = force applied (N)

d = perpendicular distance from the pivot to the line of action of the force (m)

can be

Clockwise

can be

Anticlockwise

which are equal for a body in

Equilibrium

according to

Principle of moments

sum of clockwise moment about a pivot = sum of anticlockwise moment about the same pivot

where

- Resultant force on the body is zero.
- Resultant moment on the body is zero.

Let's Review

Section A: Multiple-choice Questions

1 What is the maximum load that the tower crane shown in Figure 5.27 can bear?

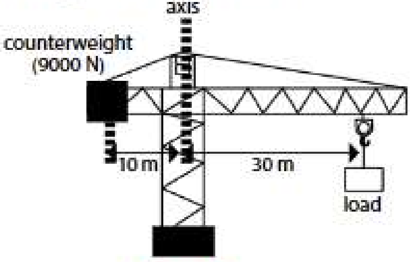


Figure 5.27

○ A 300 N
○ B 2700 N
○ C 3000 N
○ D 27 000 N

2 Figure 5.28 shows part of the inside of a computer mouse. The wheel has a diameter of 2 cm and a force of 1 N is required to turn the wheel. What is the moment generated?

Figure 5.28

○ A 1 N cm
○ B 2 N cm
○ C 1 N m
○ D 2 N m

3 A uniform rod that is 40 cm long is pivoted at its centre O (Figure 5.29). What is the value of x if the rod is balanced?

Figure 5.29

○ A 4 cm
○ B 5 cm
○ C 10 cm
○ D 15 cm

4 A diver stands at the end of a spring board (Figure 5.30). The spring board is held in place by two points X and Y. What is the magnitude and direction of the force exerted on the spring board at point Y? Assume that the spring board has negligible mass.

Figure 5.30

○ A 900 N upwards
○ B 1500 N upwards
○ C 900 N downwards
○ D 1500 N downwards

5 Figure 5.31 shows a wind chime with four identical masses. Assuming that the strings and horizontal bars have negligible mass, what is the length d?

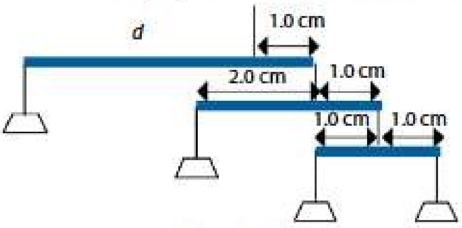


Figure 5.31

○ A 3 cm
○ B 4 cm
○ C 6 cm
○ D 8 cm

Section B: Structured Questions

1 Figure 5.32 shows a manual raise arm road barrier. It has a counterweight at one end. What is the purpose of the counterweight?

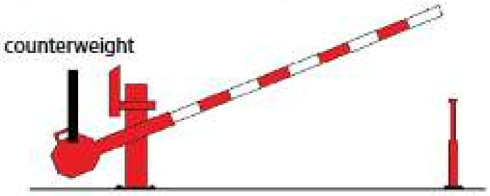


Figure 5.32

2 Figure 5.33 shows two identical composite blocks with the positions of the centre of gravity marked as "X". The blocks were lying on a horizontal plane that is then raised at one end. Which block will topple first? Why?

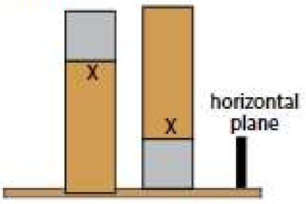


Figure 5.33

3 Figure 5.34 shows a uniform metre rule PQ that is balanced by a counterweight placed at the 5.0 cm mark. The pivot A is at the 20.0 cm mark. What is the weight of the rule?

Figure 5.34

4 A toy is placed at the edge of a table at point P (Figure 5.35). The toy can be balanced on the table by adding a ball of plasticine at the end of its tail. Explain why this is so.

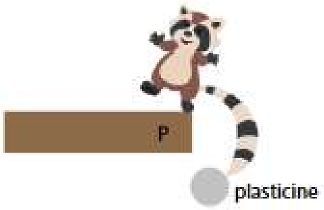


Figure 5.35

5 Figure 5.36 shows a set-up that is used to determine the weight W of an unknown object. The beam is 1 m long and its mass is negligible.

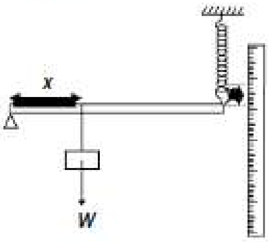
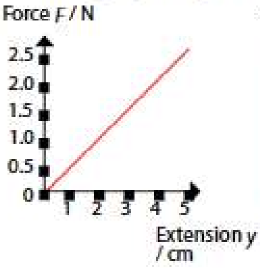


Figure 5.36

The force exerted by the spring is given by $F = ky$, where k is the spring constant and y is the extension of the spring. The characteristic of the spring is shown in Figure 5.37.

A student recorded three sets of values of x and y, and plotted the results on a graph (Figure 5.38).



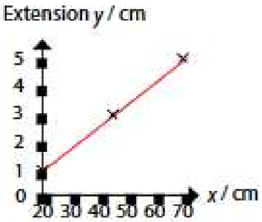


Figure 5.37 Figure 5.38

(a) By taking moments about the pivot, show that $W = k\frac{y}{x}$.

(b) Determine the value of the spring constant k in N/m.

(c) Use Figure 5.38 and the answer in (b) to determine the weight of the unknown object.

Section C: Free-response Questions

1 Figure 5.39 shows a lorry on a ramp that is used to measure the tip-over angle. The tip-over angle is the angle at which the lorry loses its stability and tips over.

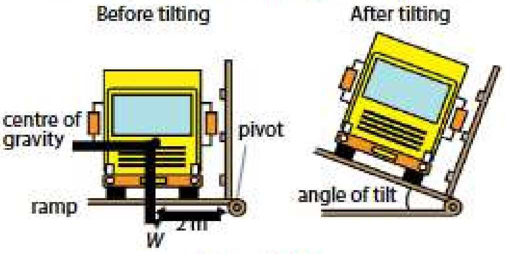


Figure 5.39

(a) Define *centre of gravity*.

(b) The lorry has a weight W of 2 tonnes. Given that the centre of gravity of the lorry is 2 m from the pivot, what is the initial moment and the direction of force exerted by the ramp?

(c) Explain why the lorry would tip over if the ramp is tilted further.

(d) State how the position of the centre of gravity affects the tip-over angle.

(e) Suggest **two** ways to improve the stability of the lorry.

2 Figure 5.40 shows the cross-sectional view of a wheel resting against a step. The weight of the wheel W is 5 N, the radius of the wheel is 13 cm and the height of the step is 8 cm.

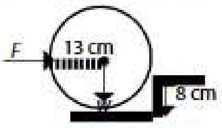


Figure 5.40

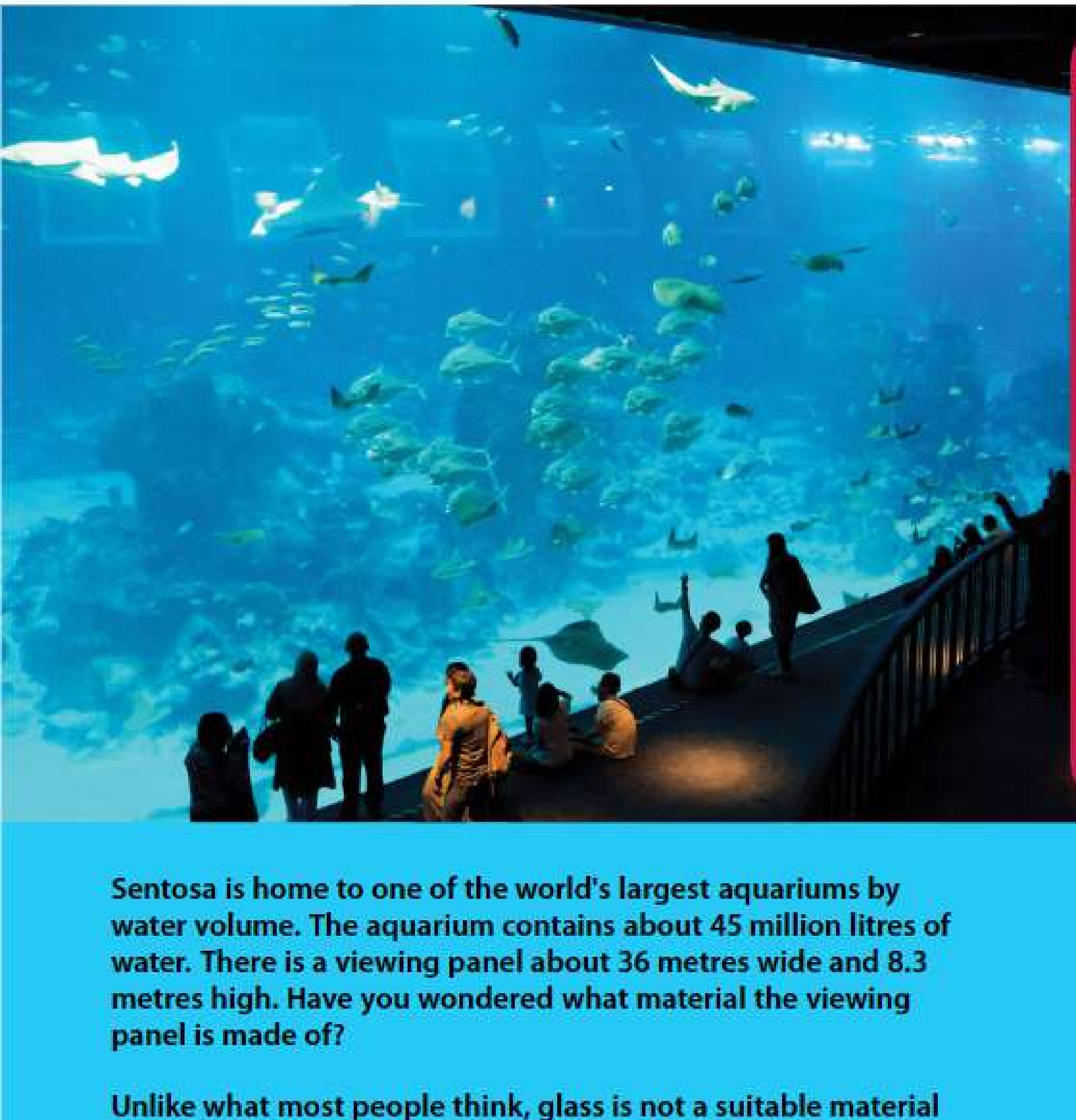
(a) If a force F is applied through the centre of gravity of the wheel, what is the magnitude of F required to move the wheel up the step?

(b) Draw on Figure 5.40, the position at which a force should be applied such that the least force is needed to move the ball up the step. Label this force as F_{min}.

(c) Calculate F_{min}.

CHAPTER

06 Pressure



What You Will Learn

- What is pressure?
- How is pressure transmitted through an enclosed liquid?
- How is the height of column of liquid used to determine pressure?

Sentosa is home to one of the world's largest aquariums by water volume. The aquarium contains about 45 million litres of water. There is a viewing panel about 36 metres wide and 8.3 metres high. Have you wondered what material the viewing panel is made of?

Unlike what most people think, glass is not a suitable material for the viewing panel. Glass is brittle so it needs to be very thick to prevent it from shattering due to the high pressure of the water. But with a greater thickness, glass distorts the view of the living things in the aquarium.

How do scientists determine the pressure of water exerted on the viewing panel? What are the uses of pressure in daily life?

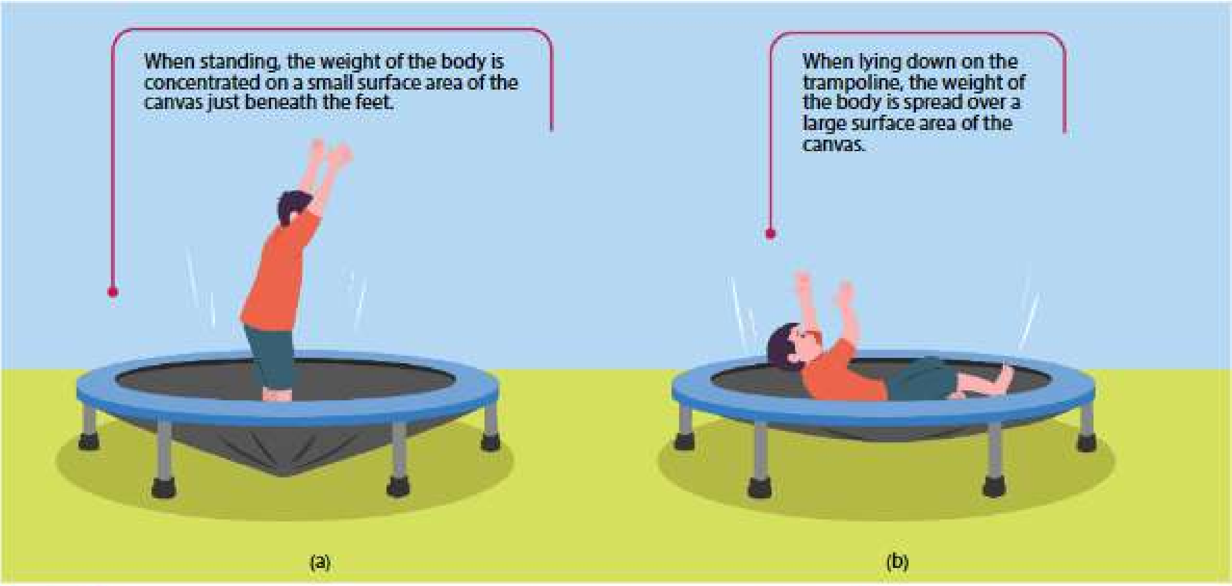
6.1 What Is Pressure?

Learning Outcomes

- Define *pressure* in terms of force and area.
- Recall and apply the relationship *pressure = force / area* to new situations or to solve related problems.

If you are stuck in quicksand, what should you do? The advice from experts is to lean back into a back float position. The back float position distributes your weight and allows your feet to float to the surface.

This scenario is similar to when we are on a trampoline. If a person is standing on a trampoline, the depression in the canvas is greater than when the person is lying down on the trampoline (Figure 6.1).


When standing, the weight of the body is concentrated on a small surface area of the canvas just beneath the feet.

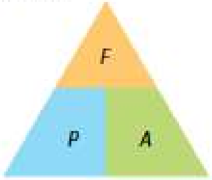
When lying down on the trampoline, the weight of the body is spread over a large surface area of the canvas.

Figure 6.1 The depression made in the canvas is greater when the person is standing on the trampoline.

The weight of the person acting on the contact area of the canvas is known as pressure. The pressure exerted by the person in Figure 6.1(a) is greater than that in Figure 6.1(b). Note that pressure is not a force, but a force exerted over the contact area.

Helpful Note

This "triangle" is a useful memory aid to recall the relationship between force F, pressure P, and area A.



▶ **Pressure** is the force acting per unit area.

▶ $P = \frac{F}{A}$

where P = pressure (Pa)
F = force (N)
A = contact area (m^2)

The SI unit of pressure is **newton per square metre (N/m^2)**. It is also known as pascal (Pa), named after the French mathematician and physicist Blaise Pascal (1623–1662).

Helpful Note

Another unit of pressure is the bar.
($1\text{ bar} = 1 \times 10^5\text{ Pa}$)

A pressure of one pascal is too small for pressures encountered in everyday life. Therefore, its multiples, kilopascal ($1\text{ kPa} = 10^3\text{ Pa}$) and megapascal ($1\text{ MPa} = 10^6\text{ Pa}$), are commonly used. Another commonly used unit of pressure is the standard atmosphere (atm).

$1 \times 10^5\text{ Pa} = 0.1\text{ MPa} = 100\text{ kPa}$
$1\text{ atm} = 101\,325\text{ Pa} = 101.325\text{ kPa}$

From the relationship between pressure, force and area, we can see that:
- the greater the magnitude of the force, the greater the pressure; and
- the smaller the contact area, the larger the pressure.

Cuttings tools such as can openers, knives and nail cutters have very sharp edges and exert very high pressures on the objects that are being cut. Can you think of scenarios whereby we need to reduce the pressure exerted on a surface?

Pressure is a scalar quantity because only the force perpendicular to the contact area is considered when calculating pressure (Figure 6.2). Since the direction of the force remains unchanged, pressure depends only on magnitude and is independent of direction.

Figure 6.2 The sharp edge of the knife has a small contact area with the food being cut. Thus, the knife exerts a large pressure on the food and the food can be cut easily.

Worked Example 6A

The mass of a girl is 50 kg. Calculate the pressure exerted by the girl on a trampoline when:
(a) she is standing upright, given that the area of her feet in contact with the trampoline is 500 cm^2; and
(b) she is lying down, given that the contact area of her body with the trampoline is 6000 cm^2.
(Take gravitational field strength $g = 10\text{ N/kg}$)

Answer

(a) Weight W of girl $= mg = 50\text{ kg} \times 10\text{ N/kg} = 500\text{ N}$
Contact area $A = 500\text{ cm}^2 = 0.05\text{ m}^2$

$$\text{Pressure } P = \frac{F}{A} = \frac{W}{A} = \frac{(500\text{ N})}{0.05\text{ m}^2} = 10 \times 10^3\text{ Pa}$$

(b) Contact area $A = 6000\text{ cm}^2 = 0.60\text{ m}^2$

$$\text{Pressure } P = \frac{F}{A} = \frac{W}{A} = \frac{(500\text{ N})}{0.60\text{ m}^2} = 833\text{ Pa}$$

Helpful Note

In Worked Example 6A, the pressure exerted by the girl when she is standing on her feet is about 12 times larger than the pressure exerted when she is lying down.

Worked Example 6B

A wooden plank has dimensions 100 cm by 20 cm by 2 cm and weighs 40 N (Figure 6.3). What is the maximum and minimum pressure exerted by the plank when it is placed on a flat horizontal table?

Figure 6.3

Thought Process

Since pressure $= \frac{\text{force}}{\text{contact area}}$, pressure is maximum when the contact area is minimum and vice versa.

Answer

Minimum contact area $A_{min} = (2 \times 10^{-2}\text{ m}) \times (20 \times 10^{-2}\text{ m})$
$= 4.0 \times 10^{-3}\text{ m}^2$

Maximum contact area $A_{max} = (20 \times 10^{-2}\text{ m}) \times (100 \times 10^{-2}\text{ m})$
$= 0.20\text{ m}^2$

The force exerted by the wooden plank on the table is equivalent to its weight W, 40 N.

Maximum pressure exerted by block on flat horizontal table

$= \frac{W}{A_{min}} = \frac{(40\text{ N})}{(4.0 \times 10^{-3}\text{ m}^2)} = 10\text{ kPa}$

Minimum pressure exerted by block on flat horizontal table

$= \frac{W}{A_{max}} = \frac{(40\text{ N})}{(0.2\text{ m}^2)} = 200\text{ Pa}$

Helpful Note

Another common term for pressure exerted by solids is normal stress. Normal stress is a force acting perpendicularly to a surface per unit area.

In determining pressure, only the component of the force acting normally or perpendicularly to the contact area is considered. Thus, we need to identify the correct contact area when calculating pressure.

Worked Example 6C

A 15 cm kitchen knife is used to cut a carrot with a varying thickness (Figure 6.4). The largest cross-sectional diameter of the cut carrot is 3 cm. The thickness of the cutting edge of the knife is 0.1 mm and the force applied is 20 N. What is the minimum pressure exerted by the knife when cutting the carrot?

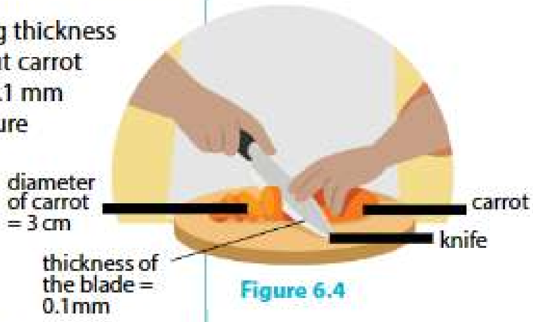


Figure 6.4

Thought Process

Not the entire blade is used in cutting the carrot.

Since pressure $= \frac{\text{force}}{\text{contact area}}$, the minimum pressure exerted would be at the thickest part of the carrot, where the contact area between the knife and carrot is the maximum.

Answer

Hence, the contact area $A = (3 \times 10^{-2}\text{ m}) \times (0.1 \times 10^{-3}\text{ m}) = 3 \times 10^{-6}\text{ m}^2$

The minimum pressure $P = \frac{F}{A} = \frac{(20\text{ N})}{(3 \times 10^{-6}\text{ m}^2)} = 6.67\text{ MPa}$

The pressure exerted is huge for a relatively small force applied. When cutting an object, it is easier to cut the thinner part of the object instead of the thicker part. This is because the contact area at the thinner part of the object is smaller. If the blade is blunt, the contact area becomes larger and hence more force is required for cutting.

Let's Investigate 6A

Aim

To investigate the relationship between pressure and area

Procedure

1 Get into a push-up position with your palms against the floor (Figure 6.5).

Figure 6.5 Push-up position

2 Lift your palms off the floor but keep your fingertips on the floor to get into a fingertip push-up position.
3 Lift up a finger on each hand.

Observation

An immediate stress is felt when we lift our palms to change to a fingertip push-up position. The stress on the fingertips increases when the number of fingers in contact with the floor is reduced.

Discussion

Pressure is the stress that is felt on the fingertips. Our weight is the force that is supported by either our palms or fingertips in the push-up position. Therefore, the force exerted in different push-up positions is the same. However, the contact area of the fingertips with the ground is smaller than that of the palm.

Since pressure = $\frac{\text{force}}{\text{contact area}}$, pressure is larger when the contact area is smaller. Hence, a greater stress is felt in the fingertip push-up position. This stress increases when more fingers are lifted off the ground.

Let's Practise 6.1

1 The pressure exerted by a person wearing a pair of roller blades is higher than that when he wears a pair of flat sole sneakers. Explain why.
2 A small cube with sides x cm is placed on a large square table with sides y cm. If the cube weighs z N, what is the pressure exerted by the cube in Pa?
3 A rectangular block has dimensions 15 cm by 10 cm by 20 cm and weighs 20 N. What is the maximum and minimum pressure exerted by the block when it is placed on a flat horizontal table?

Link

Theory Workbook
Worksheet 6A

6.2 How Is Pressure Transmitted Through an Enclosed Liquid?

Learning Outcome

- Describe and explain the transmission of pressure in hydraulic systems with particular reference to the hydraulic press.

Have you seen an excavator scooping up dirt or sand and unloading it onto a truck (Figure 6.6)? The shovel of an excavator can easily scoop up one cubic metre of dirt each time. This amount of dirt weighs approximately one and half tonnes! How is the excavator able to exert a great force into the ground to scoop up the heavy dirt?

Figure 6.6 An excavator can be used to lift a heavy load.

The excavator makes use of a hydraulic system. What are hydraulic systems and how do they work? To answer this question, let us consider the **hydraulic press**.

Word Alert

Hydraulic: liquid moving in an enclosed space

The working principle of the hydraulic press is fundamental to all hydraulic systems. Figure 6.7 shows how a hydraulic press works. At the two ends of the hydraulic press are two pistons. One of these pistons has a surface area that is larger than the other.

① A force F_1 is applied on piston 1. The pressure exerted on piston 1 and hence the liquid is $P_1 = \frac{F_1}{A_1}$, where A_1 is the area of piston 1.

$$P_1 = \frac{F_1}{A_1} \text{ ---- } (1)$$

② As a liquid cannot be compressed, the pressure P_1 would be transmitted equally to other parts of the liquid and to piston 2.

③ The pressure exerted on piston 2 is $P_1 = \frac{F_2}{A_2}$, where F_2 is the force on piston 2 and A_2 is the area of piston 2.

$$P_1 = \frac{F_2}{A_2} \text{ ---- } (2)$$

Substitute (1) into (2).

$$\frac{F_1}{A_1} = \frac{F_2}{A_2}$$

$$F_2A_1 = F_1A_2$$

$$F_2 = F_1\frac{A_2}{A_1}$$

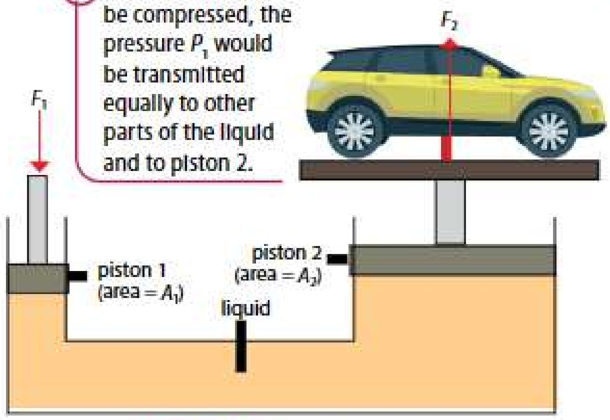


Figure 6.7 A hydraulic press

In Figure 6.7, since A_2 is very much larger than A_1, the force F_2 is very much larger than F_1.

$$F_2 = F_1 \frac{A_2}{A_1}$$

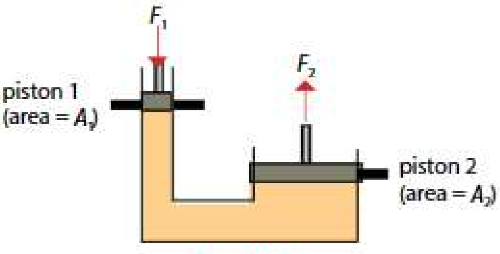


Figure 6.8

We can see that F_2 is a multiple of F_1. The multiple is given by the ratio of the areas A_2 to A_1. Thus, a hydraulic press has a multiplier effect (proportional increase). It converts a relatively small force F_1 on a small piston into a relatively large force F_2 on a large piston. This effect was first investigated by Blaise Pascal.

Pascal discovered what is now known as the **Pascal's principle** or **Pascal's law**.

If a pressure is applied to an enclosed liquid, the pressure is transmitted to all other parts of the liquid undiminished.

This is the principle behind the multiplier effect of the hydraulic press.

Worked Example 6D

Figure 6.9 shows a simple hydraulic press. A force of 50 N is applied on piston 1 with an area of 0.0025 m^2. Piston 2 has an area of 0.25 m^2.

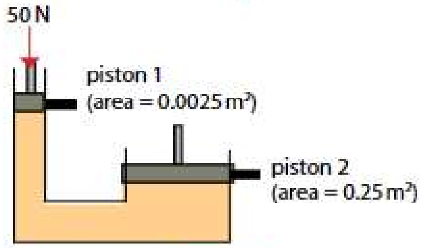


Figure 6.9

Calculate:

(a) the pressure exerted by the liquid on piston 1;
(b) the ratio of the area of the piston 2 to area of piston 1;
(c) the force exerted on piston 2; and
(d) the distance moved by piston 1 if piston 2 moves 5 cm.

Thought Process

(a) By Newton's Third Law, the force exerted by the liquid on piston 1 is equal but opposite to the applied force. Knowing the force exerted by the liquid allows us to calculate the pressure exerted on piston 1.
(c) The force exerted on piston 2 can be found by multiplying F_1 with the ratio found in (b).
(d) Since liquid cannot be compressed, the volume of liquid displacing piston 2 must be the same as the volume of liquid displaced by piston 1. Dividing this volume of liquid displaced by the cross-sectional area gives us the distance moved by piston 1.

Answer

(a) Pressure P_1 exerted by the liquid on piston 1

$$= \frac{F_1}{A_1} = \frac{50\text{ N}}{0.0025\text{ m}^2} = 20\text{ kPa}$$

Disciplinary Idea

Matter interacts through forces and fields.

Forces are exerted on bodies that are in contact with a fluid, in a gravitational field.

Forces can also be transmitted through matter.

In a hydraulic press, a small force applied on a small piston can be converted into a large force exerted on a large piston.

Word Alert

Undiminished: not reduced

Helpful Note

From Worked Example 6D, we can see that the downside to achieving a force that is 100 times greater is that the distance moved would be 100 times smaller. The gain in force exerted on piston 2 involves the drawback of having to push piston 1 over a great distance.

(b) Ratio of area of piston 2 to area of piston 1

$= \frac{A_2}{A_1} = \frac{0.25\ \text{m}^2}{0.0025\ \text{m}^2} = 100$

(c) Force F_2 exerted on piston 2

$= \frac{A_2}{A_1} \times F_1$

$= 100 \times 50\ \text{N}$

$= 5000\ \text{N}$

(d) Equating the volumes of liquid at pistons 1 and 2:

$A_1 \times d_1 = A_2 \times d_2$,

where d_1 and d_2 are the distances moved by piston 1 and piston 2 respectively

$d_1 = \frac{A_2}{A_1} \times d_2 = 100 \times 0.05\ \text{m} = 5.0\ \text{m}$

Let's Practise 6.2

1 Figure 6.10 shows a simple hydraulic press with circular pistons. The hydraulic press is used to lift a car that has a mass of 800 kg. What is the force F_1 required at piston 1 to lift the car? (Take gravitational field strength $g = 10$ N/kg)

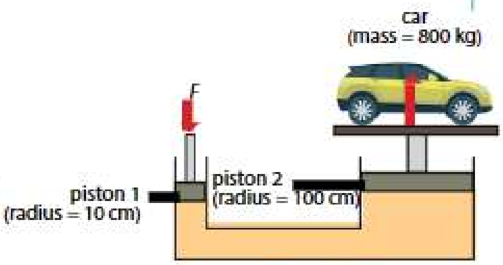


Figure 6.10

2 Figure 6.11 shows a simple hydraulic press with circular pistons. Piston 1 is attached to a lever with a yoke joint that is 25 cm from the pivot A. If the load is 500 N and the lever is 100 cm long, what is the minimum force F applied on the lever to balance the load? (Take gravitational field strength $g = 10$ N/kg)

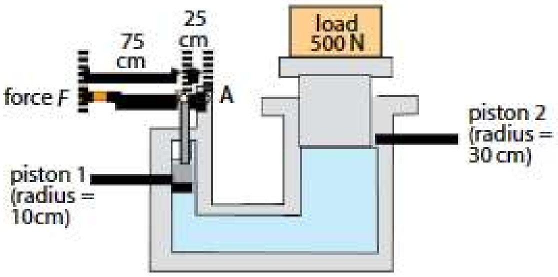


Figure 6.11

Link

We can also apply conservation of energy to solve (d) of Worked Example 6D. By the conservation of energy, work done by piston 1 must be equal to work done by piston 2. Work done is given by force applied multiplied by the distance moved in the direction of the force. You will learn about work done in Chapter 7.

Disciplinary Idea

Conservation laws constrain the changes in systems.

The total energy of an isolated system is neither created nor destroyed. Therefore, the work done on one piston is equal to the work done by the other connected piston.

You will learn more about conservation of energy in Chapter 7.

Link

Theory Workbook
Worksheet 6B

6.3 How Is the Height of a Column of Liquid Used to Measure Pressure?

Learning Outcomes

- Recall and apply the relationship *density = mass / volume* to new situations or to solve related problems.
- Recall and apply the relationship *pressure due to a liquid column = height of column × density of the liquid × gravitational field strength* to new situations or to solve related problems.
- Describe how the height of a liquid column may be used to measure the atmospheric pressure.
- Describe the use of a manometer in the measurement of pressure difference.

Density

Compare a shot put ball and a soccer ball (Figure 6.12). Which object is heavier?

Figure 6.12 Which object, a shot put ball or a soccer ball, is heavier?

The shot put ball is smaller than a soccer ball, but it is much heavier than the soccer ball. This is because the shot put ball is denser than the soccer ball. When we talk about density, we are referring to the amount of matter or mass in a given amount of space or volume.

▶ **Density** is defined as mass per unit volume.

▶ $\rho = \frac{m}{V}$

where ρ = density (pronounced as "rho")
m = mass (kg)
V = volume (m^3)

The SI unit of density is **kilogram per cubic metre (kg/m³)**. Another common unit of density is gram per cubic centimetre (g/cm³). The densities of common liquids such as water and mercury are approximately 1000 kg/m³ (1 g/cm³) and 13 600 kg/m³ (13.6 g/cm³) respectively.

Determining the Density of a Liquid

To determine the density of a liquid, we need to measure its mass and volume by following these steps.

1 Weigh an empty graduated measuring cylinder.
2 Pour the liquid into the measuring cylinder and weigh both the measuring cylinder and the liquid.
3 Determine the mass of the liquid by subtracting the reading in step 1 from the reading in step 2.
4 The volume of the liquid can be measured using the measuring cylinder.
5 The density of the liquid can be calculated using: Density of liquid = $\frac{\text{mass of liquid}}{\text{volume of liquid}}$

Disciplinary Idea

Matter and energy make up the Universe.

The amount of matter spread out over space can be accounted for using density.

The density of an object measures how much mass is packed per unit volume, while the mass of an object is the amount of matter in an object.

Helpful Note

The words "heavy" and "light" are used to describe the mass of an object, but not its density. A watermelon may be heavy (i.e., high mass), but its density is low because it has a low mass per unit of volume. The densities of some substances are shown in Table 6.1.

Table 6.1 Densities of some substances

Substance	Density/ kg/m³
polystyrene	16
ice	917
milk	1035
olive oil	900
dry air	1.28
nitrogen (0° C and 1 atm)	1.25

Determining the Density of Solids

Similarly, to determine the density of a solid, we need to measure its mass and volume. The mass of the solid can be measured using an electronic balance.

The volume of an irregular solid, such as a stone, can be found by immersing the solid in water and measuring the volume of water displaced (Figure 6.13).

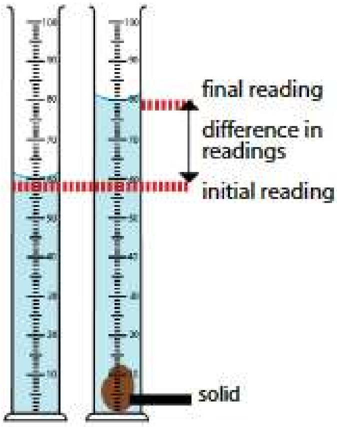


Figure 6.13 The volume of an irregular solid can be found by taking the difference between the readings.

Link

Practical Workbook
Experiment 6A

The volume of regular solids, such as a cuboid or a cylinder, can be calculated using measurements made by measuring instruments and applying appropriate geometric formulae.

Density is used to identify substances or the purity of substances. For example, the density of pure gold is 19.3 g/cm³. If a gold necklace has a different density from that of pure gold, it is not made of pure gold.

Substances that are less dense than water will float on water. Substances that are denser than water will sink in water. For instance, an iron cube sinks in water as it is denser than water (Figure 6.14). Will the iron cube sink in water if it is on the moon where the gravitational field strength is weaker?

Link

Chemistry
In Chemistry, we learn how to select suitable apparatus for experiments. For instance, when collecting gases, we need to determine if the gas is less or more dense than air to select the appropriate method of collecting the gas.

Figure 6.14 The iron cube sinks in water. Will it still sink in water if it is on the moon?

Since density $= \frac{\text{mass}}{\text{volume}}$, the gravitational field strength on the moon will not affect the densities of the iron cube and water. Therefore, the iron cube will still sink in water on the moon.

Measuring Pressure

Disciplinary Idea

Microscopic models can explain macroscopic phenomena.

Particles are in continuous motion. In liquids, the weight of the liquid and the collisions of particles on the walls of the container produce the pressure on the container.

As we dive deeper into a swimming pool, we can feel the pressure of water gradually increasing on our eardrums. How do we explain this?

The pressure in a liquid increases with depth. The pressure that we feel underwater comes from the weight of all the water above us. As we dive deeper, there is more water above us. The weight of water above us is greater and so we feel the increase in water pressure.

A simple experiment to show that the pressure in a liquid increases with depth is shown in Figure 6.15. In this simple experiment, a vessel with three outlets at different heights is filled with water.

The water flowing out of outlet 3 spurts out furthest, followed by the water from outlet 2 and then from outlet 1.

How far the water spurts depends on the water pressure. The greater the water pressure, the further the water spurts out. Thus, the water at outlet 3 experiences a greater pressure and the water at outlet 1 experiences a lower pressure.

Hence, we can conclude that water pressure increases with depth.

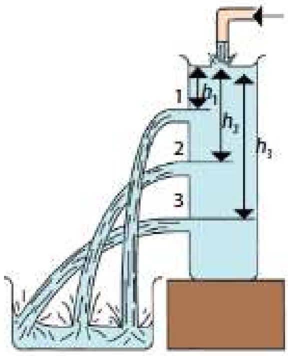


Figure 6.15 A vessel with three outlets at different heights

To determine the pressure at a certain depth of a liquid, let us consider a small volume of liquid at a certain depth of a container (Figure 6.16).

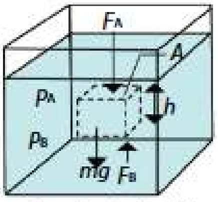


Figure 6.16 A small volume of liquid (shown by the dashed lines in the middle of the tank) with pressure P_A at the top and P_B at the bottom.

The downward forces acting on the small volume of liquid are the force F_A acting on the top surface and weight mg. The upward force acting on the small volume of liquid is the force F_B acting on the bottom surface. Since the small volume of liquid is at rest, by Newton's Second Law of Motion, the resultant force must be zero:

$F_B - (F_A + mg) = 0$

Link

Recall from Chapter 4: An object at rest would not have any acceleration, and by Newton's Second Law of Motion, would have no resultant force.

Using the relationships force = pressure × area and mass = density × volume:

$P_B A - (P_A A + \rho A h g) = 0$ where A is the cross-sectional area of the small volume of liquid
ρ is the density of the liquid
h is the height of the small volume of liquid

Dividing by A and rearranging the terms:

$P_B - P_A = h\rho g$

Therefore, the pressure between two levels in a liquid is given by $h\rho g$. When the top level is the air–liquid interface, the pressure of liquid at the surface is taken as zero. Hence, the pressure P in a liquid at any point h below the air–liquid surface is:

▶ **$P = h\rho g$** where h = height (m)
ρ = density (kg/m^3)
g = gravitational field strength (N/kg)

The pressure at a given depth beneath a liquid surface depends only on the depth, since its density and the gravitational field strength do not change.

In deriving this formula, the shape of the container does not come into the picture at all. In other words, the volume and cross-sectional area of the liquid do not affect the pressure at any point in a liquid. This is shown using an apparatus known as a Pascal's vases (Figure 6.17).

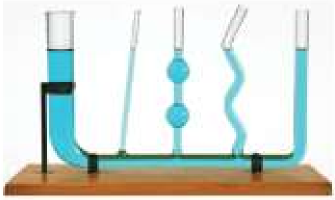


Figure 6.17 The water levels in different tubes of the Pascal's vases are the same.

The pascal vases consist of four tubes of different shapes connected to a common reservoir. The water level in each tube is at the same height regardless of the shape of the tube. This proves that the water pressure must be the same. If the water pressure in each tube is different, then the difference in pressure will cause the water levels to rise or fall.

Disciplinary Idea

Forces help us understand motion.

A net force can result in pressure differences within a fluid and can result in changes in the liquid column height.

In the Pascal's vases, since the heights of each liquid column are the same, there is no pressure difference between the columns. Hence, net force is zero.

Worked Example 6E

Consider the cross-sectional view of a lake (Figure 6.18).

(a) If the depth at point A is 10 m, what is the pressure at A?

(b) Would the pressure at B be different from the pressure at A? Explain. (Take density of water as 1000 kg/m^3, atmospheric pressure as 100 kPa and gravitational field strength g as 10 N/kg.)

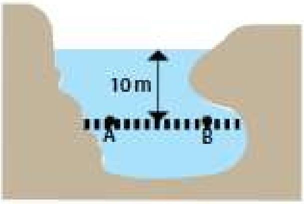


Figure 6.18

Answer

(a) Let P_{atm} be the atmospheric pressure, h be the depth, and ρ be the density of water.
The pressure at A is given by:

$$P_A - P_{atm} = h\rho g$$

$$\therefore P_A = 100 \text{ kPa} + (10 \text{ m})(1000 \text{ kg/m}^3)(10 \text{ N/kg})$$

$$= 200 \text{ kPa}$$

(b) No, the pressure at B would be the same as the pressure at A since points A and B are at the same depth. The pressure in a liquid depends only on the depth and does not depend on the shape of the cross-sectional area of the lake.

Mercury Barometer

Since pressure is proportional to the height (or depth) of a liquid, we can use the height of a liquid to measure pressure. An instrument, known as the mercury barometer (Figure 6.19), does exactly that.

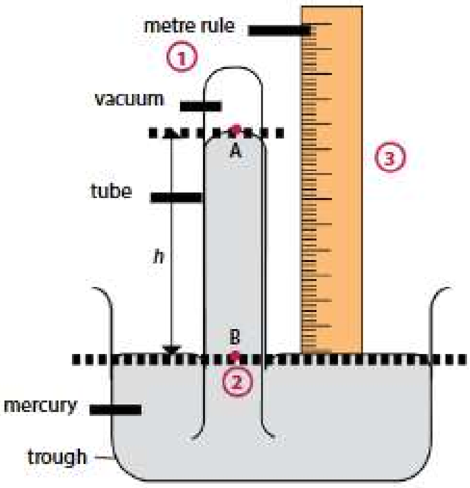


Figure 6.19 A simple mercury barometer and how it is used to measure atmospheric pressure

① A 1 m long thick-walled glass tube is filled completely with mercury.

The tube is inverted into a trough containing mercury. Some mercury flows out from the tube into the trough, while most of the mercury remains in the tube. The space above point A is a vacuum. Thus, the pressure at A (P_A) is zero.

② The mercury in the tube is supported by the atmospheric pressure exerted on the surface of the mercury in the trough. Thus, the pressure at B, which is level with the surface of the mercury in the trough, is the same as the atmospheric pressure. To determine the pressure at B (P_B), we use the result:

$$P_B - P_A = h\rho g$$
$$P_B = h\rho g$$

③ The height of the mercury column h can be measured with a metre rule. Height h is found to be 760 mm. Taking the density of mercury as 13 600 kg/m^3 and gravitational field strength as 10 N/kg, the pressure at B is:

$$P_B = (760 \times 10^{-3} \text{ m})\,(13\,600 \text{ kg/m}^3)\,(10 \text{ N/kg})$$
$$= 103 \text{ kPa}$$

Using the more accurate gravitational field strength value of 9.8 N/kg, a more accurate atmospheric pressure of 101.3 kPa is obtained.

Note that the vertical height of the mercury column depends only on the atmospheric pressure. It does not depend on the size of the tube used nor how deep the tube is placed into the trough of mercury. Even if the tube is lifted, lowered or tilted, the vertical height of the mercury column remains the same (Figure 6.20). Thus, the mercury barometer is a reliable instrument to measure atmospheric pressure.

Atmospheric pressure is often expressed in terms of mm Hg or cm Hg (Hg is the chemical symbol for mercury). One atmospheric pressure is often written as 760 mm Hg or 76 cm Hg.

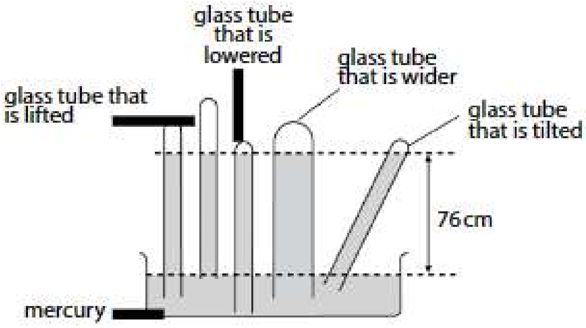


Figure 6.20 The mercury column remains at 76 cm Hg even though it is lifted, lowered or tilted.

Past to Present

In 1643, the mercury barometer was invented by Italian physicist, Evangelista Torricelli. However, the barometer he invented was not very practical as it included a one-metre tube.

In 1844, French physicist, Lucien Vidi, invented the aneroid (no liquid) barometer, which is still in use today (Figure 6.21). The aneroid barometer is smaller and more portable. Present day barometers are made even smaller. For instance, a micro-electromechanical systems (MEMS) barometer is smaller than a 10-cent coin!

Figure 6.21 An aneroid barometer

Worked Example 6F

Water may be used in the barometer instead of mercury. What would be the height *h* of the column if water is used? (Take density of water as 1000 kg/m³, gravitational field strength *g* as 10 N/kg and atmospheric pressure as 100 kPa.)

Answer

$$P_{atm} = h\rho_{water}\,g$$
$$100 \times 10^3 \text{ Pa} = h \times 1000 \text{ kg/m}^3 \times 10 \text{ N/kg}$$
$$h = 10 \text{ m}$$

Note: It would be quite impractical to use water as the liquid in barometers because a tube of more than 10 m would be required.

Manometer

Figure 6.22 shows an open tube manometer. It is the simplest form of a pressure gauge for measuring gas pressure. It consists of a U-shaped glass tube with an open end at A. The other end B is connected to a gas supply whose pressure is to be measured using the manometer. The tube is partially filled with a liquid of density ρ.

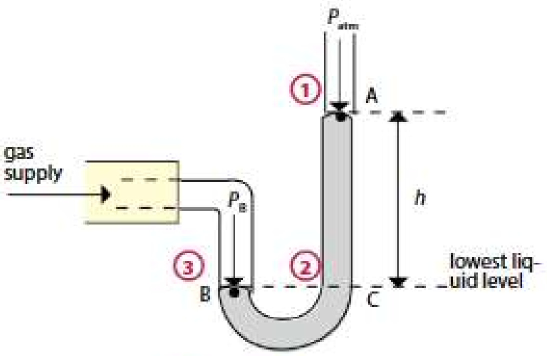


Figure 6.22 A manometer and how it measures gas pressure

① The liquid at A is exposed to the atmosphere. Thus, the pressure P_A at A is the atmospheric pressure P_{atm}.

② When the gas supply is turned on, the gas will exert pressure P_B on the liquid at B.
As P_B is higher than the atmospheric pressure, the liquid at A will rise until the pressure P_C at C, which is on the same horizontal level as B, equals the gas pressure. The pressure P_C at C is given by $P_C - P_A = h\rho g$.

③ Since $P_C = P_B$ and $P_A = P_{atm}$, we determine the pressure P_B of the gas to be:
$$P_B - P_{atm} = h\rho g$$
$$P_B = h\rho g + P_{atm}$$

Very often, it is the difference in pressure between the gas and the atmosphere that is of importance. This difference in pressure (i.e. $P_B - P_{atm}$) is given by $h\rho g$. If water is used in the manometer, then it is common to express the difference in pressure in terms of mm H_2O (H_2O is the chemical formula for water).

Tech Connect

Piezoelectric micro-electromechanical systems (MEMS) transducers are used to improve hearing. They are implanted into the ossicular chain (small bones of the middle ear) to replace the damaged middle ear bones (Figure 6.23).

The transducers detect changes in pressure in the middle ear and convert the pressure into electric signals, and then into vibrations. The vibrations are transferred to the inner part of the ear. This helps a person with hearing problems.

Why do these devices need to be small? Why are they dry and not wet like the liquid barometer?

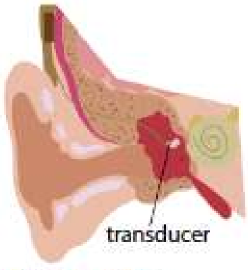


Figure 6.23 The transducer is implanted in the middle ear to improve hearing.

Helpful Note

In Figure 6.22, P_B is known as the absolute pressure of the gas. The difference in pressure (i.e. $P_B - P_{atm}$) is known as the gauge pressure.

Worked Example 6G

Figure 6.24 shows a water manometer which is connected to a gas supply. Before the gas supply is connected, the water is at the same level on both sides of the manometer.

(a) Explain why the water level moves up in the left side of the manometer after the gas supply is turned on.

(b) If the height of the water column is 10 cm, what is the pressure P_{gas} of the gas supply? (Take density of water as 1000 kg/m³, gravitational field strength g as 10 N/kg and atmospheric pressure as 100 kPa.)

(c) What is the difference in pressure between the gas and the atmosphere in cm H_2O?

(d) Suggest how the manometer can be changed to measure greater pressure differences using a tube of the same length.

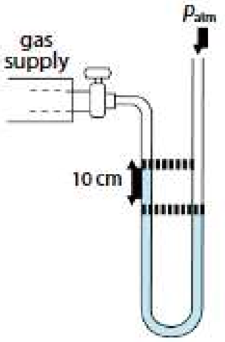


Figure 6.24

Answer

(a) The pressure from the gas supply is lower than the atmospheric pressure and thus the water level moves up in the left side of the manometer.

(b)

$$P_{atm} - P_{gas} = h\rho_{water}\,g$$

$$(100 \times 10^3 \text{ Pa}) - P_{gas} = (10 \times 10^{-2} \text{ m})\,(1000 \text{ kg/m}^3)\,(10 \text{ N/kg})$$

$$P_{gas} = 99 \text{ kPa}$$

(c) The difference in pressure, or the gauge pressure, is 10 cm H_2O as given by the height of the water column.

(d) A liquid that has a density higher than water should be used.

Let's Practise 6.3

1 Figure 6.25 shows a manometer that is connected to a sealed container. The water level in the manometer was at the same level before it was connected to the sealed container.

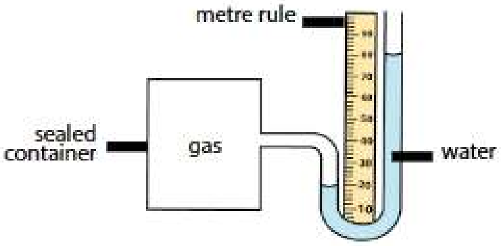


Figure 6.25

(a) Explain why water level in the right side of the tube is higher.

(b) Calculate the pressure inside the sealed container. (Take density of water as 1000 kg/m³, gravitational field strength g as 10 N/kg and atmospheric pressure as 100 kPa.)

(c) If oil of density 890 kg/m³ is used instead of water, what would be the difference in height between the liquid levels of the manometer?

Cool Career

Prosthetic Designer

Prosthetic designers take appropriate measurements, as well as design and fit prosthetic limbs (artificial body parts) for their patients.

With recent developments, prosthetic limbs are now fitted with tiny micro-electromechanical systems (MEMS) pressure sensors. These sensors monitor the change in pressure in the tendons and muscles of the patients as they move.

Prosthetic designers use the data collected by the sensors and other information collected in the rehabilitation process to design prosthetic limbs that are better suited for the patients (Figure 6.26).

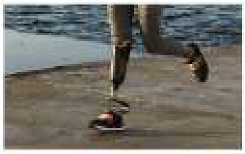


Figure 6.26 Prosthetic designers take data collected from pressure sensors into account when designing prosthetic limbs.

Link

Theory Workbook
Worksheet 6C
Let's Assess
Let's Reflect

Let's Map It

Pressure (SI unit: Pa)

is defined as

Force acting per unit area

can be found using this formula

$P = \frac{F}{A}$
where
P = pressure (Pa)
F = force (N)
A = contact area (m^2)

Pressure in liquids

is

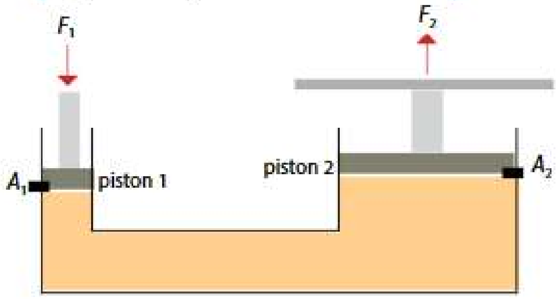
Transmitted equally to all parts of an enclosed liquid

is applied in a

Hydraulics press

Multiplier effect of a simple hydraulics press is given by the ratio of the areas of the pistons.

$F_2 = F_1\frac{A_2}{A_1}$
where
F_2 = force applied on piston 2 (N)
F_1 = force applied on piston 1 (N)
A_2 = area of piston 2 (m^2)
A_1 = area of piston 1 (m^2)



between two liquid levels is given by

$P = h\rho g$
where
P = pressure difference (Pa) or gauge pressure
h = difference in depth between two levels (m)
ρ = density (kg/m^3)
g = gravitational field strength (N/kg)

$\rho = \frac{m}{v}$
where
ρ = density (kg/m^3)
m = mass (kg)
v = volume (m^3)

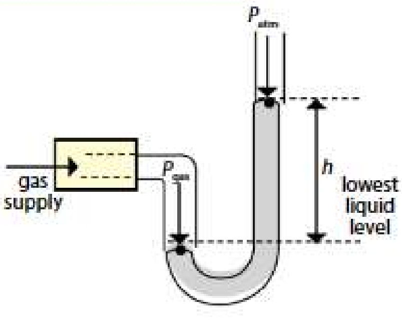
is applied in a

Manometer

to measure

Gas pressure

$P_{atm} - P_{gas} = h\rho g$ if $P_{gas} < P_{atm}$
$P_{gas} - P_{atm} = h\rho g$ if $P_{gas} > P_{atm}$
where
P_{atm} = atmospheric pressure (Pa)
P_{gas} = pressure of gas (Pa)
h = height of liquid column (m)
ρ = density of liquid (kg/m^3)
g = gravitational field strength (N/kg)

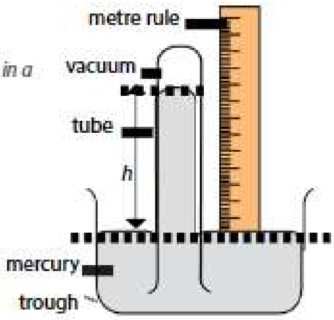


is applied in a

Mercury barometer

to measure

Atmospheric pressure



Let's Review

Section A: Multiple-choice Questions

1 Which object exerts the greatest pressure on the floor?

	Weight / N	Contact Area / cm²
○ A	30	1
○ B	66	3.5
○ C	500	20
○ D	1000	440

2 A shark swims 20 m below the surface of the ocean. What is the total pressure acting on the shark at this depth? (Take density of seawater = 1030 kg/m³, gravitational field strength = 10 N/kg and atmospheric pressure = 100 kPa.)

○ A −106 kPa ○ B 106 kPa
○ C 206 kPa ○ D 306 kPa

3 The system contains an incompressible liquid (Figure 6.27).

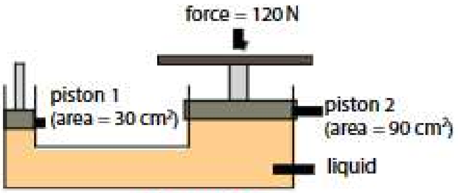


Figure 6.27

The area of piston 1 is 30 cm² and the area of piston 2 is 90 cm². If a force of 120 N is applied on piston 2, what is the upward force F on piston 1?

○ A 1.33 N ○ B 4 N
○ C 40 N ○ D 360 N

4 Figure 6.28 shows a system containing an incompressible liquid.

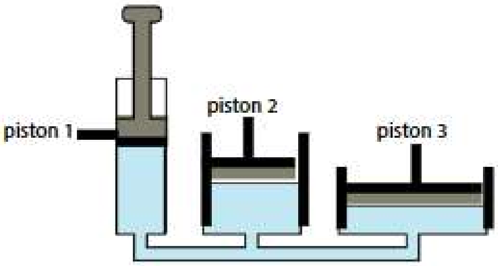


Figure 6.28

The ratio of the area of piston 1 to the area of piston 2 is 1 : 2. The ratio of the area of piston 2 to the area of piston 3 is 1 : 1.5. If a 10 N force is applied on piston 1, what is the upward force on piston 3?

○ A 15 N ○ B 20 N
○ C 25 N ○ D 30 N

5 Figure 6.29 shows a manometer connected to a gas supply.

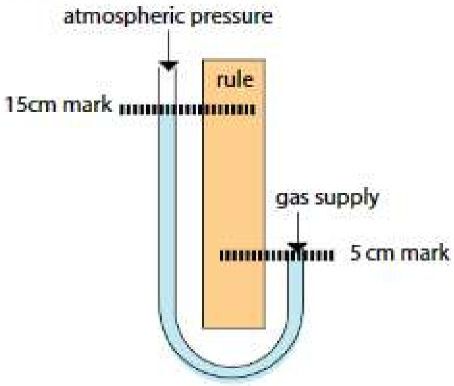


Figure 6.29

What is the difference in the pressure of the gas supply and atmospheric pressure?

○ A 5 mm water ○ B 10 mm water
○ C 15 mm water ○ D 100 mm water

Section B: Structured Questions

1 Figure 6.30 shows two containers of different sizes and shape filled with a liquid of the same density to the same height h.

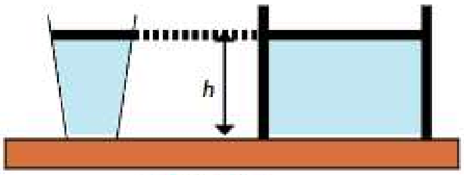


Figure 6.30

Explain why the liquid pressure at the bottom of both containers is the same.

2 Figure 6.31 shows a manometer containing oil and water. What is the density of the oil? (Take density of water as 1000 kg/m³.)

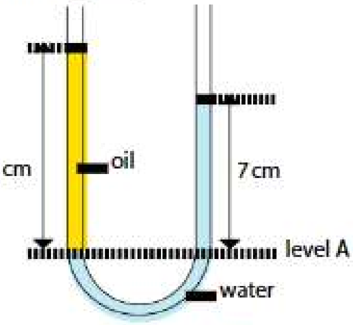


Figure 6.31

3 Figure 6.32 shows a pressure cooker containing water that has been heated. If the pressure exerted by the steam before the nozzle releases the steam is three times the atmospheric pressure, what is the force exerted on the lid? Assume that the lid is flat and has a diameter of 20 cm. (Take atmospheric pressure as 100 kPa.)

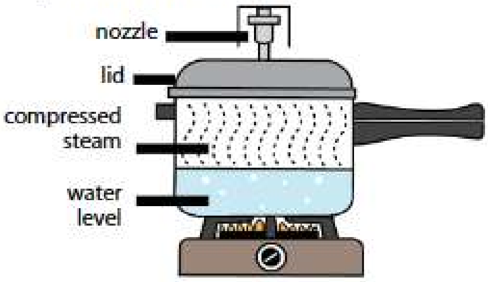


Figure 6.32

4 Figure 6.33 shows a dam.

(a) Why is the bottom part of the dam thicker than the top?

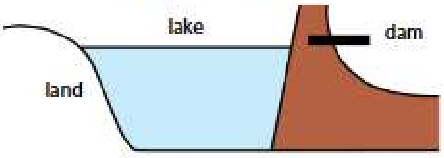


Figure 6.33

(b) Find the pressure at the bottom of the lake if the depth is 22 m. Take atmospheric pressure as 100 kPa, density of water as 1000 kg/m³, and gravitational field strength as 10 N/kg.

5 Figure 6.34 is connected to a gas supply. The U-tube on the left contains a liquid of unknown density. The U-tube on the right contains water. The apparatus is symmetrical about the line Y. The levels in the tube before being connected to the gas supply was at level X.

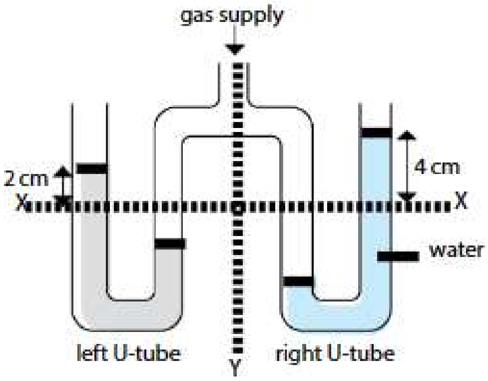


Figure 6.34

(a) Calculate the gas pressure. (Take density of water as 1000 kg/m³.)

(b) Determine the density of the liquid in the right U-tube.

(c) If the diameter of the right U-tube is doubled, what would be the height above level X?

Section C: Free-response Questions

1 A hydraulic press is used to cut a work piece (Figure 6.35).

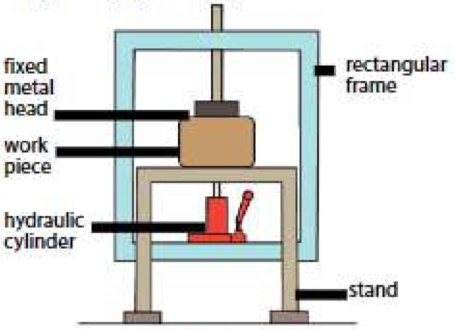


Figure 6.35

The hydraulic cylinder of the hydraulic press works on the principle shown in Figure 6.36.

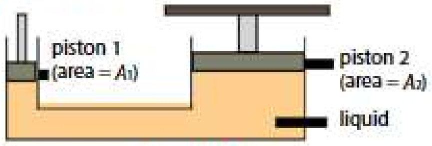


Figure 6.36

(a) Define *pressure*.

(b) Would the hydraulic cylinder of Figure 6.35 be the cylinder on the left or the right in Figure 6.36?

(c) A force of 800 N is required to cut the workpiece, and the ratio of areas A_1 to A_2 is 1 : 4. Calculate the force exerted by an operator on the lever to cut the workpiece.

(d) Would changing the liquid to a higher density in the hydraulic cylinder reduce the force exerted by the operator? Explain.

2 Liquid A is stored in a tank and is drained out from tap P as shown in Figure 6.37.

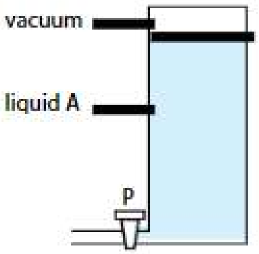


Figure 6.37

Figure 6.38 shows how the pressure exerted by liquid A on tap P varies with the depth of liquid A.

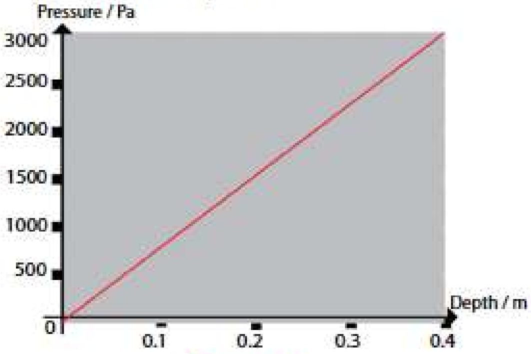


Figure 6.38

(a) Find the density of liquid A. (Take gravitational field strength = 10 N/kg)

(b) By connecting to a flow meter, the rate of flow of liquid A against the depth of the liquid is measured and recorded in Table 6.2.

Table 6.2

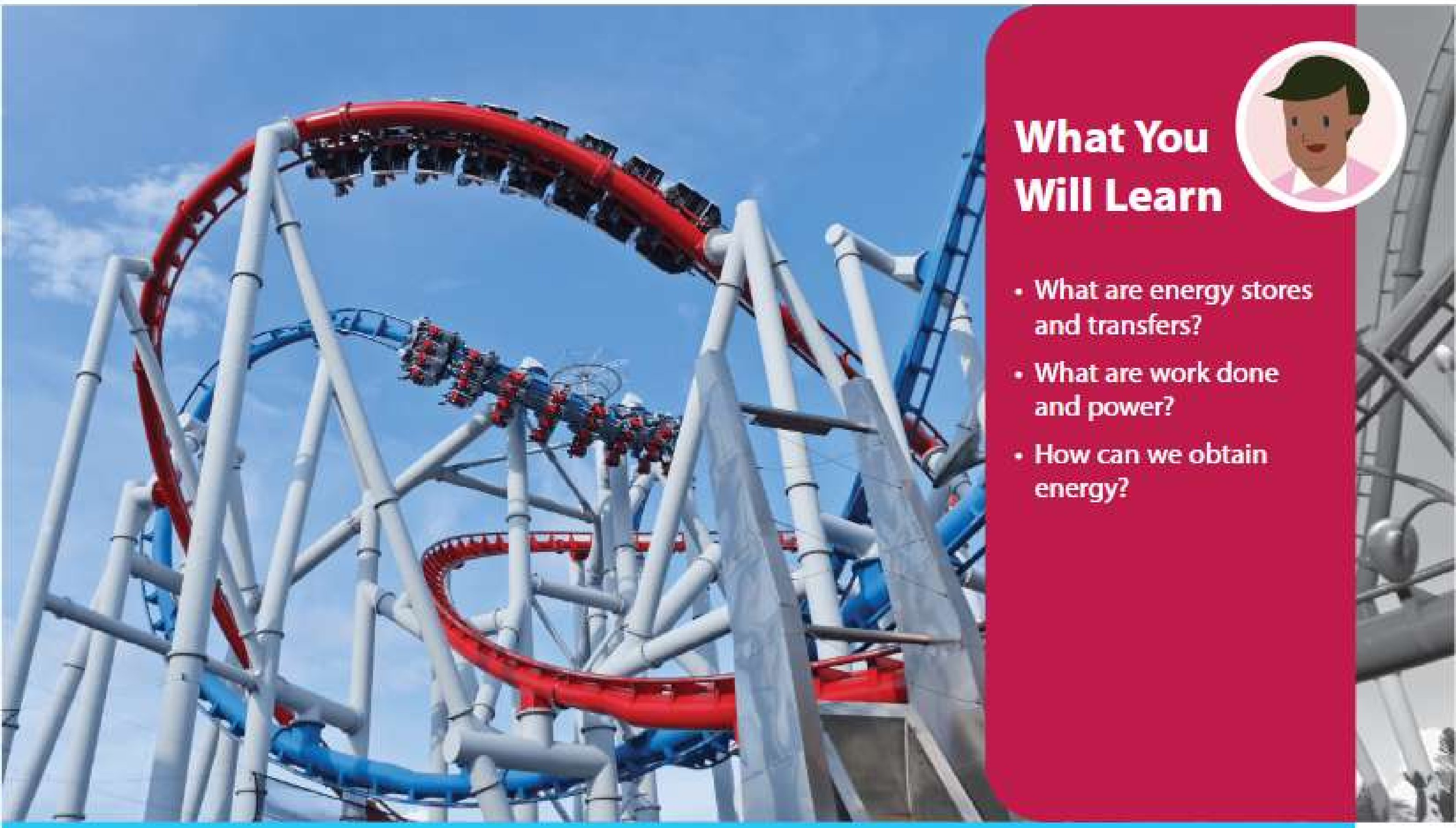
Depth of Liquid A / m	Rate of Flow / m^3/s
20	0.5
15	0.4
10	0.3
5	0.2

What conclusion can be made based on the data collected? Give an explanation why this is so.

(c) Suggest a way to increase the rate of flow.

CHAPTER

07 Energy



What You Will Learn

- What are energy stores and transfers?
- What are work done and power?
- How can we obtain energy?

Standing at 42.5 metres, the roller coaster in Sentosa is the tallest duelling roller coaster in the world. By means of a powerful motor, the 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.

Why is a powerful motor needed to launch the roller coaster cars to their starting positions?

7.1 What Are Energy Stores and Transfers?

Learning Outcomes

- Show an understanding that there are different types of energy stores.
- Show an understanding that energy can be transferred from one store to another.
- Recall and apply the relationships for kinetic energy ($E_k = \frac{1}{2}mv^2$) and gravitational potential energy near the Earth's surface ($E_p = mgh$) to new situations or to solve related problems.
- State the principle of the conservation of energy and apply the principle to new situations or to solve related problems.

Disciplinary Idea

Matter and energy make up the universe.

Examples of stores of energy include kinetic, chemical potential, internal, gravitational potential, elastic potential and nuclear.

Energy Stores

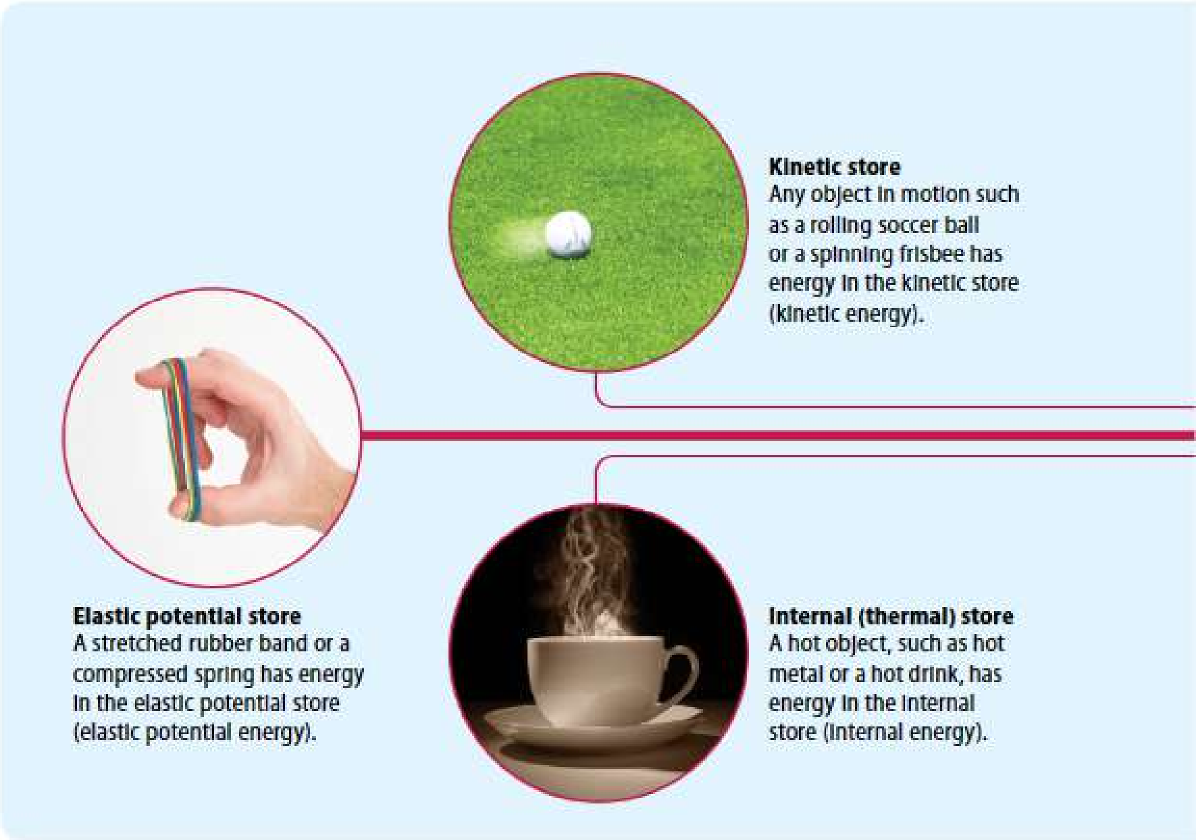
What does the term *energy* bring to mind? Someone exercising vigorously? Tidal waves crashing against the shore? Light bulbs shining brightly? Radiation from the sun?

Energy is required for things to work. The SI unit of energy is the **joule (J)**. Figure 7.1 shows six different types of **energy stores**.

Helpful Note

We can use the following terms when referring to energy in the different stores.

- "Kinetic energy" to mean "energy in the kinetic store".
- "Elastic potential energy" to mean "energy in the elastic potential store".
- "Internal energy" to mean "energy in the internal store".
- "Gravitational potential energy" to mean "energy in the gravitational potential store".
- "Chemical potential energy" to mean "energy in the chemical potential store".
- "Nuclear energy" to mean "energy in the nuclear store".



Kinetic store
Any object in motion such as a rolling soccer ball or a spinning frisbee has energy in the kinetic store (kinetic energy).

Elastic potential store
A stretched rubber band or a compressed spring has energy in the elastic potential store (elastic potential energy).

Internal (thermal) store
A hot object, such as hot metal or a hot drink, has energy in the internal store (internal energy).

Figure 7.1 Types of energy stores

A *system* consists of different parts working together. The gravitational potential store of an object is actually an energy store of the object–Earth system. In the rest of this chapter, when we refer to the gravitational potential store of the object, it is understood that Earth has been considered as part of the system.

Energy Transfers

One useful model about energy is to think of energy like a non-physical and invisible substance that can be transferred from one energy store to another. The total amount of energy remains constant.

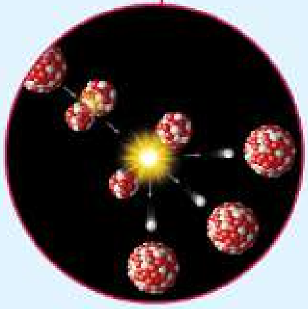
An analogy to understand this model is to think of energy as money and energy stores as different bank accounts where money can be stored. We can transfer money (energy) from one bank account (energy store) to another bank account (energy store) but the total amount of money is a constant.

Money (energy) can be transferred between the bank accounts (energy stores) in different ways. For example, we can transfer money using Internet banking or at the Automated Teller Machines (ATMs). Similarly, energy can be transferred to different energy stores through different pathways.

Types of Energy Stores

Gravitational potential store
An object such as a book above the ground has energy in the gravitational potential store (gravitational potential energy).

Chemical potential store
The food that we eat, fossil fuels and batteries have energy in the chemical potential store (chemical potential energy).



Nuclear store
The nuclei of atoms have energy in the nuclear store (nuclear energy).

Disciplinary Idea

Matter interacts through forces and fields.

An object experiences a gravitational force when placed in Earth's gravitational field. Its position in the field determines its gravitational potential energy.

Past to Present

Compared to the "energy forms and conversions" approach that is still widely used today, the "energy stores and transfers" approach is a new pedagogical (methods of teaching and learning) model.

All models have their inadequacies (i.e. limitations) but some are more useful in certain situations. The "energy stores and transfers" model seeks to develop a deeper understanding of energy. In the model, energy is modelled as an invisible substance that can be transferred between energy stores.

As science is a model-building enterprise to understanding our world, the two models show that models can change with time.

Disciplinary Idea

Matter and energy make up the universe.

The energy in a system can be accounted for by discussing various energy stores and the energy transfers between stores and/or systems by the four pathways. Energy can be transferred:

- mechanically (by a force acting over a distance);
- by heating (as a result of a temperature difference);
- by propagation of waves (both electromagnetic and mechanical); and
- electrically (by charges moving through a potential difference).

Helpful Note

Figure 7.3 is called the LOL diagram. Each "L" is an energy bar graph. The energy bar graph on the left shows the initial distribution of energy in the system. The "O" shows the energy transfers that take place between the system (e.g. ball and Earth) and the surroundings. The energy bar graph on the right shows the final distribution of energy in the system.

Energy can be transferred from one store to another in four different pathways.

1. Energy Transferred Mechanically by a Force Acting Over a Distance

Observation: Figure 7.2(a) shows a cart of mass *m* moving horizontally at a constant speed of 1.0 m/s along a smooth surface. When it is pushed by an applied force *F* over a short distance *s*, its speed increases to 2.0 m/s (Figure 7.2(b).

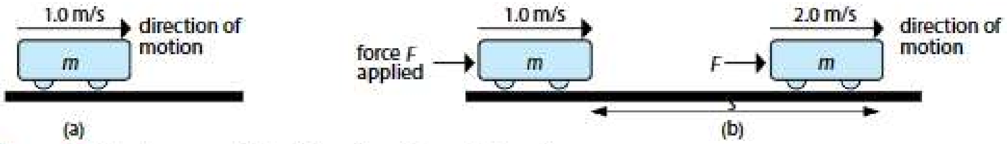
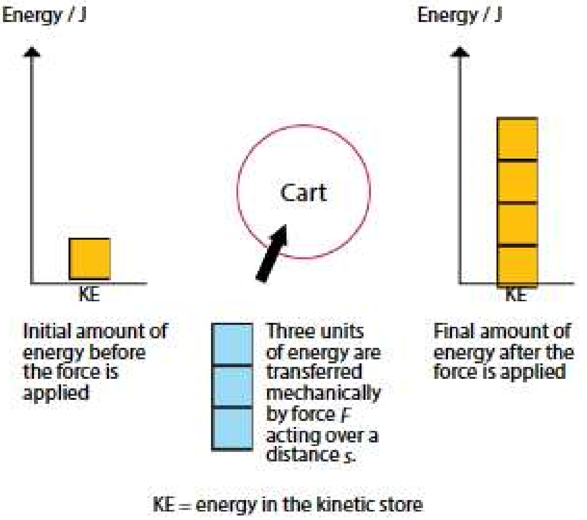


Figure 7.2 A cart moves faster after a force is exerted on it.

Explanation: Assuming negligible friction between the cart and the surface, the resultant force acting on the cart is the applied force *F*. By Newton's Second Law of Motion, this resultant force *F* causes the cart to accelerate in the direction of the applied force. We will learn that when a force moves an object through a distance, mechanical work done is done. We will also learn that the energy in the kinetic store of an object is directly proportional to the square of its speed.

Energy Analysis: Figure 7.3 shows the initial and final amounts of energy of the system (cart) before and after the force *F* is applied

Before the force is applied, the system (cart) has energy in its kinetic store. The energy in its kinetic store is represented by one unit.



After the force is applied, the energy in the kinetic store of the system (cart) increases. The energy in its kinetic store is represented by four units.

The increase in the energy in its kinetic store is due to the mechanical work done by force *F* acting on the cart over the distance *s*.

Figure 7.3 Energy transfer when a moving cart is pushed by an applied force over a distance along a frictionless surface

Note that the cart is travelling on a smooth surface. As there is no friction, the energy transferred out of the system is zero.

2. Energy Transferred by Heating due to a Temperature Difference

Observation: A small block of solid butter at room temperature is placed on a pan that is on an electric stove. When the electric stove is turned on, the butter melts after some time (Figure 7.4).

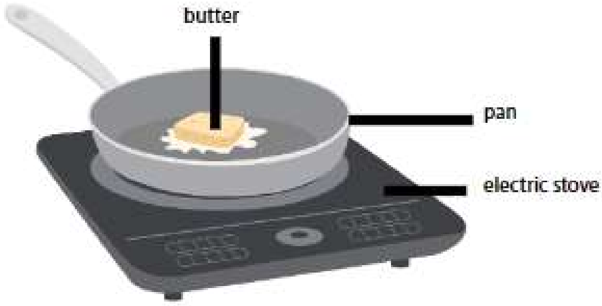
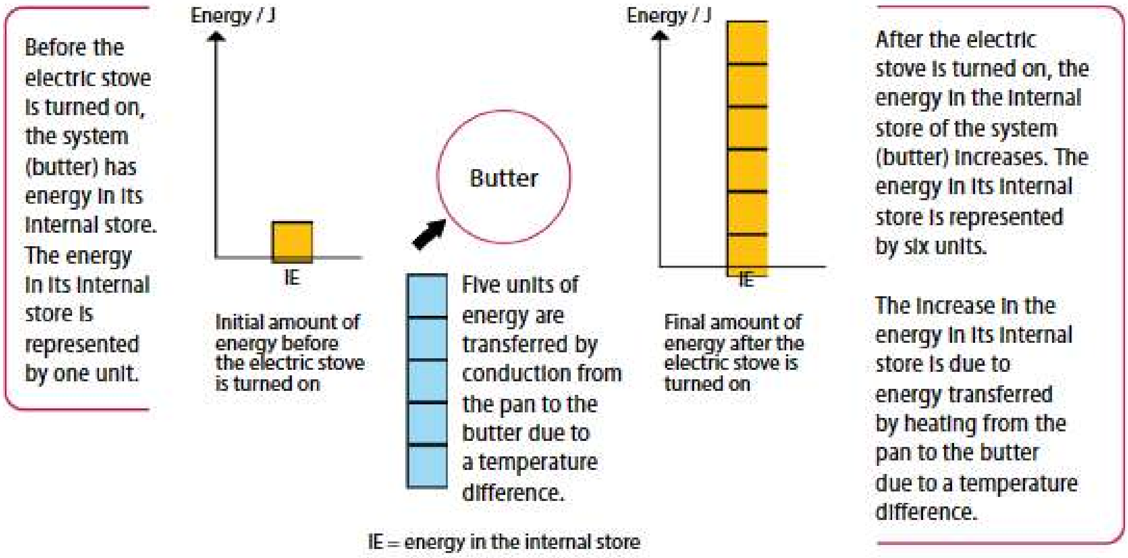


Figure 7.4 The butter is heated when the electric stove is turned on.

Explanation: When the electric stove is turned on, energy is transferred by heating from the hot surface of the pan to the butter. This transfer of energy is due to the temperature difference between the hot surface of the pan and the butter.

Energy Analysis: Figure 7.5 shows the initial and the final amounts of energy in the system (butter) before and after the electric stove is turned on.



Before the electric stove is turned on, the system (butter) has energy in its internal store. The energy in its internal store is represented by one unit.

Five units of energy are transferred by conduction from the pan to the butter due to a temperature difference.

After the electric stove is turned on, the energy in the internal store of the system (butter) increases. The energy in its internal store is represented by six units.

The increase in the energy in its internal store is due to energy transferred by heating from the pan to the butter due to a temperature difference.

Figure 7.5 Energy transfer when a small block of butter is heated

Disciplinary Idea

Waves can transfer energy without transferring matter.

Waves transfer energy between energy stores and/or systems. However, the overall distribution of matter remains unchanged. For instance, the air particles from the teacher's vibrating vocal cords need not travel to the students so that they can hear the teacher.

Word Alert

Propagation: process of spreading something

Physics Connect

Scan the QR code to watch a clip on how a food seller harnesses the energy from the sun's nuclear store.

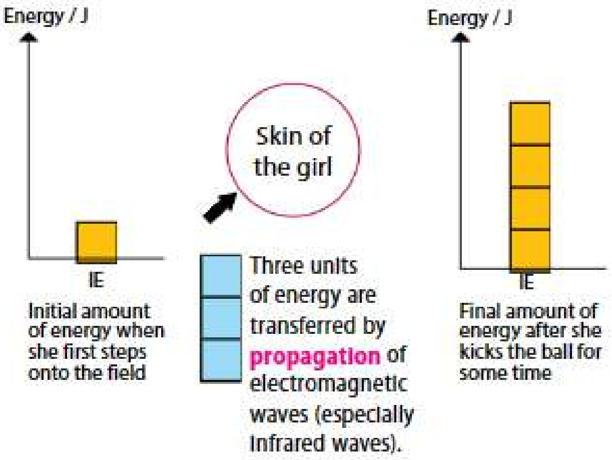
3A. Energy Transferred by Propagation of Waves (Electromagnetic Waves)

Observation: A girl is kicking a ball in an open field on a sunny day. After some time, she feels warm and starts to perspire (Figure 7.6).

Explanation: Electromagnetic waves (especially the infrared waves) from the sun interact with the skin of the girl to create a sensation of warmth.

Energy Analysis: Figure 7.7 shows the initial and final amounts of energy in the system (skin of the girl) when she first steps onto the field and after she kicks the ball for some time.

Figure 7.6 A girl kicks a ball under the sun.



When she first steps onto the field, the system (skin of the girl) has energy in the internal store. The energy in the internal store is represented by one unit.

Three units of energy are transferred by **propagation** of electromagnetic waves (especially infrared waves).

After she is beneath the sun for some time, the energy in the internal store of the system (skin of the girl) increases. The energy in the internal store is represented by four units.

The increase in the energy in the internal store is due to energy transferred from the sun into the system by the propagation of electromagnetic waves.

IE = energy in the internal store

Figure 7.7 Energy transfer when a girl stands underneath the sun

3B. Energy Transferred by Propagation of Waves (Mechanical Sound Waves)

Observation: A sound is heard each time the boy hits two cymbals together (Figure 7.8).

Explanation: When the cymbals are hit, the cymbals vibrate to and fro. This causes the air particles next to the vibrating cymbals to vibrate to and fro to produce sound waves.

Energy is transferred by the sound waves to the boy's ear drums. The ear drums vibrate and sound is detected by the boy.

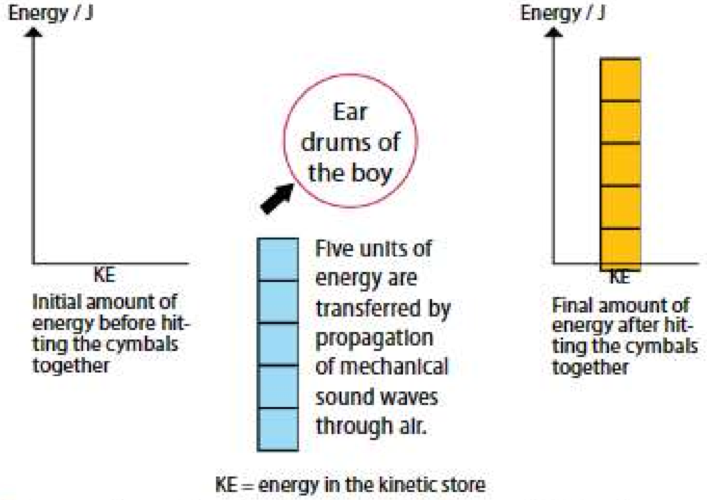
Figure 7.8 A boy hears a sound each time he hits two cymbals together.

Link

Sound is produced by a vibrating source. You will learn about the transmission of sound in Chapter 12.

Energy Analysis: Figure 7.9 shows the initial and final amounts of energy in the system (ear drum of the boy) before and after he hits the cymbals together.

Before hitting the cymbals together, the system (ear drums of the boy) has zero energy in the kinetic store as they are at rest.



After hitting the cymbals together, the energy in the kinetic store of the system (ear drums of the boy) increases. The energy in the kinetic store is represented by five units.

The increase in the energy in the kinetic store is due to energy transferred by the propagation of mechanical sound waves from the cymbals.

Figure 7.9 Energy transfer when the boy hits two cymbals together

4. Energy Transferred Electrically by an Electric Current

Observation: Consider a bulb in a simple circuit in an initial state and final state. At the initial state before the switch is closed, the bulb does not light up. At the final state after the switch is closed, the bulb lights up (Figure 7.10).

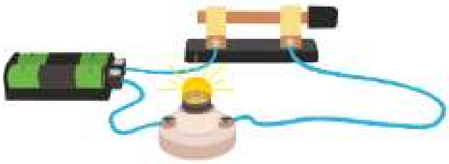
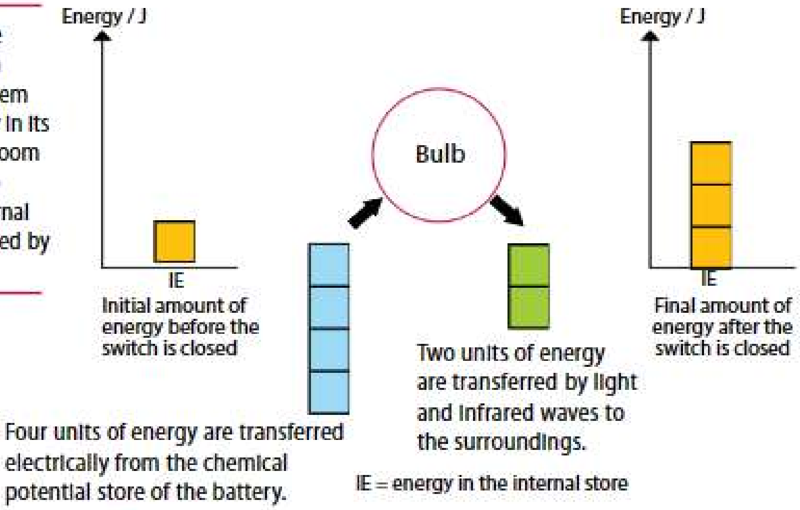


Figure 7.10 The bulb lights up when the circuit is closed.

Explanation: The battery has energy in the chemical potential store. It contains chemicals that undergo reactions. An electric current flows in the circuit when the switch is closed. The flow of electric current increases the temperature of the filament in the bulb and causes it to light up.

Energy Analysis: Figure 7.11 shows the initial and the final amounts of energy in the system (bulb) before and after the switch is closed.

At the initial state before the switch is closed, the system (bulb) has energy in its internal store at room temperature. The energy in its internal store is represented by one unit.



At the final state after the switch is closed, the energy in the internal store of the system (bulb) increases. The energy in its internal store is represented by three units.

Four units of energy are transferred electrically from the chemical potential store of the battery into the system (bulb). Two units of energy are transferred out of the system by light and infrared waves to the surroundings. Overall, there is an increase in energy in the internal store of the system.

Figure 7.11 Energy transfer when a bulb lights up

Another Example of Energy Transfer

Figure 7.12 shows a nail that is hammered into a wooden block.

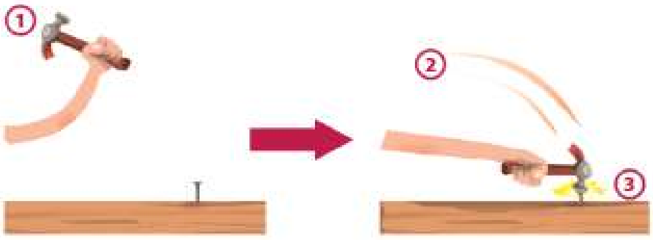
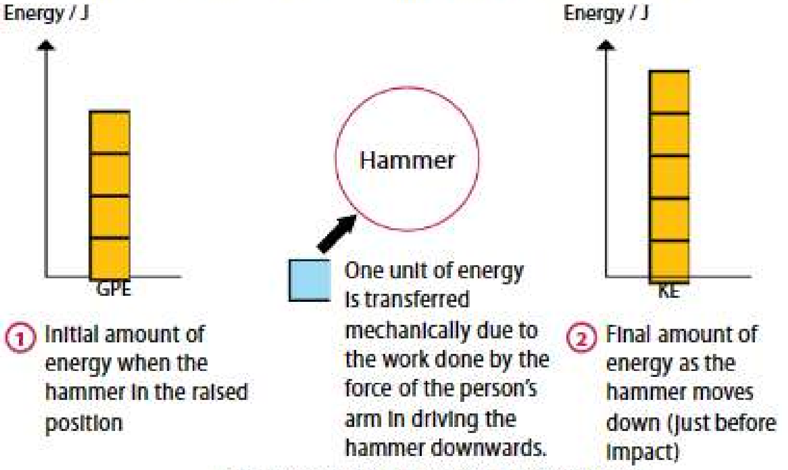


Figure 7.12
Hammering a nail

Figures 7.13(a) and 7.13(b) show the initial and final amounts of energy in the system (hammer on Earth) as the hammer moves downwards and hits the nail.

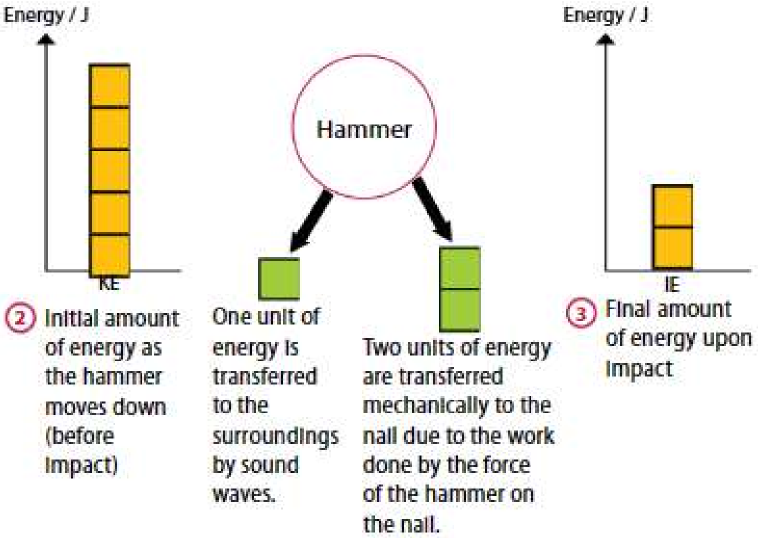
In the initial state, when the person raises the hammer above the ground, there is energy in the gravitational potential store of the hammer–Earth system. There is zero energy in the kinetic store.



GPE = energy in the gravitational potential store
KE = energy in the kinetic store

Figure 7.13(a) Energy transfer when the hammer moves downwards

At the position just before the hammer hits the nail, the energy in the kinetic store increases. The energy in the kinetic store is represented by four units. Four units of energy are transferred from the gravitational potential store to the kinetic store of the system. Additionally, one unit of energy is transferred mechanically due to the work done by the force of the person's arm to the kinetic store of the system. Overall, there is an increase in energy in the kinetic store of the system.



KE = energy in the kinetic store
IE = energy in the internal store

Figure 7.13(b) Energy transfer when the hammer hits the nail

At the final state, after the hammer hits the nail, the energy in the internal store of the hammer increases. The energy in the internal store is represented by two units. Two units of energy are transferred from the kinetic to the internal store of the system.

Calculating the Size of an Energy Store

To calculate the amount of energy in the kinetic store of a body moving at speed v, we use the following equation:

▶ $E_k = \frac{1}{2}mv^2$ where E_k = energy in the kinetic store (J)
m = mass of the body (kg)
v = speed of the body (m/s)

To calculate the amount of energy in the gravitational potential store of a body near the Earth's surface at a height h above the ground, we use the following equation:

▶ $E_p = mgh$ where E_p = energy in the gravitational potential store (J)
m = mass of the body (kg)
g = gravitational field strength (N/kg)
h = height (m)

Worked Example 7A

A golf ball of mass 0.046 kg travels at a speed of 5 m/s (Figure 7.14). Calculate the amount of energy in the kinetic store of the golf ball by using the equation for energy in the kinetic store.

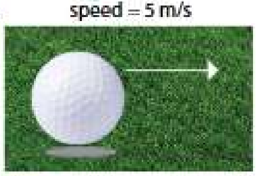


Figure 7.14

Answer
Amount of energy in the kinetic store of the golf ball
= kinetic energy of golf ball
$= \frac{1}{2}mv^2 = \frac{1}{2}(0.046)(5)^2 = 0.575$ J

Worked Example 7B

Figure 7.15 shows a package of 5 kg being lifted vertically through a distance of 10 m at a constant speed. Calculate the amount of energy in the gravitational potential store of the package at its raised position by using the equation for energy in the gravitational potential store. Take gravitational field strength g as 10 N/kg.

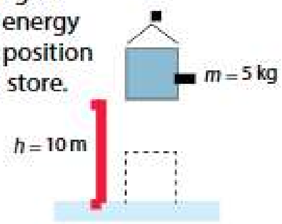


Figure 7.15

Answer
Amount of energy in the gravitational potential store of the package in its raised position
= increase in gravitational potential energy of the package
$= mgh =$ (5 kg)(10 N/kg)(10 m) = 500 J

Principle of Conservation of Energy

If you strike a match, you will get a burning flame. The energy in the chemical potential store of the match head is transferred by heating to the internal store of the surroundings. The total amount of energy (e.g. 20 J) before and after the transfer is the same (Figure 7.16).

Figure 7.16 When energy is transferred from one energy store to another, the total amount of energy remains constant.

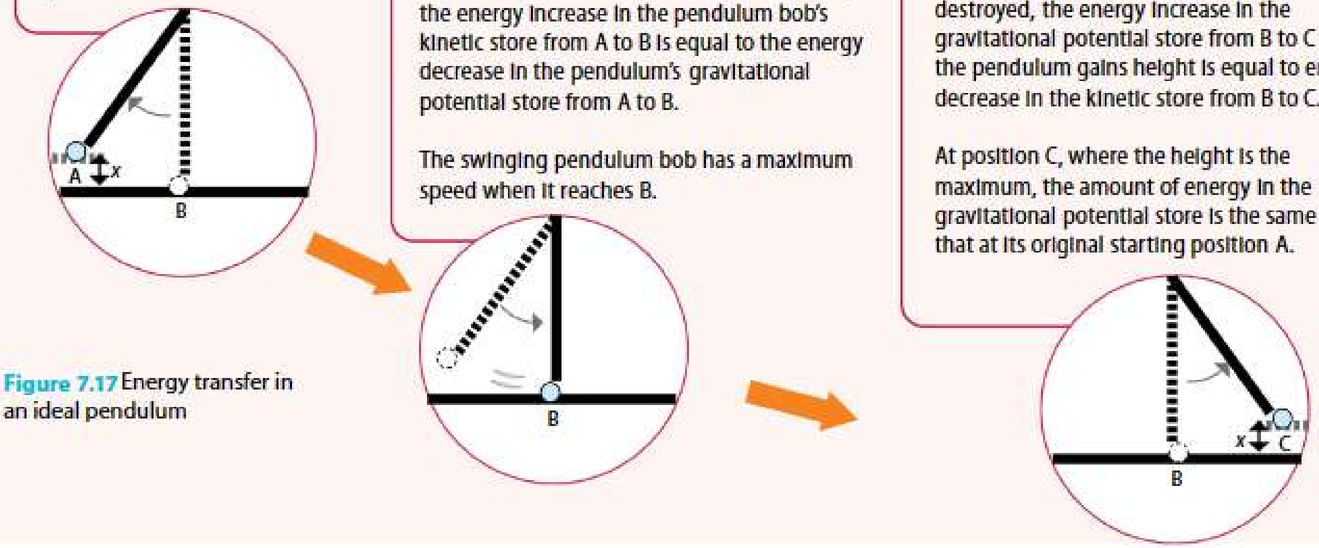
The **principle of conservation of energy** states that energy cannot be created or destroyed. Energy can be transferred from one store to another. The total energy of an isolated system is constant.

Word Alert

Conserved: kept the same

Principle of Conservation of Energy and the Ideal Pendulum

To illustrate the principle of conservation of energy, we use an ideal pendulum swinging in the absence of air resistance. Figure 7.17 shows the energy transfers with the total amount of energy being **conserved** as the energy in the gravitational potential store is being transferred to the kinetic store and vice versa.



① The pendulum bob is displaced to position A. It is at height x above the horizontal level.

At position A, the amount of energy in the gravitational potential store of the pendulum bob is the maximum due to its height x above its original position B.

② When the pendulum bob is released, it swings downwards with an increasing speed (due to an accelerating resultant force of its weight and tension in the string acting on it). As the height x decreases to zero at position B, energy is transferred mechanically from the gravitational potential store at A to the kinetic store at B.

Since energy cannot be created or destroyed, the energy increase in the pendulum bob's kinetic store from A to B is equal to the energy decrease in the pendulum's gravitational potential store from A to B.

The swinging pendulum bob has a maximum speed when it reaches B.

③ As the pendulum bob swings to position C, the pendulum slows down (due to a decelerating resultant force of its weight and tension in the string acting on it). As the height increases from zero to x at position C, energy is transferred mechanically from the kinetic store at B to the gravitational potential store at C.

Since energy cannot be created or destroyed, the energy increase in the gravitational potential store from B to C as the pendulum gains height is equal to energy decrease in the kinetic store from B to C.

At position C, where the height is the maximum, the amount of energy in the gravitational potential store is the same as that at its original starting position A.

Figure 7.17 Energy transfer in an ideal pendulum

Disciplinary Idea

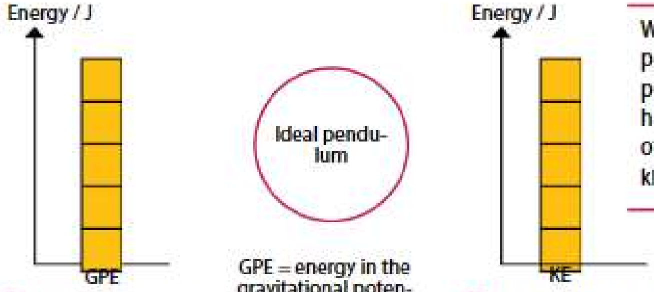
Conservation laws constrain the changes in systems.

The total amount of energy in an isolated system is conserved.

When no work is done on a body, its kinetic energy is constant and hence its speed is constant.

Figure 7.18(a) shows the initial amount of energy in the system (ideal pendulum on Earth) at position A and the final amount of energy in the system at position B.

The ideal pendulum has five units of energy in its gravitational potential store.



When the ideal pendulum is at position B, it has five units of energy in its kinetic store.

Figure 7.18(a) Energy transfer when the ideal pendulum moves from A to B

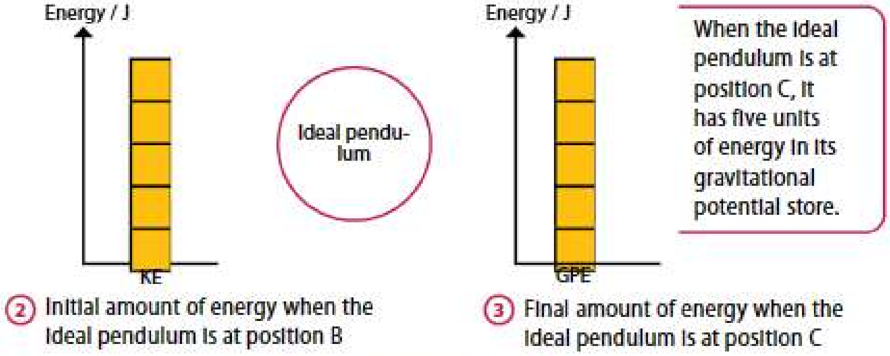
① Initial amount of energy when the ideal pendulum is at position A

GPE = energy in the gravitational potential store

KE = energy in the kinetic store

② Final amount of energy when the ideal pendulum is at position B

Figure 7.18(b) shows the initial amount of energy in the system (ideal pendulum on Earth) at position B and the final amount of energy in the system at position C.



When the ideal pendulum is at position C, it has five units of energy in its gravitational potential store.

② Initial amount of energy when the ideal pendulum is at position B

③ Final amount of energy when the ideal pendulum is at position C

KE = energy in the kinetic store, GPE = energy in the gravitational potential store

Figure 7.18(b) Energy transfer when the ideal pendulum moves from B to C

In the real world, the presence of air resistance opposes the movement of the swinging pendulum bob. An oscillating pendulum bob will eventually come to a stop.

Figure 7.19 shows the energy transfer when the pendulum bob swings from A to B and towards C in the real world.

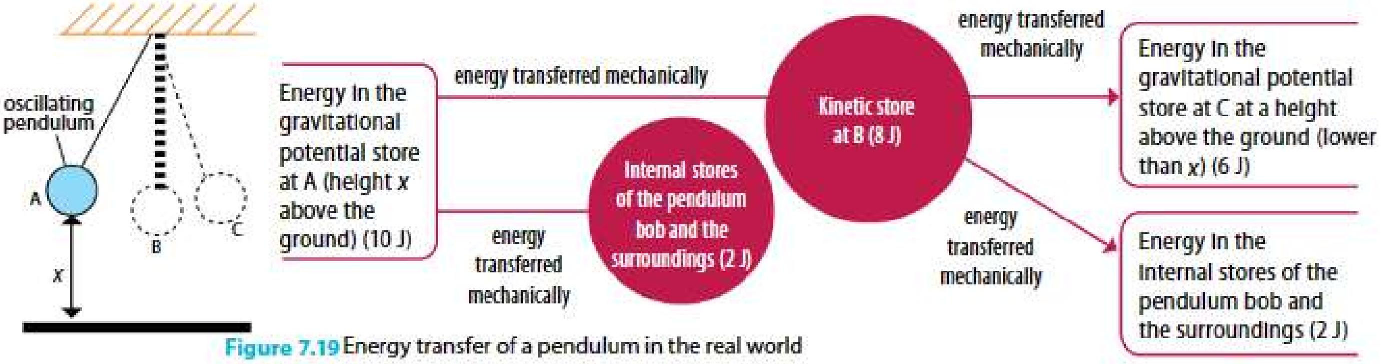


Figure 7.19 Energy transfer of a pendulum in the real world

Figure 7.19 shows that there is a continuous dissipation of energy to the internal stores of the pendulum bob and the surroundings. This explains why the height reached by the pendulum bob decreases with every swing and it eventually comes to a stop.

The principle of conservation of energy is still applicable by considering the pendulum and the surroundings as a system. In other words, the total amount of energy in the energy stores of the pendulum bob and the surroundings remains constant.

Worked Example 7C

Figure 7.20 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 energy in the kinetic store of the pendulum;

(b) the maximum energy in the gravitational potential store of the pendulum as it rises to its greatest height at Q; and

(c) the greatest height h.
(Take gravitational field strength $g = 10$ N/kg)

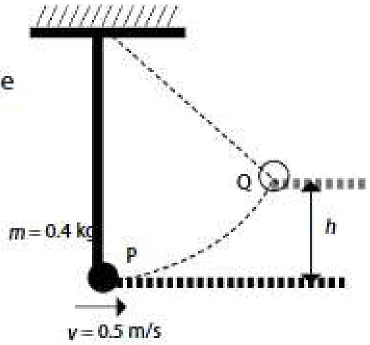


Figure 7.20

Answer

(a) Maximum kinetic energy at P
$= \frac{1}{2}mv^2 = \frac{1}{2}(0.4 \text{ kg})(1.5 \text{ m/s})^2 = 0.45$ J

(b) Based on the principle of conservation of energy, decrease in E_k from P to Q = increase in E_p from P to Q.
Therefore, maximum energy in the gravitational potential store at Q = 0.45 J.

(c) Maximum energy in the gravitational potential store = $mgh = 0.45$ J

$$\therefore h = \frac{0.45 \text{ J}}{mg} = \frac{0.45 \text{ J}}{(0.4 \text{ kg})(10\text{N/kg})} = 0.113 \text{ m}$$

Figure 7.21 shows a battery-operated robot waiter. It is carrying a food tray. The robot uses energy in the chemical potential store of the battery to perform its functions. The robot also has two lights to show that it is in operation.

What happens to the energy in the chemical potential store of the robot? The three restaurant guests give their own explanations. Which explanation is scientifically correct?

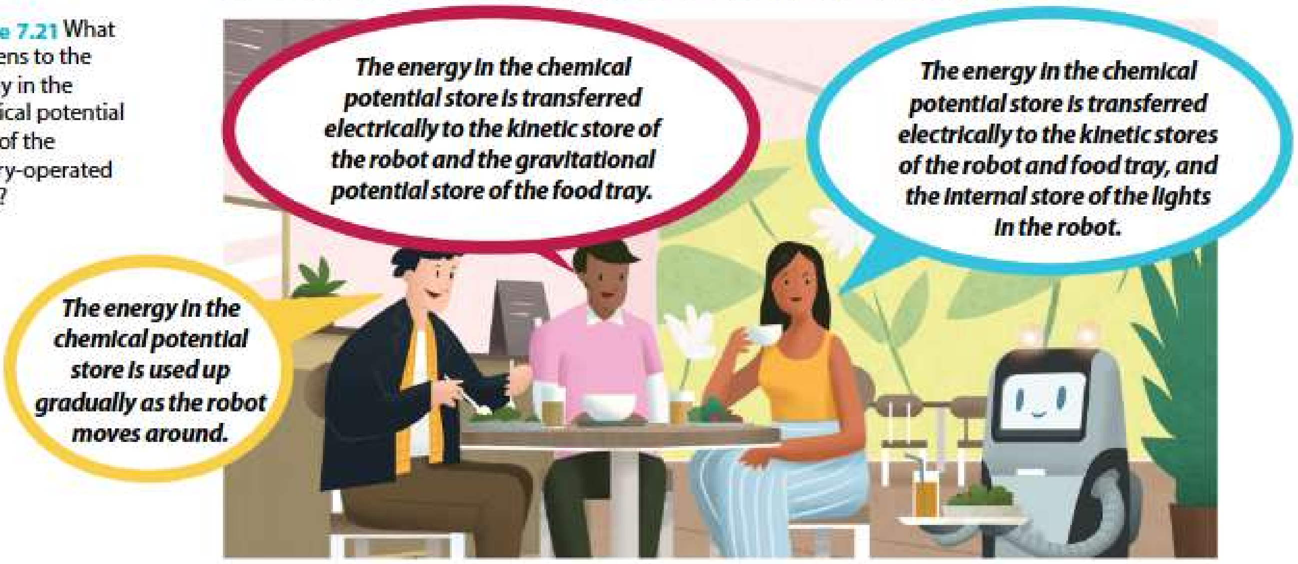


Figure 7.21 What happens to the energy in the chemical potential store of the battery-operated robot?

Based on the principle of conservation of energy, energy cannot be created or destroyed so energy cannot be used up. In Figure 7.21, the girl's explanation is correct. Energy is transferred electrically from the chemical potential store of the battery to the other stores.

It is important to note the following:

- As the robot is moving across the floor, there is no change in the gravitational potential store of the food tray since the height of the tray above the floor is constant.
- The flow of electric current increases the temperature of the filament wire of the lights and causes them to light up.
- Energy is transferred from the lights of the robot to the surroundings by electromagnetic waves.

Let's Practise 7.1

1 Identify the pathways and energy transfers in each system.
  (a) A ball free falling from a height (system: ball)
  (b) A bulb in a closed circuit (system: bulb)
2 A 2.0 kg flower pot falls from a height of 45 m towards the ground.
  (a) What is the amount of energy in the gravitational potential store of the flower pot before the fall?
  (b) What is the speed of the flower pot just before it hits the ground, assuming negligible air resistance? (Take gravitational field strength $g = 10$ N/kg)
3 When a roller coaster is set in motion from a high place, energy is transferred between different energy stores.
  Since energy is conserved, why could the roller coaster **not** continue its motion perpetually (continue without stopping)?

Link
Theory Workbook
Worksheet 7A

7.2 What Are Work Done and Power?

Learning Outcomes

- Recall and apply the relationship *work done = force × distance* moved in the direction of the force to new situations or to solve related problems.
- Recall and apply the relationship *power = energy transfer / time taken* to new situations or to solve related problems.
- Calculate the efficiency of an energy transfer using the formula *efficiency = useful energy output / total energy input*.

Disciplinary Idea

Matter interacts through forces and fields.

The work done by a force is the product of the force and the displacement in the direction of the force.

When work is done on a body by an external force (e.g. to move the body from position A to B), the amount of energy in the body's various energy stores changes.

Work Done by a Force

Look at Figure 7.22. Both the lady and the boy are exerting forces on objects. Is work being done in both situations?

Figure 7.22 Is work being done by the lady and the boy?

Disciplinary Idea

Conservation laws constrain the changes in systems.

Energy can be transferred to an object when work is done on it. For instance, work is done by Earth's gravitational force on a falling object to increase its kinetic energy. Work is also done by an external force to increase the kinetic energy of an object when it moves from one position to another.

In physics, work is done only when an object moves under the influence of a force. Therefore, in Figure 7.22, 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.

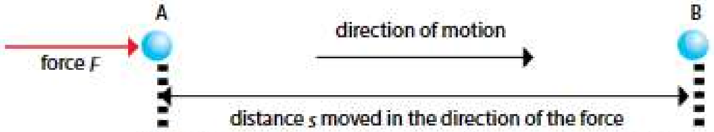


Figure 7.23 Work is done by the object when it moves from A to B.

Using Figure 7.23, 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:

$W = Fs$ where W = work done by a constant force F (J)
F = constant force (N)
s = distance moved in the direction of the force (m)

The SI unit of work is the **joule (J)**. 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.

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 7.22 is equal to the energy transferred mechanically to the kinetic store of the stroller.

Recall the example of the robot in Figure 7.21. The robot contains a battery. The work done by the battery in driving electric charges through the electric circuit of the robot is equal to the energy transferred electrically to the kinetic and internal stores of the other electric components in the robot (e.g. its motor).

Worked Example 7D

Figure 7.24 shows two students carrying a pile of books. Work is not done on the books. Explain why.

Figure 7.24

Thought Process
The students exerted an upward force on the books. Work is done only when the object moves in the direction of the force.

Answer
In both cases, the distance s moved by the students in the direction of the force F is zero.
Work done W by the upward force $F = Fs = 0$ J

Worked Example 7E

A librarian pushes a trolley of books for shelving (Figure 7.25). 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) Describe the main energy transfer process when the trolley is being pushed by the librarian.

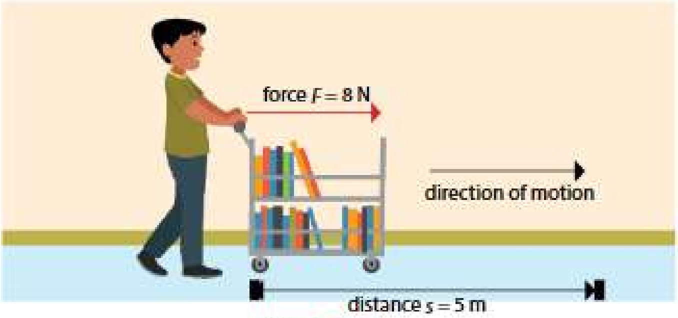


Figure 7.25

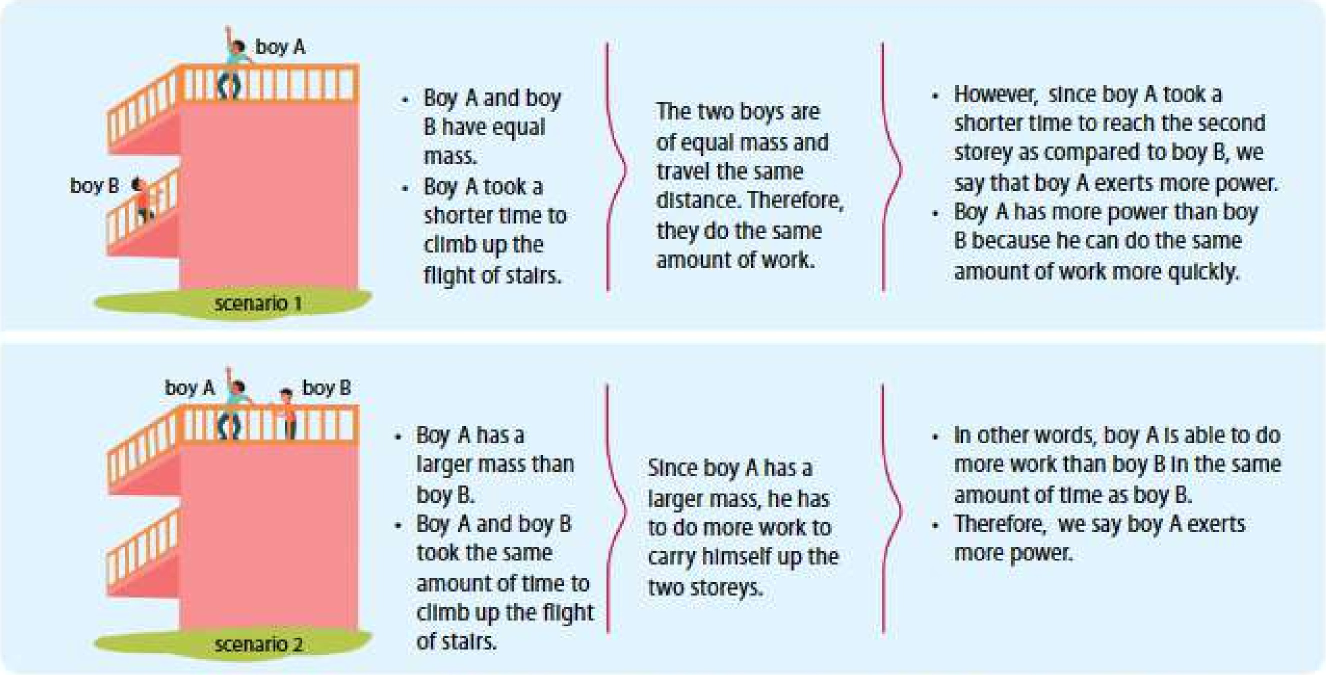
Answer

(a) Work done $W = Fs = 8\ \text{N} \times 5\ \text{m} = 40\ \text{J}$

(b) Energy is transferred mechanically when work is done by the force F in moving the trolley to the kinetic store of the trolley.

Power

To explain what power is, we consider the two scenarios of two boys climbing up the same flight of stairs in Figure 7.26.



- Boy A and boy B have equal mass.
- Boy A took a shorter time to climb up the flight of stairs.

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 second storey as compared to boy B, we say that boy A exerts more power.
- Boy A has more power than boy B because he can do the same amount of work more quickly.

- Boy A has a larger mass than boy B.
- Boy A and boy B took the same amount of time to climb up the flight of stairs.

Since boy A has a larger mass, he has to do more work to carry himself up the two 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 exerts more power.

Figure 7.26 The amount of work done 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:

▶ $P = \frac{W}{t} = \frac{E}{t}$ where P = power (W)
W = work done (J)
E = energy transferred (J)
t = time taken (s)

Note that the product of power P and time taken t (i.e. Pt) tells us the amount of work done W or the amount of energy E being transferred from one energy store to another.

For example, in a 1500 W electric kettle (Figure 7.27), the amount of energy transferred electrically from the power source to the internal stores of the heating element and water is 1500 joules per second.

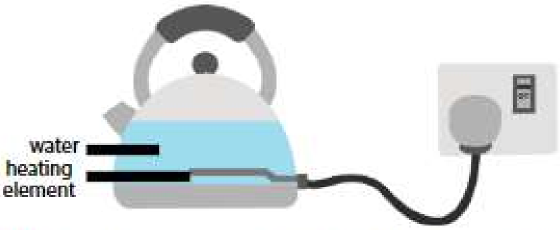


Figure 7.27 Energy is transferred electrically from the power source to the internal stores of the heating element and water.

Worked Example 7F

Eugene, who weighs 450 N, runs up ten steps. Each step is 0.20 m high. Calculate the power exerted by Eugene if he takes five seconds to run up the steps at a constant speed.

Answer

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 $W = Fs$, 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

Concept of Efficiency

In an ideal machine, the total energy output is equal to its total energy input. However, in reality, the useful energy output of a machine is always less than the energy input.

Applying the principle of conservation of energy:
Total energy input = useful energy output + non-useful energy

The efficiency of an energy transfer can be calculated using the following formula:

$$\textbf{Efficiency} = \frac{\text{useful energy output}}{\text{total energy input}} \times 100\%$$

For example, in the Senoko Power station, some of the total energy input for the production of electricity is **dissipated** during energy transfer as non-useful energy (internal store of the surroundings). The energy in the internal store of the surroundings is considered non-useful energy as the energy cannot be harnessed to power electric motors and lights. The efficiency of the power station is about 40% to 50% (Figure 7.28).

Link

Biology
In Biology, we learn that in food chains, energy in the producers is passed to primary consumers, and subsequently to secondary consumers by feeding. In the process, some energy is transferred from the living things to the surroundings through respiration. Not all the energy is transferred from the producers to the secondary consumers. Thus, the useful energy output is always less than the energy input.

Word Alert

Dissipated: scattered dispersed

Figure 7.28 The Senoko Power Station is one of the largest power stations in Singapore.

Worked Example 7G

A filament lamp connected to a battery is lit up for five minutes. 12 kJ of the energy was transferred from the battery to the lamp.

(a) Assuming 100% efficiency, what is the power of the light bulb in watts?

(b) In practice, the efficiency of a filament lamp is much lower than 100%. What happens to most of the energy input?

Answer

(a) Energy transferred $E = 12\text{ kJ} = 1.2 \times 10^4\text{ J}$
Time $t = 5 \times 60\text{ s} = 300\text{ s}$
Power P of the light bulb $= \frac{E}{t} = \frac{1.2 \times 10^4\text{ J}}{300\text{ s}} = 40\text{ W}$

(b) Based on the principle of conservation of energy, most of the energy input from the chemical potential store of the battery is transferred electrically to raise the amount of energy in the internal stores of the various components of the light bulb (non-useful energy). Some of the energy input is used to raise the temperature of the filament in the bulb to produce light (useful energy).

Disciplinary Idea

Conservation laws constrain the changes in systems.

Energy tends to dissipate and transfer to less useful stores.

Let's Investigate 7A

(Note: Do not attempt this activity if you have been advised not to do strenuous activity, to keep yourself from possible injuries.)

Aim

To estimate the power required for climbing

Procedure

1 Look for a long flight of steps that has about 100 steps or a staircase of five stories with about 20 steps in each staircase.
2 Measure the height of a few steps and determine the average height of each step.
3 Calculate the total height h of the flight of steps.
4 Use a weighing machine to measure your mass m.
5 Calculate the work you have to do to climb up the flight of steps.
6 Measure the time taken to run up the flight of steps.
7 Repeat step 6 twice to find the average time needed to run up the flight of steps. Remember to rest after each run.
8 Calculate the power needed to run up the flight of steps.

Question

Assume:

- The human body is 30% efficient in transferring energy from the chemical potential store of food to the kinetic store of the person running up the flight of steps.
- A small glass of 50 cm^3 of low fat milk has about 100 kJ of energy.

How many glasses of milk will you need to have sufficient energy in your chemical potential store to run up the flight of steps?

Let's Practise 7.2

1 (a) A mother carrying her baby in a stationary position does no work. Explain.
  (b) 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.
    (i) Calculate the work done by the force.
    (ii) Calculate the energy increase in the kinetic store of the box.
2 (a) Calculate the power involved when a force of 50 N moves an object through a distance of 10 m in 5 s.
  (b) An electric motor in a washing machine has a power output of 1.0 kW. Calculate the work done in half an hour.
3 (a) What does it mean when a solar cell has an efficiency of 45%?
  (b) A machine produces 35 J of useful output energy for every 50 J of total energy input. Calculate the efficiency of the machine.

Link

Theory Workbook
Worksheet 7B

7.3 How Can We Obtain Energy?

Learning Outcome

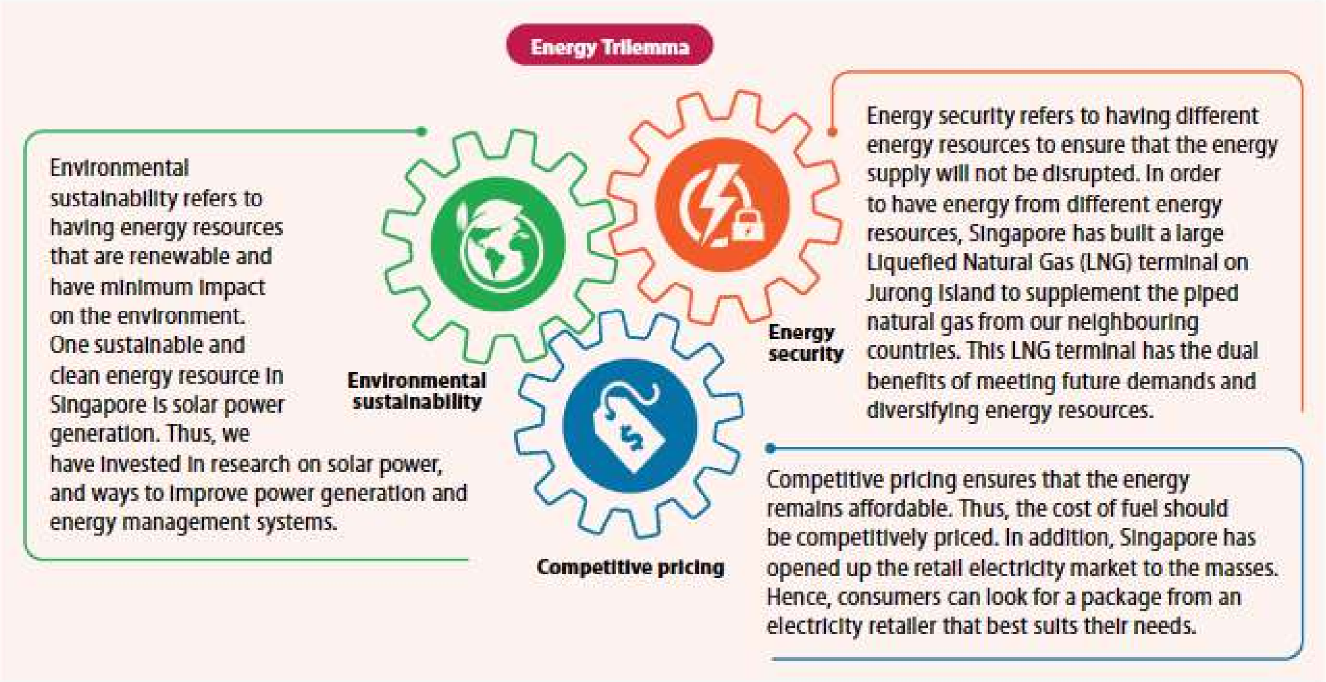
- Discuss the use of non-renewable energy resources and renewable energy resources to generate electricity in terms of efficiency of energy transfer, cost, reliability and their environmental impact.

We consume large amounts of energy every day to improve the quality of our lives. Some of these energy stores are held in chemical potential stores of petrol and diesel to power cars and buses. Some are held in the chemical potential store of gas for cooking food and heating water. Most of the energy stores are transferred electrically to run machines and light up buildings and streets at night (Figure 7.29).

Figure 7.29 Singapore looks beautiful at night. Large amounts of electrical power is needed to light up the city.

As a small country with limited natural energy resources, Singapore faces an "energy trilemma". That is, Singapore needs to strike a balance between energy security, competitive pricing and environmental sustainability (Figure 7.30).

Figure 7.30 Singapore's energy trilemma



Environmental sustainability refers to having energy resources that are renewable and have minimum impact on the environment. One sustainable and clean energy resource in Singapore is solar power generation. Thus, we have invested in research on solar power, and ways to improve power generation and energy management systems.

Energy security refers to having different energy resources to ensure that the energy supply will not be disrupted. In order to have energy from different energy resources, Singapore has built a large Liquefied Natural Gas (LNG) terminal on Jurong Island to supplement the piped natural gas from our neighbouring countries. This LNG terminal has the dual benefits of meeting future demands and diversifying energy resources.

Competitive pricing ensures that the energy remains affordable. Thus, the cost of fuel should be competitively priced. In addition, Singapore has opened up the retail electricity market to the masses. Hence, consumers can look for a package from an electricity retailer that best suits their needs.

There are different energy resources to produce electrical power (Table 7.1). These energy resources have some advantages and disadvantages.

Table 7.1 Major energy resources

Energy Resources	Advantages	Disadvantages
Fossil fuels • Examples of **fossil fuels** are petroleum, natural gas, wood and coal (Figure 7.31). • Fossil fuels have energy in the chemical potential stores. • When a fuel is burnt in air for cooking food, heating transfers energy from the chemical potential store of the fuel to the internal stores of the food and the surroundings.  Figure 7.31 Coal is mined from the ground.	• More reliable than other resources as fossil fuels do not depend on environmental factors • Relatively cheaper cost of production compared to other resources	• Non-renewable energy resource • Environmental pollution from the gases produced during burning contributes to global warming
Nuclear fuels • **Nuclear fuels** undergo nuclear reactions to release energy. Most nuclear fuels such as uranium undergo a nuclear reaction called nuclear fission (Figure 7.32). • During nuclear fission, the nuclei of uranium splits into two or more parts. Energy is transferred from the nuclear store of this nuclei to the large kinetic stores of these two or more moving parts. This in turn raises the temperature of the water surrounding the fuel rods to produce steam. • Electrical power is generated when steam moves the turbines in the nuclear power station.  Figure 7.32 Uranium fuel rods found in a nuclear reactor	• Low carbon energy resource that helps to reduce greenhouse gas emissions that cause global warming • Higher reliability in supplying uninterrupted power	• Non-renewable energy resource • Risk of accidents and pollution from the improper disposal of radioactive waste

Link

Chemistry

In Chemistry, we learn that the combustion of fuels is an exothermic reaction, where energy is transferred to the surroundings.

Besides being used as a source of energy, crude oil (a kind of fossil fuel) is a mixture and can be separated into fractions (parts). The fractions have different uses.

Link

You will learn more about nuclear processes and the release of energy from nuclear fuels in Chapter 22.

Energy Resources	Advantages	Disadvantages
Biofuels • Examples of **biofuels** are ethanol, biodiesel and biogas, which are derived from biomass. Biomass comes from living materials such as corn and animal manure (Figure 7.33). • Biofuels have energy in the chemical potential stores. • When cooking, heating transfers energy from the chemical potential store of the biofuel to the internal stores of the food and the surroundings.  Figure 7.33 Biofuel plant processes animal manure to form biogas.	• Renewable energy resource • Widely available on a large scale • Relatively cheaper cost of production compared to other resources	• Environmental pollution from the gases produced during burning contributes to global warming
Wind • The energy in the kinetic store of the wind is transferred mechanically to the kinetic store of the rotor blades of the wind turbines (Figure 7.34). • Electrical power is generated when the rotor blades connected to the generators rotate.  Figure 7.34 Wind turbines can be found in open fields, on mountains and in water.	• Renewable energy resource • Clean method of producing electricity (i.e. no harmful gases are produced)	• **Intermittent** power as it is not easy to find places where there is a steady wind blowing at a speed of 20–25 km/h • Noise pollution and loss of habitat for wildlife as land is cleared to build wind turbines
Tides • Water movement from changing high and low tides causes the turbines below the water surface to rotate (Figure 7.35). • The energy in the kinetic store of the water is transferred mechanically to the kinetic store of the turbines. • Electrical power is generated when the turbines connected to the generators rotate.  Figure 7.35 Tidal turbines are placed below the water surface where there is a strong tidal flow.	• Renewable energy resource • More reliable than wind or the sun • Clean method of producing electricity	• High cost of building tidal barrages, turbines and generators • Marine life affected due to alterations of water currents, noise and emission of electromagnetic fields

Word Alert

Intermittent: not happening continuously

Energy Resources	Advantages	Disadvantages
Hydropower • **Hydropower** can be obtained from water behind hydroelectric dams (Figure 7.36). • Water behind hydroelectric dams has energy in the gravitational potential store. By releasing the water and letting it flow downwards, energy in the gravitational potential store is transferred mechanically to the kinetic store of the water. • The flowing water causes the turbines to spin. Electrical power is generated when the turbines connected to the generators rotate.  Figure 7.36 Hydropower is one of the most widely used renewable sources of energy.	• Renewable energy resource as the water movement can be continually regenerated • Clean method of producing electricity	• High cost of building dams, turbines and generators • Possible damage to the environment surrounding the river caused by damming of river for hydroelectric power station
Geothermal reservoirs • In certain areas, such as volcanic regions, geological forces push large amounts of hot molten rocks near Earth's surface. These places are known as geothermal hotspots (Figure 7.37). • Water that makes its way to these geothermal hotspots is heated and subjected to great pressure. • This heated water has a large amount of energy in the internal store. The water is forced to the surface as boiling water and steam to drive turbines.  Figure 7.37 Geothermal power stations are found near geothermal hotspots such as volcanoes.	• Renewable energy resource • Clean source of naturally available energy in the internal stores	• Environmental pollution caused by the release of poisonous gases such as hydrogen sulfide into the atmosphere • Not widely available as they are found only in certain areas around the world
Solar power • **Solar power** comes from the sun. The sun has energy in the nuclear store. • The energy in the nuclear store of the sun is transferred by electromagnetic waves from the sun to the internal stores of the solar panels. • Solar panels comprise many individual solar cells (Figure 7.38). Each cell is made of semiconductors such as silicon. When the solar panels are irradiated by sunlight, electricity is generated.  Figure 7.38 Solar panels are installed on the rooftops of some buildings in Singapore.	• Renewable energy resource • Clean method of producing electricity	• Not always available as there is no sunlight at night, and it is weather-dependent • Solar panels or collectors take up a lot of space

The efficiency of energy transfer for electricity generation in fossil fuel power plants is about 32% (in coal plants) to 45% (in natural gas plants). The average efficiency of energy transfer for electricity generation in nuclear power plants is about 33%, which is comparable to that of the coal power plants.

The efficiency of energy transfer for electricity generation using hydropower and tides is higher than that of fossil fuels power plants. The efficiency of energy transfer for electricity generation using biofuels, wind, geothermal reservoirs and solar power is lower than that of fossil fuels power plants.

It is important to note that the efficiency of energy transfer for electricity generation depends on the technologies employed. Improvements in technologies can improve the efficiency of energy transfer for generating electricity. In addition, the efficiency of energy transfer for electricity generation is dependent on different factors such as the types of fuels, location and weather. Thus, the efficiency of energy transfer differs across different power plants and locations even though the plants and locations may use the same type of energy resource for electricity generation.

Let's Practise 7.3

1 Give an example of:
  (a) a renewable energy resource and a non-renewable energy resource; and
  (b) a major energy resource that transfers energy from a chemical potential store to an internal store.
2 Nuclear power stations use the process of nuclear fission to generate electricity. State **one** advantage and **one** disadvantage of using nuclear power.

Link

Theory Workbook
Worksheet 7C
Let's Assess
Let's Reflect

Tech Connect

To complement nuclear fission reactors, research to develop a nuclear fusion reactor has been ongoing. One promising multi-nation project is the International Thermonuclear Experimental Reactor (ITER) in Southern France to be launched in 2025 (Figure 7.39).

In the reactor, energy is transferred to the internal store of the reactant during the fusion of atoms. Unlike nuclear fuels, fusion reactions do not produce long-lived radioactive waste.

What are the challenges faced in the design and development of this nuclear fusion reactor? Why is there a need to develop a nuclear fusion reactor?

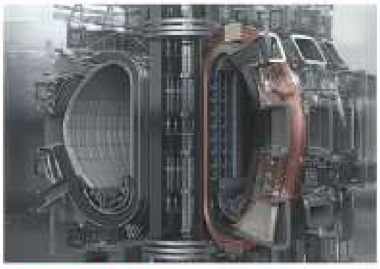


Figure 7.39 The ITER is an experimental machine to harness the energy of nuclear fusion.

Cool Career

Solar Engineer

Have you considered a cool career that taps on the hot and sunny climate in Singapore?

Solar engineers apply science and technology to harness energy from the sun. They may be involved in the design, development or maintenance of the solar power systems (Figure 7.40).

Figure 7.40 Solar engineers need to consider the newest technologies when designing and developing solar power systems.

Let's Map It

Energy E (SI unit: J)

are related to

Power P (SI unit: W)

Work W (SI unit: J)

is governed by

The Principle of Conservation of Energy

states that

- Energy cannot be created or destroyed.
- It can be transferred from one energy store to another.
- The total energy of an isolated system remains constant.

is defined as

$P = \frac{W}{t} = \frac{E}{t}$

where

W = work done

E = energy transferred

t = time taken

is defined as

$W = Fs$

where

F = force

s = distance moved in the direction of the force

Efficiency

- Where some of the energy input is transferred to the internal store of the surroundings as non-useful energy
- Can be calculated using the following formula:

$$\text{Efficiency} = \frac{\text{useful energy output}}{\text{total energy input}} \times 100\%$$

types of energy stores

- Kinetic store
- Gravitational potential store
- Elastic potential store
- Chemical potential store
- Internal store
- Nuclear store

To find the amount of energy in the kinetic and gravitational stores:

- Kinetic energy
  $E_k = \frac{1}{2}mv^2$
- Gravitational potential energy
  $E_p = mgh$

energy transfers depend on the

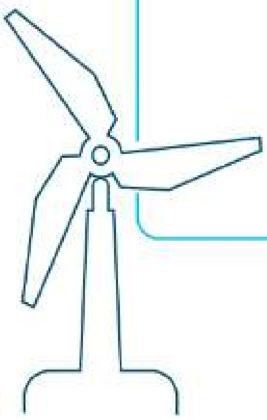
can be obtained or produced from energy resources

Non-renewable energy resources

- Fossil fuels
- Nuclear fuels

Renewable energy resources

- Biofuels
- Wind
- Tides
- Hydropower
- Geothermal reservoirs
- Solar power



energy can be transferred from one store to another in four different pathways

Pathways of energy transfers

1. Energy transferred mechanically by a force acting over a distance
2. Energy transferred electrically by an electric current
3. Energy transferred by heating due to a temperature difference
4. Energy transferred by propagation of waves (both electromagnetic and mechanical sound waves)

Let's Review

Section A: Multiple-choice Questions

1 The following shows the main energy stores associated with different objects. Which row in the table is **incorrect**?

	Object	Energy Store
○ A	compressed spring	elastic potential
○ B	object in motion	kinetic
○ C	object above ground	gravitational potential
○ D	sun	internal

2 A car comes to a stop to avoid colliding with a van. Assuming that the road is level, which of the following shows the transfer of energy between the energy stores?

○ **A** Kinetic store of the car ⟶ internal stores of the tyres and surroundings

○ **B** Kinetic store of the car ⟶ chemical potential store of the car

○ **C** Kinetic store of the car ⟶ internal stores of the tyres

○ **D** Kinetic store of the car ⟶ elastic potential store and internal store of the tyres

3 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

4 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

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

6 Which of the following energy resources is the odd one out?

○ **A** Biofuels

○ **B** Hydropower

○ **C** Nuclear fuels

○ **D** Wind

Section B: Structured Questions

1 A cyclist pedals up to the top of a hill.

(a) State the energy store(s) associated with the cyclist when he stops at the top of the hill.

(b) State the energy store(s) associated with the cyclist when he reaches the bottom of a hill without pedalling.

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 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 7.41).

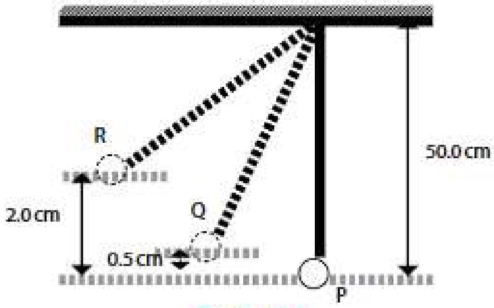


Figure 7.41

The pendulum bob is displaced to point R, 2.0 cm above P and released from rest. Assuming that air resistance is negligible, calculate the:

(a) amount of energy in the gravitational potential store of the pendulum bob at point R; and

(b) amount of energy in the kinetic store of the bob at point Q, 0.5 cm above P.

4 (a) Define the *joule*.
  (b) A model car of mass 1.5 kg, with a string attached to its front end, is placed on a slope (Figure 7.42). 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.

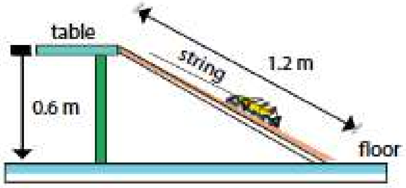


Figure 7.42

Calculate:
  (i) the energy increase in the car's gravitational potential store as it moves from the floor to the table; and
  (ii) the work done by the force as it moves the car up the slope from the floor to the table;

5 (a) Define the *watt*.
  (b) The same volume 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.

Section C: Free-response Questions

1 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) State the principle of conservation of energy.
  (b) Calculate the decrease in energy in the gravitational potential store of the train when it moves from point P to point Q.
  (c) If 20% of the energy in the gravitational potential store is dissipated to the surroundings, calculate the
    (i) energy in the kinetic store of the train at point Q; and
    (ii) speed of the train at point Q.

2 The energy input and useful energy output (i.e. electricity) for five power stations were measured. The results are listed in Table 7.2.

Table 7.2

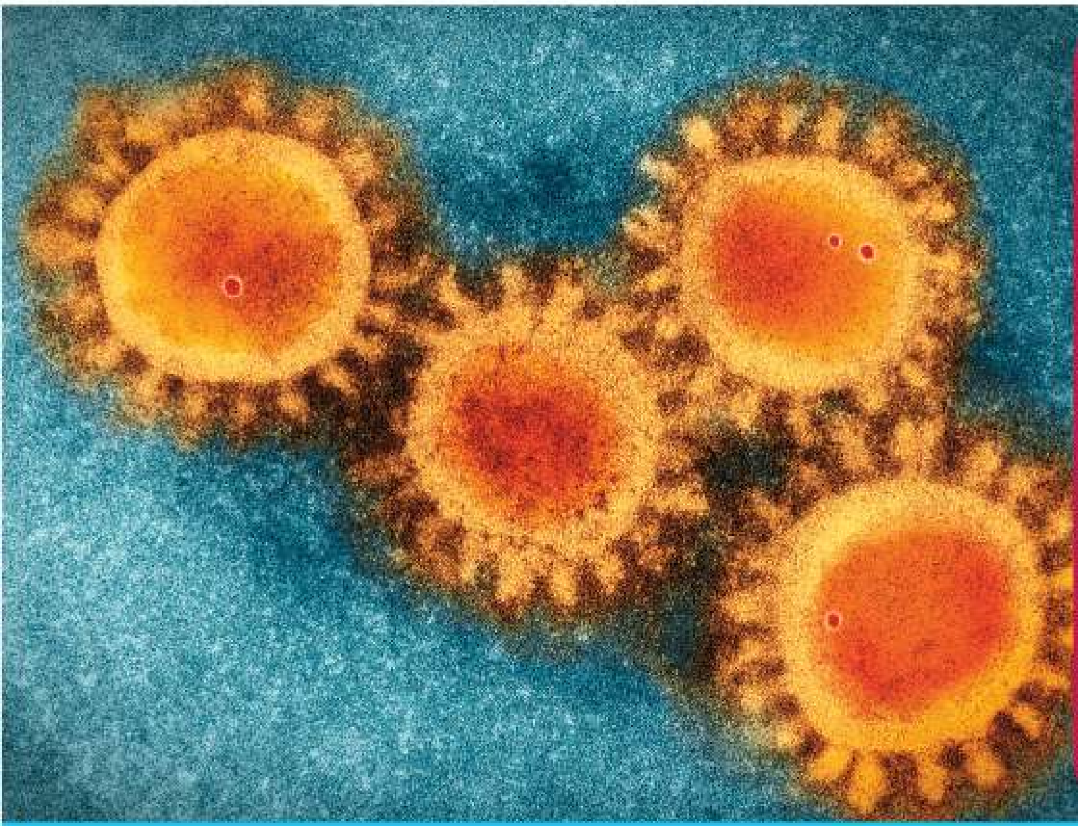
Power Station	Energy Input / 10^{14} J	Useful Energy Output / 10^{13} J
P	10.8	32.8
Q	17.1	21.3
R	2.5	10.1
S	2.1	7.5
T	2.0	4.1

  (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 7.2 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?

Link
Theory Workbook
Revision Worksheet 2

CHAPTER

08 Kinetic Particle Model of Matter



What You Will Learn

- How does the kinetic particle model relate to the states of matter?
- How does the kinetic particle model relate to temperature and pressure?

The image above shows the structure of the SARS-CoV-2 virus produced by a transmission electron microscope. Such microscopic images help scientists understand how the virus infects living cells and cause the Coronavirus Disease 2019 (COVID-19). As mutated variants of the virus emerged, researchers were again able to use the images of the new strains to understand why they were more infectious.

Microscopy technology can also produce images of atoms in a solid. How are the different atomic arrangements and motions at the microscopic (visible under a microscope) level linked to the different macroscopic properties (observable properties) of matter?

8.1 How Does the Kinetic Particle Model Relate to the States of Matter?

Learning Outcomes

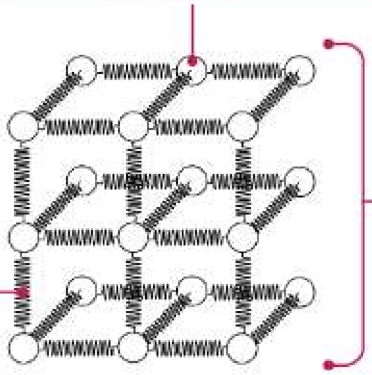
- Compare the physical properties of solids, liquids and gases.
- Use the kinetic particle model to describe the different states of matter, relating their physical properties to the arrangement and motion of the particles and the forces and distances between particles.
- Infer from a Brownian motion experiment the evidence for the random movement of molecules in a liquid or gas.

Kinetic Particle Model

We know that water can be frozen into ice and can be heated to become water vapour or steam. How does the transfer of energy by heating to a substance change its state? What happens to the atoms when a substance changes its state? We shall find the answers to these questions using the kinetic particle **model**.

▶ The **kinetic particle model of matter** is made up of tiny particles that are in continuous motion.

Figure 8.1 shows a visual representation of the kinetic particle model of a solid that shows the particles (atoms), the forces between particles and the energy of particles in a solid.



① **Particles**
Each sphere represents a particle. The particles have positive and negative electric charges that may not be uniformly distributed. This allows them to exert forces on one another.

② **Forces**
The forces between the particles are represented by springs.

Due to the spring, there are attractive forces pulling the particles together. We will learn how this behaviour is crucial in allowing a change of state.

③ **Energy of particles in a solid**
As energy is transferred to them, the particles vibrate more vigorously. The sum of the kinetic and potential energy stores of the model is called the internal energy (internal store).

Figure 8.1 Visual representation of the kinetic particle model of a solid

Word Alert

Model: a representation of a system or process that helps us understand the system or process; usually an incomplete representation of reality

Disciplinary Idea

Matter interacts through forces and fields.

Particles in matter can exert attractive electrostatic forces on one another.

Link

You will learn about the electrostatic forces between charged particles in Chapter 15.

Helpful Note

The volume of a solid or liquid is fixed when the temperature is kept constant.

When someone shakes the structure in Figure 8.1, energy is transferred to the kinetic store of the structure. The shaking would cause all the particles to vibrate. In the process, some particles will get closer or further than their equilibrium separation.

This spring becomes compressed or extended which increases the energy in the elastic potential store. Therefore, when energy is transferred to the structure, the energy in the kinetic and elastic potential stores increases.

When energy is transferred to a real substance, its particles will also vibrate more. As the vibrations increase, the particles push each other further apart and the matter expands.

Recall that the attractive forces get weaker with increased separation. If energy is continuously transferred to the matter, more and more particles will break away from their positions to roam freely. The transition from the orderly arrangement of particles to freely roaming particles corresponds to a change from the solid state to the liquid state (Figure 8.2).

Link

You will learn that in matter, the total potential and kinetic energy of the particles is called *internal energy* in Chapter 10.


particles in the solid state
particles in the liquid state

Figure 8.2 How the arrangement of particles changes when a substance changes from a solid state to a liquid state

Worked Example 8A

In the kinetic particle model, when matter is in a solid state, two neighbouring particles exert either attractive or repulsive forces on each other.

(a) What kind of force do the two particles exert on each other when they move further apart from their equilibrium separation?

(b) Based on your answer in (a), explain why the particles are able to totally break free from each other.

Answer

(a) Attractive force

(b) The magnitude of the force decreases as the particles separate. It becomes easier to separate when the particles are further apart.

Disciplinary Idea

Microscopic models can explain macroscopic phenomenon.

Macroscopic properties like shape, volume and compressibility of solids, liquids and gases are related to the particles' motion, spacing and the forces between the particles.

Disciplinary Idea

Forces help us understand motion.

The forces and distances between particles vary for the same substance in the three states of matter.

- Solid — strong attractive force, particles are close together and vibrate in position but do not move around freely
- Liquid — significant attractive force, particles are close together but move around freely
- Gas — weak attractive force, particles are far apart and move around freely

Disciplinary Idea

Conservation laws constrain the changes in systems.

Mass is conserved in a closed system. For instance, when a gas in a closed syringe is compressed, its volume decreases but its mass remains the same.

Word Alert

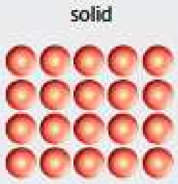
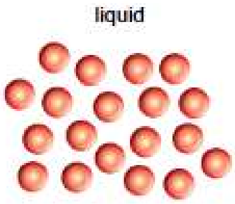
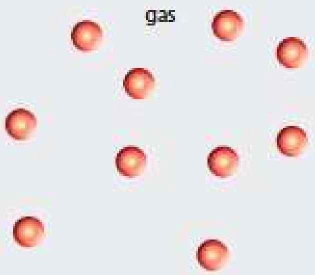
Hypothesis: proposed explanation that has not been proven

Theory: an explanation based on scientific facts and principles; can be used to make predictions about natural phenomenon

Kinetic Particle Model and the Properties of Solids, Liquids and Gases

The kinetic particle model is used to explain the different properties of each state of matter (Table 8.1).

Table 8.1 Physical properties of each state of matter explained using the kinetic particle model

State of Matter	At the Particle Level	Observable Properties
	**Arrangement** Particles are closely packed and arranged in a regular pattern. The particles in solids have the least energy among the three states of matter.	Solids have the highest densities.
	Motion Particles vibrate about fixed positions. They are held in position by strong attractive forces between the particles.	Solids have a fixed volume and a fixed shape.
	**Arrangement** Particles are slightly less closely packed than in solids and arranged in an irregular pattern.	Liquids have a slightly lower density than solids.
	Motion The particles slide over each other throughout the liquid without fixed positions. The forces holding the particles together are weaker than in a solid.	Liquids have a fixed volume and no fixed shape.
	**Arrangement** Particles are very far apart from one another in an irregular pattern. The particles in gases have the most energy among the three states of matter.	Gases have the lowest densities.
	Motion The particles can move freely in any direction. The attractive forces between the particles are weak.	Gases have no fixed volume (compressible) and no fixed shape. A gas takes up the volume and shape of its container.

Evidence for Movement of Particles

Since the 5th century BCE, the Greeks hypothesised that matter is made up of tiny particles called *"atomos"*. About 2000 years later, John Dalton, an English scientist, discovered physically measurable data to support the **hypothesis**.

In 1827, Robert Brown, a Scottish scientist, observed with a microscope that pollen grains in water were moving constantly and randomly in all directions. This random motion of particles in a fluid is called **Brownian motion**. It is named after Robert Brown. The development of the particle theory shows that improvements in technology can help to gather evidence to support the **theory**.

Let's Investigate 8A

Aim

To investigate Brownian motion

Procedure

1 Place a droplet of water containing microbeads between two glass slides.
2 Place the glass slides under a high-power microscope (Figure 8.3).
3 Turn on the light source of the microscope to illuminate and allow the microbeads to be seen.
4 Repeat steps 1 to 3 with a droplet of water containing bigger microbeads.

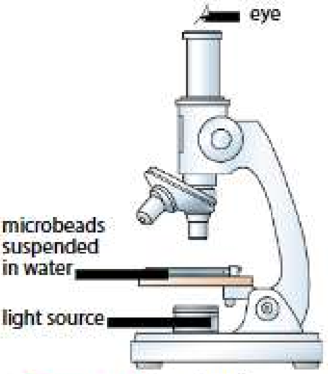


Figure 8.3 Set-up to observe Brownian motion

Observations

1 The microbeads were seen to be moving in a random way (Figure 8.4).
2 Larger microbeads moved slower and less randomly than smaller microbeads.

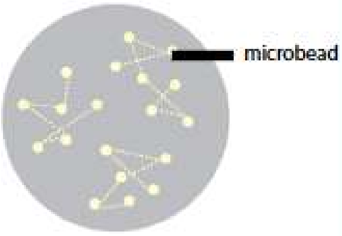


Figure 8.4 Random motion of microbeads (represented by the dotted lines)

Discussion

The microbeads moved randomly as they were hit by the water molecules that were constantly and randomly moving. This is similar to the movement of pollen grains due to the water molecules that Robert Brown observed through a microscope in 1827.

Questions

1 Explain if the random motion of the microbeads is due to the flow of water.
2 Why is there a difference in motion between small and large microbeads?

Link

Biology

In Biology, we learn that particles move from a region of higher concentration to a region of lower concentration. This process is called diffusion. For example, oxygen particles move from the red blood cells (higher concentration of oxygen) to the other body cells (lower concentration of oxygen).

Let's Practise 8.1

1 Describe and compare the average separation and motion of the particles in the (a) solid state; (b) liquid state; and (c) gaseous state.

Link

Theory Workbook
Worksheet 8A

Past to Present

A light microscope can differentiate two points that are at least 200 nm apart. Hence, it cannot reveal the surface features and shape of a virus, such as the SARS-CoV-2 virus that is about 100 nm in diameter.

Today, many advanced microscopy solutions, such as the transmission electron microscopy, have been developed. They reveal the structures and mechanics of objects at the microscopic level (Figure 8.5).

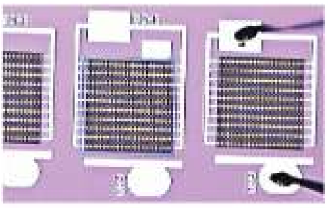


Figure 8.5 Image of micro-structures on a semiconductor generated by a high power microscope

8.2 How Does the Kinetic Particle Model Relate to Temperature and Pressure?

Learning Outcomes

- Relate the rise in temperature of a body to the increase in average kinetic energy of all the particles in the body.
- Explain the pressure of a gas in terms of the motion of its particles.

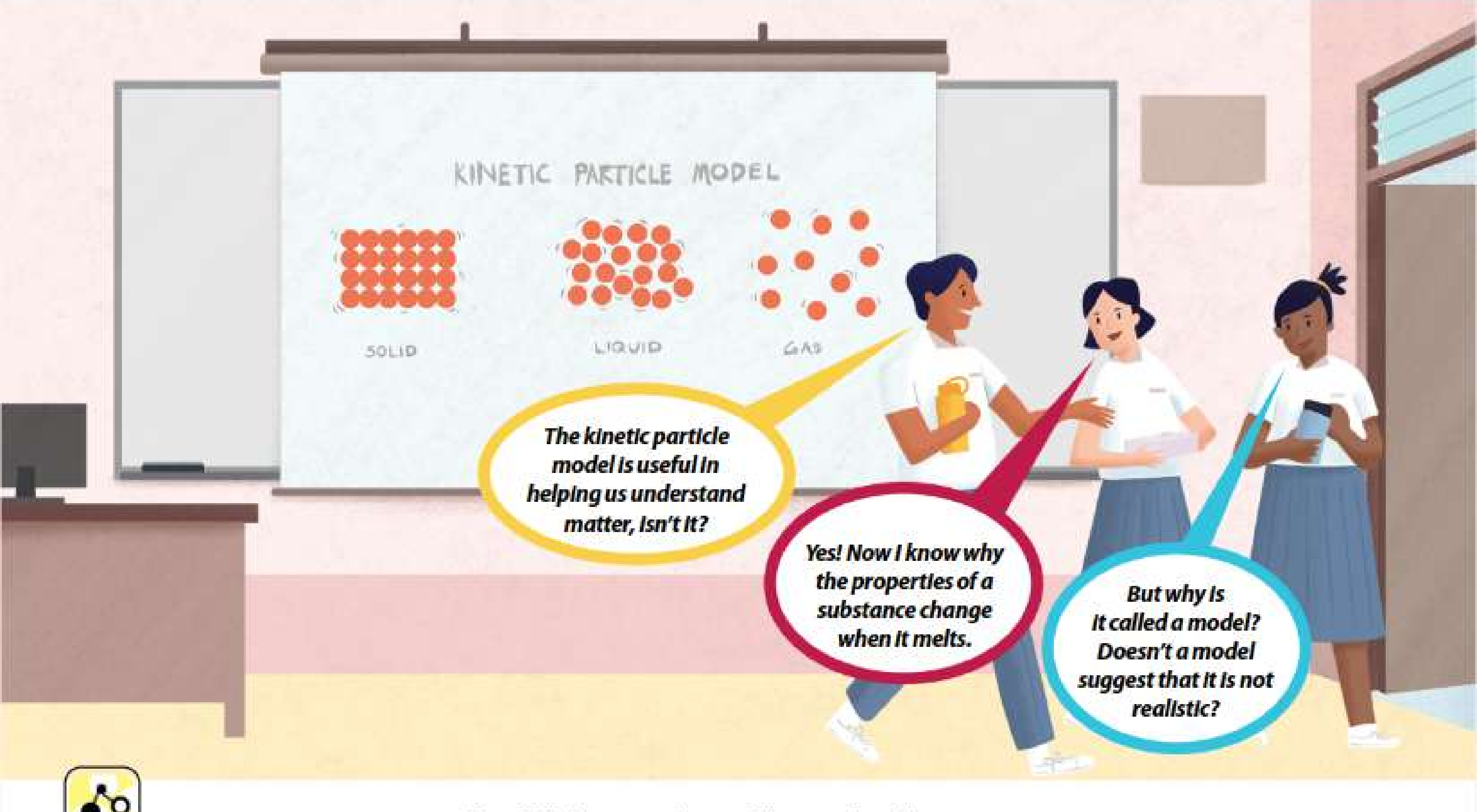


Figure 8.6 A model helps us to understand the natural world.

Link

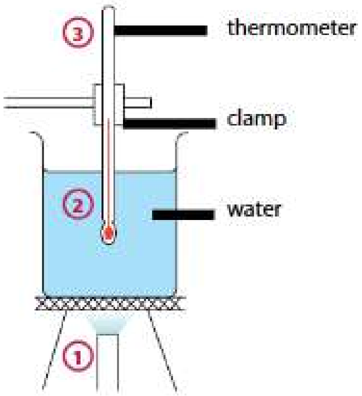
Chemistry
In Chemistry, we learn about the kinetic particle theory. It states that all matter is made up of tiny particles that are in constant and random motion. The kinetic particle model is a representation of the kinetic theory of matter.

Indeed, a model is only a representation of an idea, process or theory that is useful for our understanding. A model may not be able to accurately portray all of the ideas, processes or theories fully (Figure 8.6). On the other hand, a theory is an explanation based on sound principles and evidence.

The simple kinetic particle model that we have learnt cannot explain the plasma state of matter and other phenomena like magnetism and light emission. However, it is still helpful in understanding macroscopic properties (measurable properties) in matter such as temperature and pressure.

Temperature

To understand any quantity such as temperature, we should know how it is measured. For instance, it is important to know how a liquid-in-glass thermometer measures the temperature of a substance such as hot water (Figure 8.7).



① When a substance such as water is heated, the energy in the kinetic store of the particles increases and the particles vibrate or move faster.

② Hence, when the thermometer is in contact with the water, the more energetic particles in the water transfer some of the energy to the less energetic particles in the thermometer through collisions.

③ With more energy, the particles tend to push each other further apart so the matter expands. However, liquids expand more easily than solids. The liquid column in the thermometer expands noticeably along the calibrated scale but the length of the thermometer's glass body hardly changes.

Figure 8.7 How a thermometer measures the temperature of a substance

The temperature reading of a substance is thus an indication of the kinetic energy of the particles of the substance.

▶ **Temperature** rises with the average kinetic energy of the particles in a body and vice versa.

The term "average" implies that the concept of temperature is applicable only to a collection of particles, never to a single particle.

Pressure

In Chapter 6, we learnt that pressure is the average force per unit area. For a thick book resting on a table top, the pressure due to the book is equal to its weight divided by the area of contact with the table. At the particle level, this pressure is the average force per unit area exerted by the particles of the book when they collide with the table surface.

Link

Recall from Chapter 6: Pressure increases with depth in a liquid such that the pressure difference p is $P = \rho hg$, where ρ is the density, h is the height difference and g is the gravitational field.

Similarly, the particles in a gas exert pressure on the inner walls of its container (Figure 8.8).

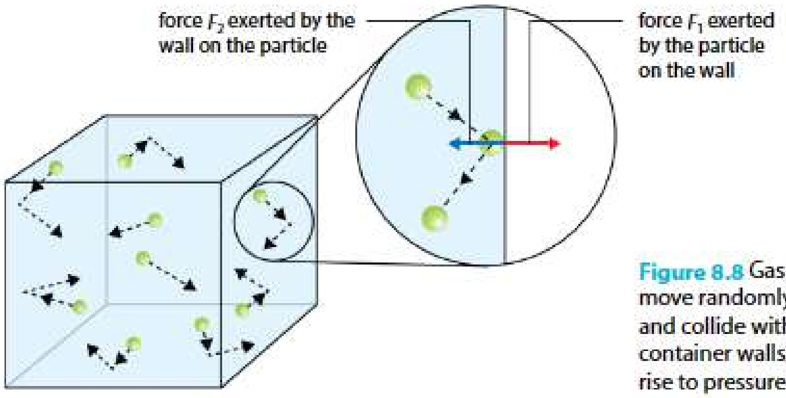


Figure 8.8 Gas particles move randomly and collide with the container walls, giving rise to pressure.

Helpful Note

By Newton's Third Law, $F_1 = F_2$. It is not practical to measure the pressure due to a single collision between a particle and a surface. Hence, pressure is the average force from multiple collisions over a large area.

When a gas particle collides with the inner wall of the container, it exerts a force F_1 on the wall. The reaction force F_2 causes the particle to bounce back from the wall.

When there are many gas particles colliding with the inner wall of the container, the forces add up. The total force exerted by the gas per unit area is the pressure.

▶ At the particle level, pressure is the average force exerted by the particles per unit area.

Gas pressure in the container is very nearly the same throughout the container. On the other hand, pressure due to a liquid increases much faster with depth due to the much higher density of liquids than gases.

Disciplinary Idea

Microscopic models can explain macroscopic phenomenon.

The pressure of a gas is due to the collisions of the gas particles with the walls of the container. The average force exerted by the gas particles per unit area is the gas pressure.

Worked Example 8B

(a) How does an increase in temperature affect the kinetic store of the particles in matter?

(b) Containers A and B have the same number and type of particles at the same temperature. The volume of container B is larger than container A. Explain whether the two containers have the same gas pressure.

Answer

(a) When temperature increases, the average kinetic energy of the particles in the body increases.

(b) No, the gas pressure in B is lower than in A. Since container B has a larger volume, the number of particles per unit volume decreases. Therefore, the gas particles collide less frequently with the inner wall of the container. This leads to a smaller average force exerted per unit area.

Link

Theory Workbook
Worksheet 8B
Let's Assess
Let's Reflect

Let's Practise 8.2

1 A gas is kept in a container.
  (a) Explain what happens to the gas pressure in the container when the temperature of the container is increased.
  (b) Explain what happens to the gas pressure in the container after some gas is released from the container.

Cool Career

Nanotechnologist

A nanotechnologist needs to understand the structures of matter at the particle level (Figure 8.9). Nanotechnology is an interdisciplinary field involving different sciences, engineering and technology. Hence, nanotechnologists often work with others of different specialisations.

Nanotechnologists apply the knowledge of the structures of matter in different areas such as in food safety, development of new materials and medicine. One example is the development of higher capacity batteries that can be charged faster and yet safer to be used in electric cars.

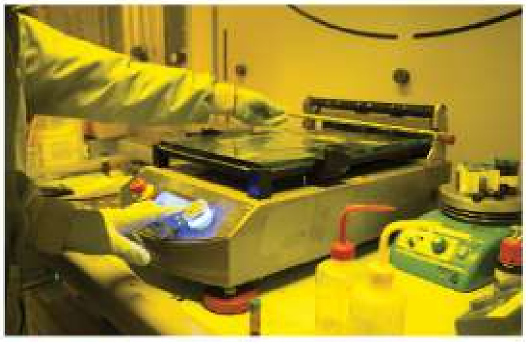
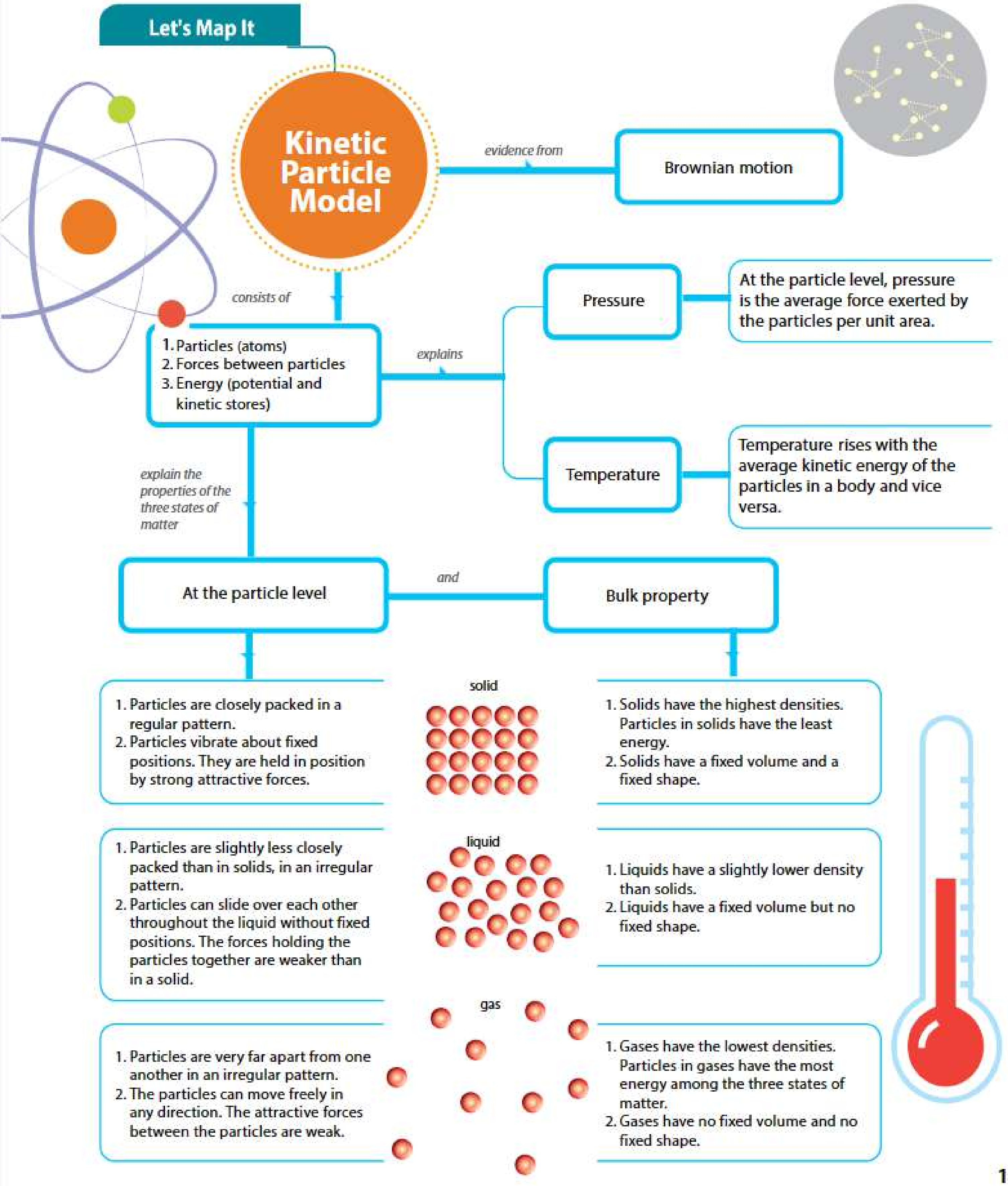


Figure 8.9 Nanotechnologists research on the structures of matter in laboratories that specialise in research on nanotechnology.

Let's Map It



Kinetic Particle Model

evidence from

Brownian motion

consists of

1. Particles (atoms)
2. Forces between particles
3. Energy (potential and kinetic stores)

explains

Pressure

At the particle level, pressure is the average force exerted by the particles per unit area.

Temperature

Temperature rises with the average kinetic energy of the particles in a body and vice versa.

explain the properties of the three states of matter

At the particle level

and

Bulk property

solid

1. Particles are closely packed in a regular pattern.
2. Particles vibrate about fixed positions. They are held in position by strong attractive forces.

1. Solids have the highest densities. Particles in solids have the least energy.
2. Solids have a fixed volume and a fixed shape.

liquid

1. Particles are slightly less closely packed than in solids, in an irregular pattern.
2. Particles can slide over each other throughout the liquid without fixed positions. The forces holding the particles together are weaker than in a solid.

1. Liquids have a slightly lower density than solids.
2. Liquids have a fixed volume but no fixed shape.

gas

1. Particles are very far apart from one another in an irregular pattern.
2. The particles can move freely in any direction. The attractive forces between the particles are weak.

1. Gases have the lowest densities. Particles in gases have the most energy among the three states of matter.
2. Gases have no fixed volume and no fixed shape.

Let's Review

Section A: Multiple-choice Questions

1 Which is a correct description of the motion of particles in a liquid and a gas?

	Liquid	Gas
○ A	randomly vibrate about fixed positions	move freely in any direction
○ B	move in random directions	energetically vibrate in random directions
○ C	randomly vibrate about fixed positions	energetically vibrate in random directions
○ D	move in random directions	move freely in any direction

2 Which of the following describes a substance in the liquid state?

○ A The substance has a fixed volume and the particles vibrate very fast.

○ B The substance does not have a fixed volume and the particles move very fast.

○ C The substance has a fixed volume and the particles move around freely and randomly.

○ D The substance has a fixed volume and the particles in it are arranged in a regular manner.

3 Which statement about Brownian motion of smoke particles in air is correct?

○ A Brownian motion describes the random motion of the air particles.

○ B Brownian motion of smoke particles is due to random collisions by air particles.

○ C Brownian motion can be more easily observed when the smoke particles are bigger.

○ D With better understanding of Brownian motion, we can predict the exact path of the smoke particles.

4 Which of the following correctly describes the average attractive force and the average separation of particles of a solid compared to a liquid?

	Average attractive force	**Average separation**
○ A	stronger	smaller
○ B	stronger	larger
○ C	weaker	smaller
○ D	weaker	larger

5 Which of the following will definitely cause the pressure in a container of gas to increase?

○ A cooling the gas and pumping in more gas

○ B cooling the gas and increasing the volume of the container

○ C increasing the gas temperature and letting out some gas

○ D increasing the gas temperature and compressing the gas

Section B: Structured Questions

1 A container with a moveable piston is filled with some gas (Figure 8.10).

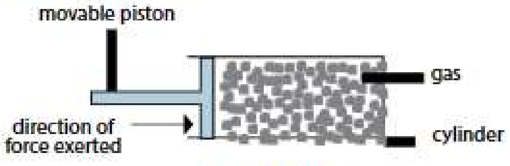


Figure 8.10

(a) Explain why the pressure in the container increases when the piston is pushed in.

(b) Explain why a gas can be compressed but not a liquid.

(c) Explain why the number of collisions per unit area inside the container decreases when the container is put inside a freezer.

2 Solid, liquid and gas have different properties. Using the kinetic particle model, explain:

(a) why a solid cannot be compressed;

(b) why a liquid does not have a fixed shape; and

(c) why a gas is able to fill up a container of any shape and size.

Section C: Free-response Question

1 Some smoke particles are trapped inside a small glass cell and observed to be moving randomly under a microscope.

(a) Draw the path of a smoke particle observed under the microscope.

(b) Draw the path of a much bigger smoke particle.

(c) Compare and describe the difference in the paths of the smoke particles in (a) and (b).

CHAPTER

09 Thermal Processes

What You Will Learn

- What is thermal equilibrium?
- How is energy transferred by heating?
- What are some applications of thermal processes?

How often do you find yourself in an air-conditioned space? In the warm, tropical climate of Singapore, air conditioning has become an important part of our lives. However, the energy usage for cooling has seen a sharp increase not only in Singapore, but all over the world.

Air conditioning makes use of greenhouse gases called refrigerants. When these refrigerants leak into the atmosphere, the amount of greenhouse gases that cause global warming increases. As Earth heats up, the demand for air conditioning will increase. This will create a vicious cycle that will only worsen the problem of global warming.

Can you think of some ways to cool our spaces more efficiently and lower energy demand of our nation and the world?

9.1 What Is Thermal Equilibrium?

Learning Outcome

- Show an understanding that energy is transferred (by heating) from a region of higher temperature to a region of lower temperature until thermal equilibrium is achieved between the two regions.

Figure 9.1 Changes in temperature of different drinks.

Hot drinks cool down and cold drinks warm up after some time when left at room temperature (Figure 9.1). Have you ever wondered why? Why do some drinks not change in temperature?

All matter contains *energy in the internal store* (internal energy). The energy in the internal store of a substance is equal to the sum of all the potential energy due to the intermolecular forces and all the kinetic energy due to the motion of the particles.

Energy is transferred from a region of higher temperature (hotter object) to a region of lower temperature (cooler object) until both regions have the same temperature. The two regions are said to be in a state of thermal **equilibrium**.

► **Thermal equilibrium** describes a state in which two or more objects have the same temperature and that there is no net transfer of energy between them.

Helpful Note

Temperature is a macroscopic quantity (i.e. it is an average for a large number of particles).

Link

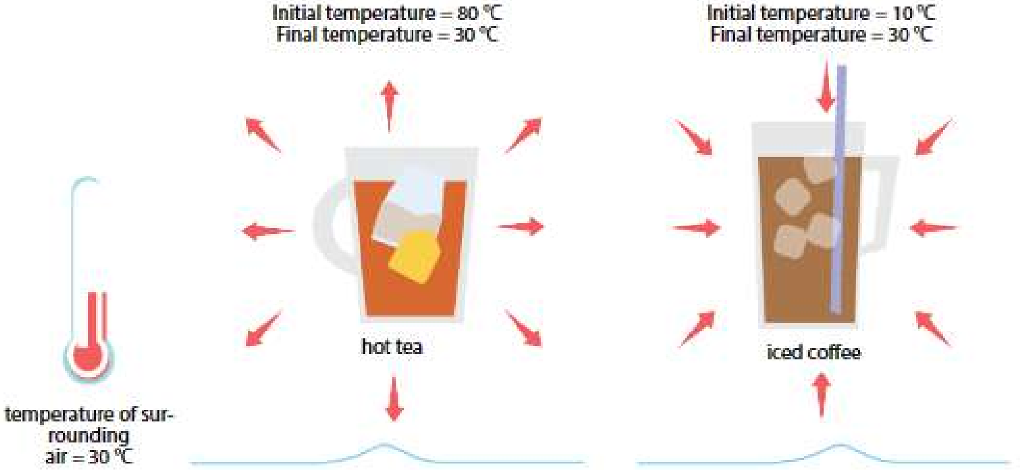
Biology

In Biology, we learn that our body maintains thermal equilibrium at a constant temperature of approximately 37 °C. This is achieved through a process called homeostasis, where conditions within the body are kept constant.

Word Alert

Equilibrium: balance

The energy transfer by heating occurs only when there is a difference in temperature (Figure 9.2).



The hot tea was at a higher temperature than the surrounding air. Hence, energy was transferred from the hot tea to the surrounding air.

As the energy in the internal store of the tea decreased, its temperature decreased until it was the same as the surrounding temperature.

The iced coffee was at a lower temperature than the surrounding air. Hence, energy was transferred from the surrounding air to the iced coffee.

As the energy in the internal store of the coffee increased, the ice started to melt. After the ice had melted completely, the temperature of the iced coffee continued to increase until it was the same as the surrounding temperature.

Figure 9.2 Temperature difference causes energy transfer.

Disciplinary Idea

Conservation laws constrain the changes in systems.

When two objects of different temperatures interact, energy is transferred from the hotter object to the colder object until thermal equilibrium is achieved.

Worked Example 9A

Nature has a tendency to progress towards thermal equilibrium. Is energy always transferred from a region of higher temperature to a region of lower temperature? Give an example to support your answer.

Answer
No. Air conditioners transfer energy from a cooler room to a warmer exterior outside the room. A system of objects, when left by itself without external influence, has a natural tendency to progress towards thermal equilibrium. However, an external influence can cause energy in the system to be transferred from a colder region to a hotter region.

Let's Practise 9.1

1 Two objects of different temperatures are in contact. Describe how thermal equilibrium is reached.
2 An iced drink is placed in the chiller section of a refrigerator. The chiller section of the refrigerator is usually maintained at 4 °C. Would the ice cubes still be present in the drink the next day? Explain your answer.

Link

Theory Workbook
Worksheet 9A

9.2 How Is Energy Transferred by Heating?

Link

Infrared radiation is responsible for the sensation of heat we feel when we are near something hot. You will learn more about this in Chapter 13.

Learning Outcomes

- Describe, in microscopic terms, how conduction occurs in solids.
- Describe, in terms of density changes, how convection occurs in fluids.
- Explain that energy transfer by electromagnetic radiation does not require a material medium and that this rate of energy transfer to/from a body is affected by its surface temperature, surface area and surface colour and texture.

When we walk towards a barbeque pit, we feel warm even before we reach the barbeque pit (Figure 9.3). The metal tongs left on the pit can become too hot for us to hold. The air above the pit can become so hot that when a wind blows the hot air towards us, we involuntarily back away from the pit. All these happen due to the three processes of energy transfer — radiation, conduction and convection.

Figure 9.3 Energy transfers by radiation, conduction and convection around a barbeque pit.

Thermal Conduction

Conduction is a process of energy transfer where energy is transferred through the passing on of vibrational motion from one particle to another.

The handle of a metal ladle left in a pot of hot soup will quickly become too hot to touch (Figure 9.4). Energy is transferred from the hot soup to the handle of the ladle via conduction.

If the ladle is made of wood, its handle would not get hot so quickly. Why are some materials better thermal conductors than others?

Figure 9.4 A metal ladle heats up much faster than a wooden one.

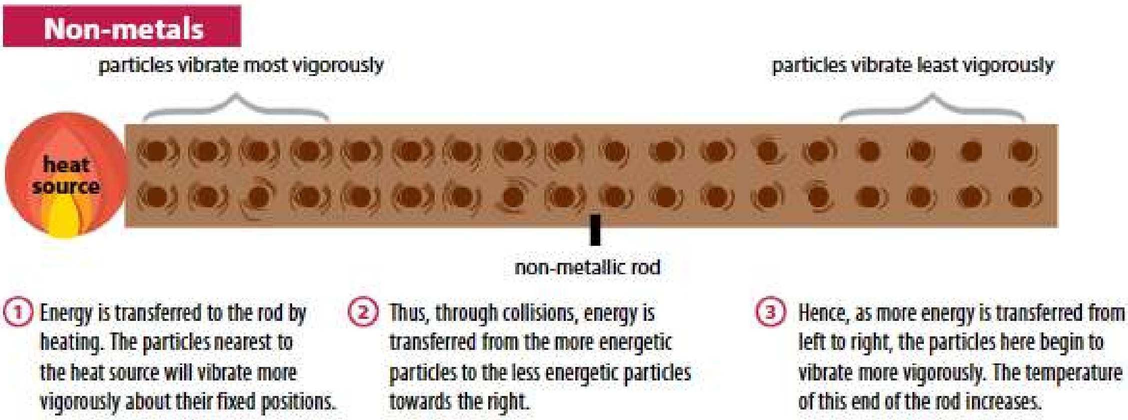
Helpful Note

An object may feel cold but it may not be at a low temperature. Energy is transferred by heating from your hand to the object quickly.

The ability of a material to transfer energy by conduction depends on how quickly energy is transferred from the hotter end to the cooler end. Materials that can transfer energy quickly by conduction are good **thermal conductors**. Materials that transfer energy slowly by conduction are poor thermal conductors. Poor thermal conductors are also known as **thermal insulators**.

Conduction in Solids

In general, metals are better thermal conductors than non-metals. Both metals and non-metals are made up of atoms and molecules (Figure 9.5). However, metals consist of tiny particles called free electrons that are absent in most non-metals. Electrons are extremely small compared to atoms. Due to their small size and high speed, the free electrons move very fast through the metal and transfer energy easily.

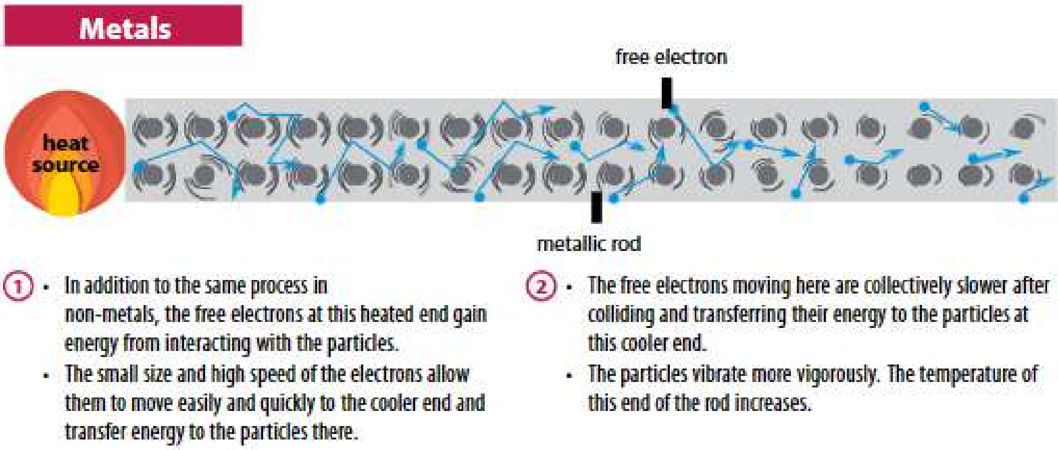


① Energy is transferred to the rod by heating. The particles nearest to the heat source will vibrate more vigorously about their fixed positions.

② Thus, through collisions, energy is transferred from the more energetic particles to the less energetic particles towards the right.

③ Hence, as more energy is transferred from left to right, the particles here begin to vibrate more vigorously. The temperature of this end of the rod increases.

(a) Energy transfer in non-metals occurs by vibration of particles.



①
- In addition to the same process in non-metals, the free electrons at this heated end gain energy from interacting with the particles.
- The small size and high speed of the electrons allow them to move easily and quickly to the cooler end and transfer energy to the particles there.

②
- The free electrons moving here are collectively slower after colliding and transferring their energy to the particles at this cooler end.
- The particles vibrate more vigorously. The temperature of this end of the rod increases.

(b) Energy transfer in metals occurs by lattice vibration and movement of electrons.

Figure 9.5 Two mechanisms for thermal conduction

Due to the role of free electrons, materials that consist of free electrons are usually good electrical and thermal conductors. However, there are exceptions. For instance, diamond is a very good thermal conductor but a poor electrical conductor.

Link

Recall from Chapter 8: Matter is made up of tiny particles constantly in motion and temperature rises with the average kinetic energy of the particles in a body and vice versa.

Link

Chemistry

In Chemistry, we learn about metallic bonding in metals. A metallic bond is the force of attraction between the positive metal ions and the sea of mobile (or delocalised) electrons.

Disciplinary Idea

Microscopic models can explain macroscopic phenomena.

Molecular vibrations and free electron diffusion (for metals) explain how energy is transferred by conduction in solids.

Let us investigate the rate of energy transfer in different solids.

Let's Investigate 9A

Aim
To investigate the rate of energy transfer in different solid rods

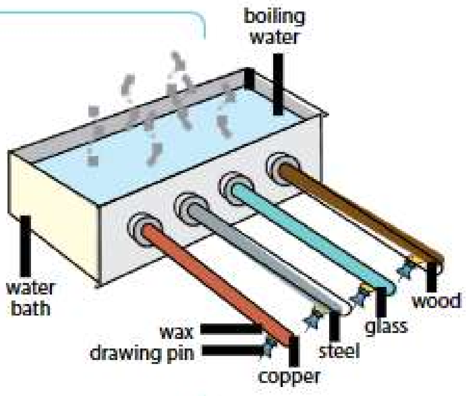


Figure 9.6

Procedure

1. Add a few drops of melted wax on one end of a copper rod (Figure 9.6).
2. Place a drawing pin on the melted wax and allow the wax to harden.
3. Repeat steps 1 and 2 with the other rods. Ensure that the drawing pins are placed at the same position on each rod.
4. Insert the rods inside a water bath to the same depth.
5. Pour boiling water into the bath.
6. Observe the rods to determine which drawing pin falls first.

Observation
The drawing pins fell first from the copper rod, followed by steel, glass and then wood.

Questions

1. What does the observation tell us about the ability of different solid rods to transfer energy by conduction?
2. The rods might be very hot during and after the experiment. What are some precautions you can take to handle them?
3. Do you think all the energy that is transferred to the hotter ends of the rod will eventually reach the cooler ends of the rod? Explain your answer.
4. If you want to investigate how fast energy can be transferred along the rod, how would you modify the set-up?

Conduction in Liquids and Gases

We often see cup sleeves on cups of hot drinks (Figure 9.7). A cup sleeve is usually made of cardboard with parallel ridges that contain air pockets. As both cardboard and air are poor conductors, the sleeve effectively insulates our fingers from the hot drink.

Compared to solids, conduction through liquids and gases is not as effective because the particles in liquids and gases are spaced farther apart than those in solids. Thus, the probability of the particles transferring their energy by collisions is lower in liquids and gases. This explains why liquids and gases are usually poor thermal conductors. Do you think metals in liquid form are poor conductors?

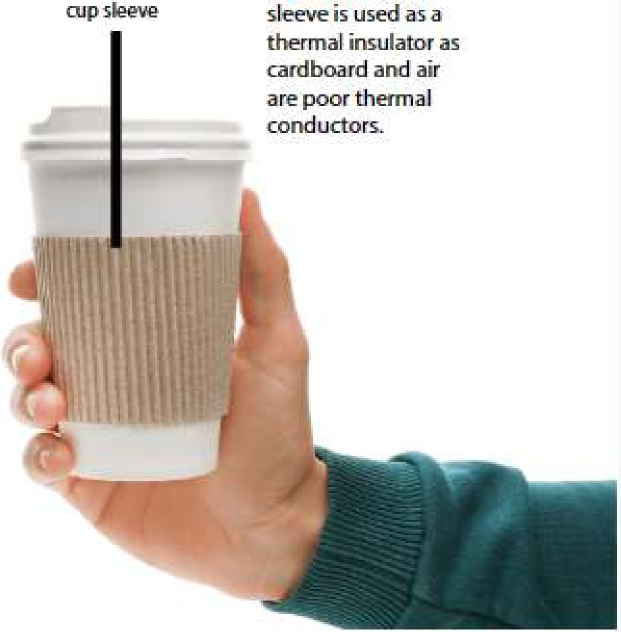


Figure 9.7 A cup sleeve is used as a thermal insulator as cardboard and air are poor thermal conductors.

Link

Practical Workbook
Experiment 9A

Tech Connect

An aerogel is a solid foam that is made up of 99.8% air, so it is extremely light and porous (Figure 9.8).

Aerogels are excellent absorbers of liquids. They are also great thermal and sound insulators. Can you explain why they have such properties?

The first aerogels were produced from silica gels, which made the aerogels brittle. Advancements in technology have allowed researchers to use their creativity to make aerogels out of various materials and improve their durability.

There are many uses of aerogels. What are some possible uses that you can think of?

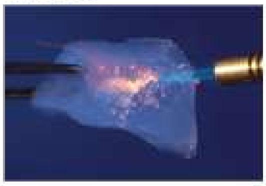
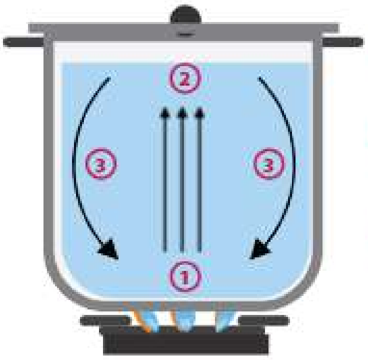


Figure 9.8 Aerogels are made up mostly of air.

Convection

Convection is a process of energy transfer by means of convection currents of a fluid (liquid or gas), due to a difference in density.

When a liquid is heated, it expands and increases in volume. As volume increases, density decreases. The warm liquid, being less dense than its surroundings, will rise. The cold liquid, being denser, will sink. This difference in density results in **convection currents** (Figure 9.9).



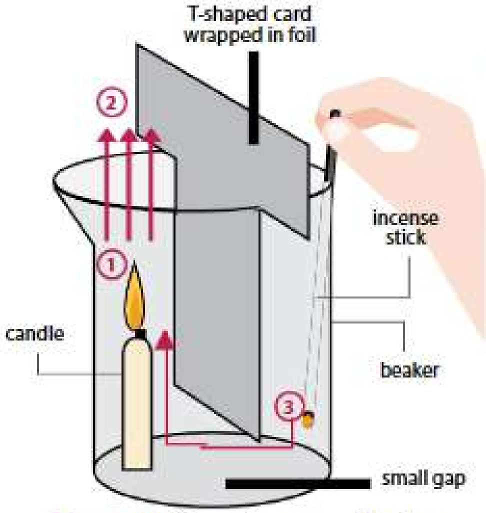
① The liquid at the bottom of the pot expands due to heating via conduction through the bottom of the pot.

② The warmer and less dense liquid starts rising towards the top.

③ At the same time, the surrounding denser liquid sinks to take the place of the rising liquid.
The process repeats and causes convection currents. The circulating convection currents carry warmer liquid away from the heat source and cooler liquid towards it. This allows the pot of liquid to gain internal energy.

Figure 9.9 Convection currents in a heated pot of liquid

Convection in air can be made visible with the set-up in Figure 9.10. Instead of rising, the smoke from the incense stick moves under the T-shaped card, towards the side with a lit candle before rising.



① The air near the candle flame expands due to heating via conduction.

② The warmer and less dense air starts rising towards the top.

③ At the same time, the air above the opposite side of the beaker flows downwards under the T-shaped card.
The process repeats and causes convection currents. The circulating convection currents carry warmer air away from the candle flame and cooler air towards it.

Figure 9.10 Convection currents in air

Can you explain why we often use a lid to cover a pot of hot food or a hot drink (Figure 9.11)?

Figure 9.11 Using a barrier, such as a lid, to keep the food or drink warm

Disciplinary Idea

Matter and energy make up the Universe.

Energy transfer can take place via bulk movement of matter (convection in fluids) or through collisions between particles in matter (conduction in matter).

Disciplinary Idea

Microscopic models can explain macroscopic phenomena.

When fluids are heated, the intermolecular spacing between particles increases. This causes a change in density, which results in bulk movement in convection.

For bulk movement of fluids during convection, the changes in density result in greater buoyant forces, causing the less dense fluid to float.

Radiation

In both conduction and convection, a physical medium is needed for energy transfer to occur. However, with a vacuum between the sun and Earth, how does the sun's energy reach us? The energy from the sun reaches us through radiation (Figure 9.12).

Disciplinary Idea

Waves can transfer energy without transferring matter.

Energy transfer in the process of infrared (IR) radiation does not require a medium (presence of matter).

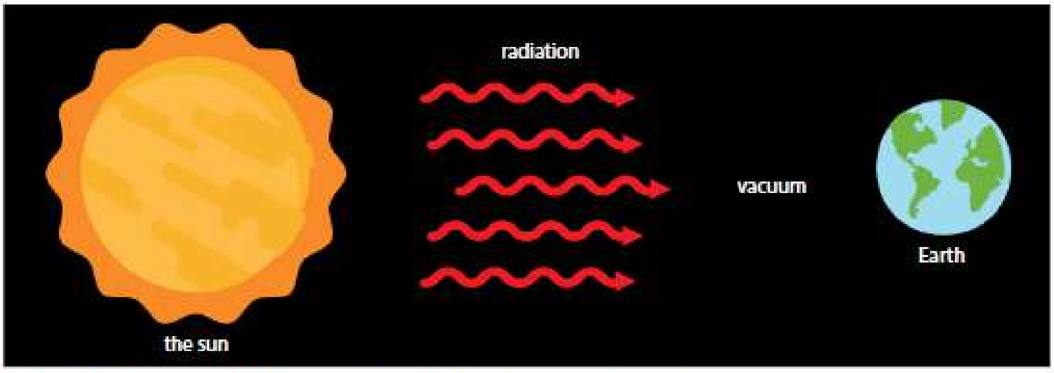


Figure 9.12 Energy from the sun is transferred to Earth by radiation only.

▶ **Radiation** is the process of energy transfer by electromagnetic waves. It does not require a medium.

The radiation from the sun is a form of electromagnetic (EM) wave that can travel through a vacuum at the speed of light. The types of EM radiation includes radio waves, infrared, visible light and others.

All objects with a temperature above absolute zero (0 K or –273 °C) emit and absorb EM radiation at the same time (Figure 9.13). For example, as the plant in Figure 9.13 receives light from the lamp above it, it is also emitting radiation to the surroundings at the same time.

Link

You will learn more about electromagnetic waves in Chapter 13.

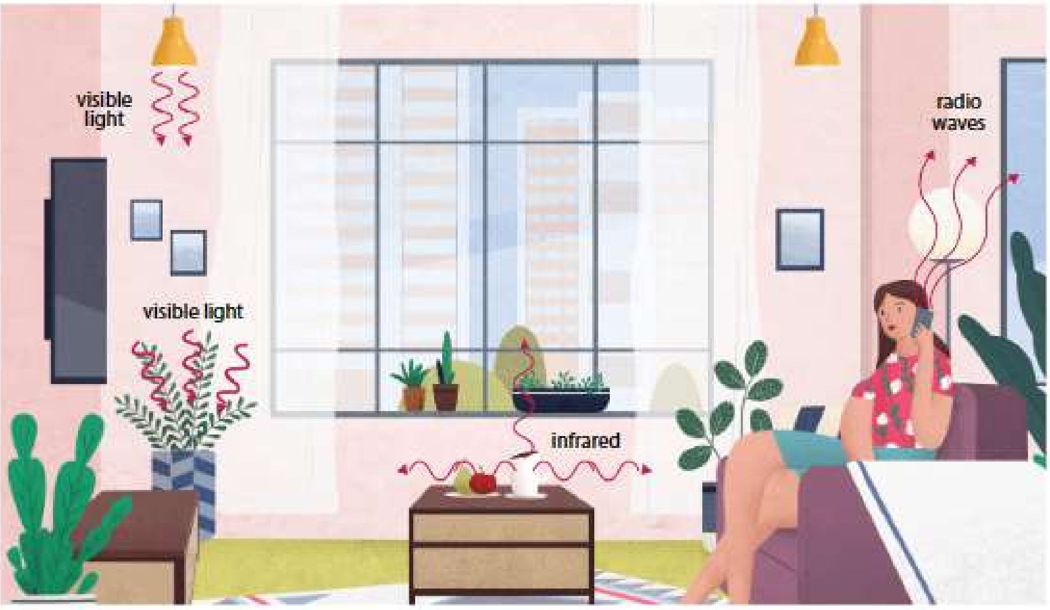


Figure 9.13 All objects emit and absorb different forms of radiation.

The rate at which an object emits or absorbs radiation is affected by the following three factors.

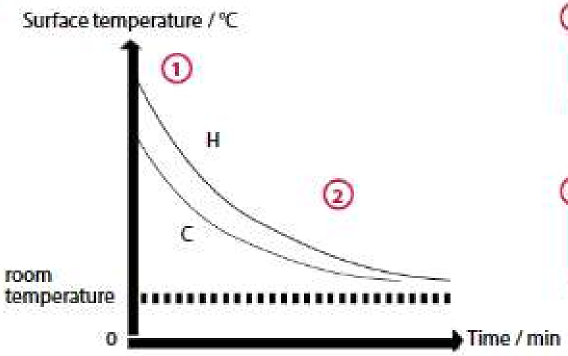
- Surface temperature
- Surface area
- Surface colour and texture

Surface Temperature

Imagine the following scenario.

- There are two identical objects that have different surface temperatures, which are both above the room temperature. H is the hotter object while C is the cooler object.
- Energy is transferred from object H by radiation at a rate of R_H.
- Energy is transferred from object C by radiation at a rate of R_C.
- When all other variables remain the same, R_H will be higher than R_C.

Figure 9.14 shows a temperature–time graph for objects H and C where their energy is transferred by radiation.



① Initially when the surface temperature is higher, the rate of temperature decrease is higher (i.e. the rate of emission of radiation is higher).

② As time passes, the surface temperature decreases, and the rate of temperature decrease becomes lower (i.e. the rate of emission of radiation is lower).

Figure 9.14 The rate of energy transfer by radiation is higher at higher temperatures.

Object H loses energy faster than object C such that the difference in their temperatures becomes smaller. However, object H is still hotter and transfers energy by radiation at a higher rate than object C. The higher the temperature of an object's surface, the higher the rate of emission of radiation.

Surface Area

Consider two steel blocks A and B that are hung from a beam in a laboratory. The blocks have the same initial temperature, mass and volume but have different surface areas. The temperatures of the blocks are recorded at regular intervals and plotted against time (Figure 9.15).

Link
Practical Workbook
Experiment 9B

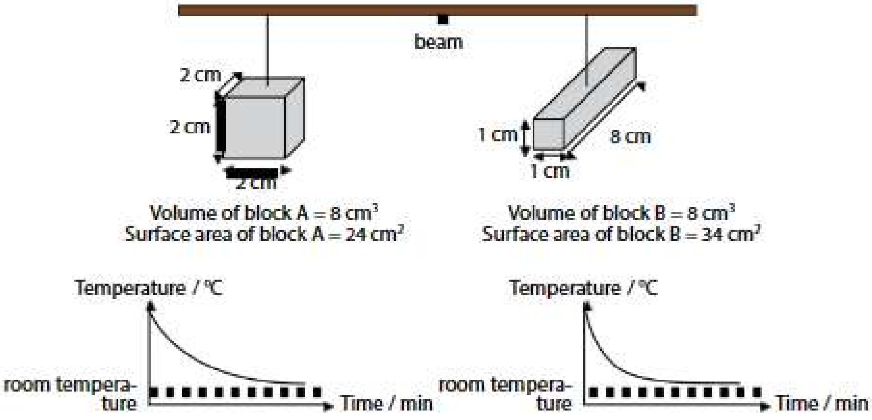


Figure 9.15 A greater surface area leads to a higher rate of energy transfer by radiation.

Block B has a bigger surface area and cools faster than block A. A larger surface area will emit energy at a higher rate via radiation. Similarly, a larger surface area will also absorb energy at a higher rate via radiation.

Surface Colour and Texture

Surface colour affects the rate of energy transfer by radiation.

Visible light and infrared radiation are part of the EM spectrum. Infrared radiation is just beyond the red light in the visible spectrum. We cannot see infrared radiation, but when it falls on our skin, we can sense the warmth. As red light is near the infrared radiation in the EM spectrum, a surface that reflects red light is often a good reflector for infrared radiation.

A white light source emits light that is made up of the colours in a rainbow. Under the white light source, a surface will appear white when the surface reflects all the colours from that light source. A surface will appear yellow if it reflects mainly yellow light and little of the other colours. Hence, a white surface reflects more light than a yellow surface.

Besides colour, the texture of a surface also affects the amount of light reflected. A shiny or very smooth surface reflects more light than a matt or rough surface.

The shiny, smooth and light-coloured surface of an object absorbs incoming radiation at a slower rate. The same surface also emits radiation at a slow rate. Hence, a poor emitter of radiation is also a poor absorber of radiation. The reverse is true for matt, rough and dark-coloured surfaces. In general, the rate of emission or absorption of radiation follows the order in Figure 9.16.

Figure 9.16 Order of the rate of emission or absorption of radiation

We have learnt that while an object is emitting radiation, it is also absorbing radiation from surrounding bodies. Whether an object is experiencing a net emission or absorption of radiation is determined by the combined effect of the object's surface temperature, area, colour and texture.

Worked Example 9B

(a) A student picked up a metal rod and a wooden rod that were left on a wooden table for some time. The metal rod felt much colder than the wooden rod. Explain whether the two rods had the same temperature and why the metal rod felt colder.

(b) The student went to collect some hot water from a big cylindrical metal boiler via a tap at the bottom of the cylinder. The student felt warm when standing near the boiler. Discuss if each of the three energy transfer processes contributed to the warmth felt by the student.

Past to Present

Temperatures in space vary greatly from −150 °C to 120 °C. Spacesuits are thus used to protect astronauts during space explorations.

Spacesuits have since come a long way (Figure 9.17). They have been developed and improved over the years to increase thermal comfort. Many modern spacesuits consist of special materials such as aluminised polymer insulation layers to maintain a comfortable thermal environment for the astronaut. This is achieved by reflecting solar radiation out when the astronaut is exposed to the sun, and reflecting the astronaut's body heat in the suit when in the shade.

Why do you think most spacesuits are white in colour?

Mercury spacesuit (1963)

Prototype spacesuit (2019)

Figure 9.17 All objects emit and absorb different forms of radiation.

Thought Process

(a) Since the rods had been left on the table for some time, they should be at thermal equilibrium with the surroundings.

(b) The student was near the boiler but not touching the boiler, so most of the energy was not transferred through convection currents or through a medium.

Answer

(a) The two objects had been in the same environment for a long time, so they should have the same temperature as the surroundings. However, the metal rod felt colder because it is a better thermal conductor that allows energy to be transferred away from the student's hand more quickly.

(b) As air is a poor conductor, energy transfer by conduction would be insignificant.
Convection currents would have carried the heated air upwards and away from the bottom where the tap was located, so energy transfer by convection was also not a significant contributor.
Radiation is the main process by which energy was transferred to the student's hands.

Worked Example 9C

Tom places a slice of frozen meat on a defrosting board. The board is made of metal and there are grooves on the board (Figure 9.18). The board defrosts the meat faster than when the meat is placed on a ceramic plate.

(a) Explain the main energy transfer process that takes place to defrost the meat.

(b) Suggest how the grooves on the board help to increase the rate at which the meat defrosts.

Figure 9.18

Answer

(a) Energy is transferred from the board to the meat by conduction, defrosting the meat from the bottom.

(b) The grooves on the board help to drain the melted ice water away so that energy can be transferred from the board to the meat instead of to the water.

Let's Practise 9.2

1 "A very good thermal insulator blocks the transfer of energy through it." Is this statement true or false? Explain your answer.

2 In a large beaker filled with water, will convection occur if the water is heated at the top with a blowtorch? Why?

3 State **three** factors that affect the rate of transfer of energy by radiation.

Link

Theory Workbook
Worksheet 9B

9.3 What Are some Applications of Thermal Processes?

Learning Outcome

- Apply the concepts of conduction, convection and radiation in everyday examples.

Figure 9.19 Different materials are chosen to make different objects to allow for or prevent energy transfer by conduction.

Look at Figure 9.19. Why is a metal pan used for cooking and a wooden spatula used for stirring?

If you look around you, you will find many examples of how we make use of our understanding of the energy transfer processes.

Conduction

Hair Dryers

- Hair dryers make use of fast-flowing hot air to dry our hair quickly.
- A motor pumps cool air through a heating element (Figure 9.20).
- Energy is transferred from the heating element to the fast-flowing air via conduction.

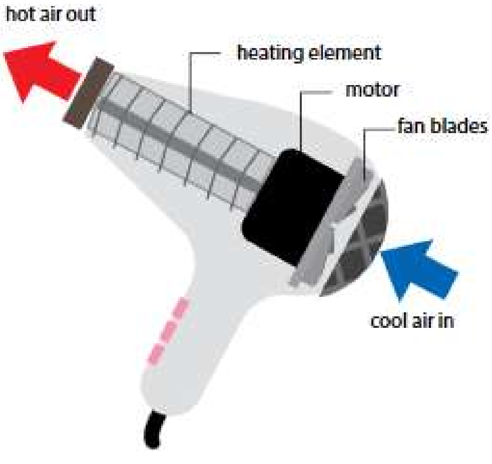


Figure 9.20 A hair dryer uses a heating element to transfer energy to fast-flowing air via conduction.

Instant Water Heaters

- Instant water heaters employ a similar mechanism as hair dryers to heat water quickly.
- Cold water is passed through heating elements that transfer energy to the water via conduction (Figure 9.21).

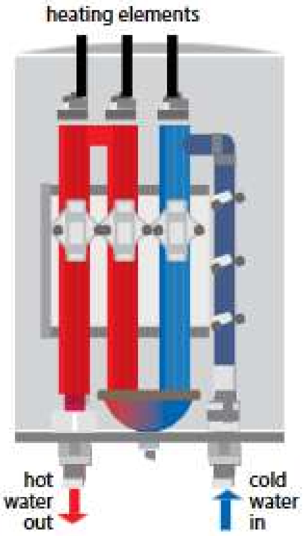


Figure 9.21 An instant water heater uses heating elements to transfer energy to cold water via conduction.

Link

Heating elements are made of metals with high electrical resistance. You will learn more about this in Chapter 18.

Thermal Wear

- Thermal wear contains porous materials like down feathers and microfibres that trap tiny pockets of air (Figure 9.22).
- As air in trapped in a constrained space, there is no convection current.
- The trapped air in the thermal wear acts as an insulating layer and reduces body heat to the surroundings via conduction.

Figure 9.22 Down feathers in thermal wear trap air and keep us warm.

Double-/Triple-glazed Windows

- Air is poor thermal conductor. A thin layer of air trapped between two glass panes reduces energy transfer via conduction through the window (Figure 9.23).
- Energy transfer through the window is further reduced with three glass panes and two layers of trapped air.
- Double- or triple-glazed windows help to keep the interior of the home cool during summer and keep the interior warm during winter.

Figure 9.23 Double-glazed (top) or triple-glazed (bottom) windows reduce energy transfer via conduction through the windows.

Convection

Electric Kettles

- Heating elements are usually placed at the bottom of electric kettles.
- When the kettle is switched on, the water around the heating element heats up and expands.
- The heated water rises while the cooler water at the top part of the kettle sinks to replace the heated water (Figure 9.24).
- A convection current is set up, which allows the water in the kettle to be heated up more quickly and evenly.

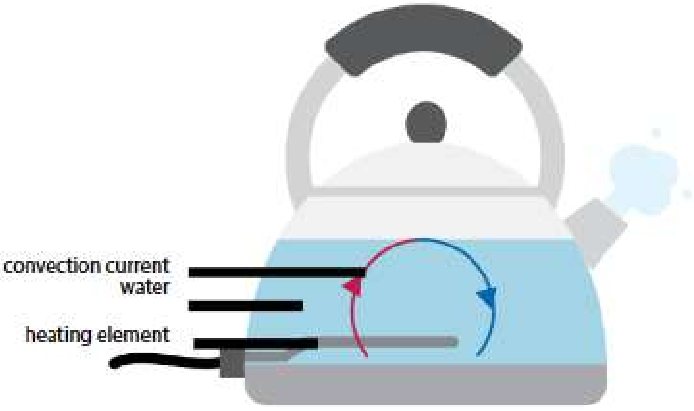


Figure 9.24 Convection current in kettle

Sea Breeze

Figure 9.26(a) Convection currents near the sea during the day

- During the day, the land heats up faster compared to the seawater.
- The air above the land heats up and rises.
- The cooler air above the sea rushes inland to replace the space left by the warm air.
- This sets up a convection current, creating a sea breeze (Figure 9.26(a)).

Hot Air Balloons

- The burner at the bottom of a hot air balloon heats up the air above it.
- The heated air expands and rises to the top of the balloon, and displaces the cooler air.
- The cooler air sinks to the bottom of the balloon, where it gets heated up. This movement of air sets up a convection current (Figure 9.25).
- Hot air has a lower density than cool air. When sufficient air in the balloon is heated up, the balloon rises.

Figure 9.25 Convection current in hot air balloon

Land Breeze

Figure 9.26(b) Convection currents near the sea at night

- During the night, the land cools down faster compared to the seawater.
- The air above the sea heats up and rises.
- The cooler air above the land rushes out towards the sea to replace the space left by the warm air.
- This sets up a convection current, creating a land breeze (Figure 9.26(b)).

Helpful Note

If you are observant, you'll notice that the wind direction at the seaside does not always follow the directions of the sea and land breezes as explained. One reason is because there are also other more powerful convection currents caused by larger scale temperature differences between the equator and the poles.

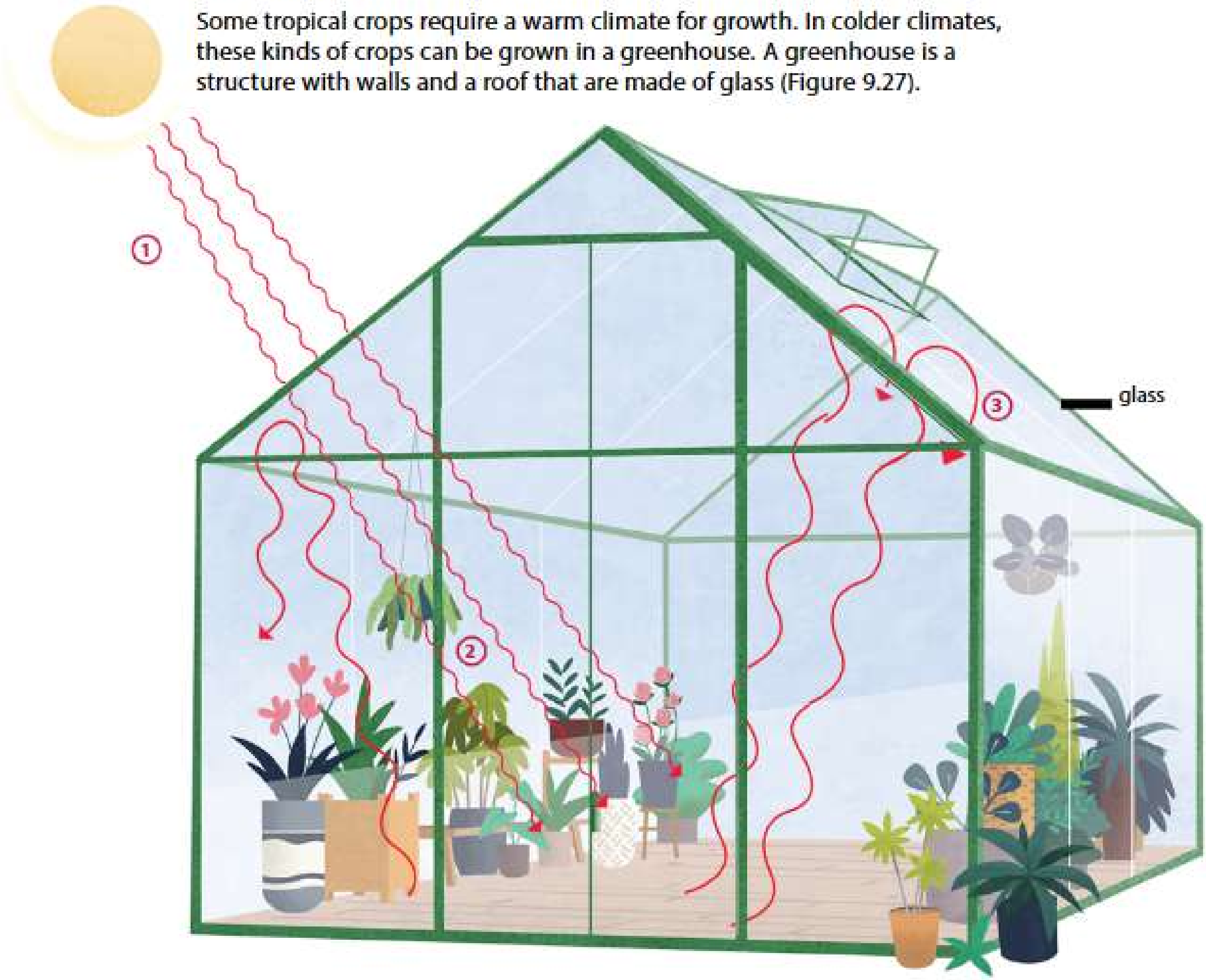
Link

Seawater heats up and cools down more slowly than the land as it has a higher specific heat capacity. You will learn more about this in Chapter 10.

Radiation

Greenhouses

Some tropical crops require a warm climate for growth. In colder climates, these kinds of crops can be grown in a greenhouse. A greenhouse is a structure with walls and a roof that are made of glass (Figure 9.27).



① The sun's radiation passes through the glass and heats up the ground in the greenhouse.

② The ground in the greenhouse becomes warm and re-radiates infrared radiation with longer wavelengths.

③ The infrared radiation with longer wavelengths is unable to pass through the glass roof. It gets reflected and trapped in the greenhouse. This keeps the greenhouse warm to support plant growth.

Figure 9.27 A greenhouse traps energy in the form of infrared radiation to allow plants to grow during cold seasons.

Space Blanket

- A space blanket has a shiny and smooth surface.
- It is useful in emergency situations such as to keep a person, who had fallen into very cold water, warm as it is a poor emitter of infrared radiation (Figure 9.28).
- It can be used to wrap up houses to protect the houses against large scale bushfires as it is a poor absorber of infrared radiation. It prevents the radiation from reaching and damaging the houses.

Figure 9.28 A space blanket can effectively keep infrared radiation in or out.

Global Warming

Earth's atmosphere is like a greenhouse. The solar radiation that enters the atmosphere warms Earth's surface. The surface then re-radiates infrared radiation at longer wavelengths that are more easily absorbed by the atmospheric greenhouse gases. The radiation absorbed by these greenhouse gases are then re-radiated in all directions. Some of the radiation will escape into outer space while the remaining will have to go through more cycles of re-absorption and re-radiation before it escapes into space.

The amount of greenhouse gases in the atmosphere has increased drastically due to human activities such as the burning of fossil fuels. Thus, more energy is trapped by the greenhouse gases and the temperature on Earth increases, leading to global warming (Figure 9.29).

What can we do to reduce global warming?

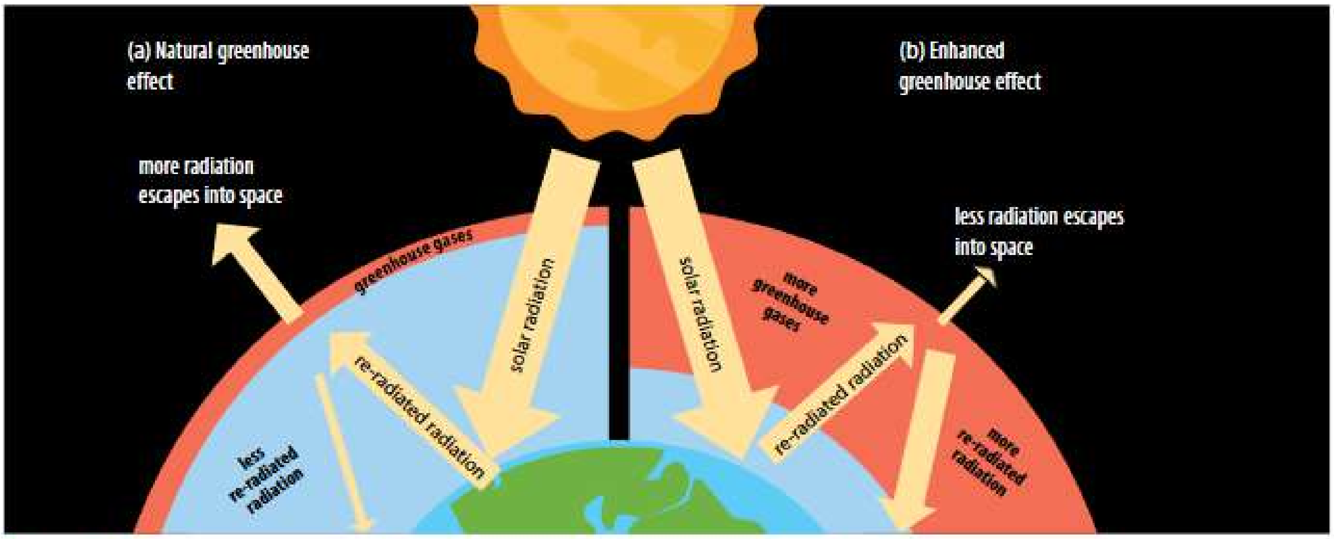


Figure 9.29 Greenhouse effect on Earth

Worked Example 9D

Figure 9.30

Figure 9.31

(a) Figure 9.30 shows an ant that is found in a very harsh environment. Study the ant's appearance and deduce the kind of environment it lives in. Explain your answer.

(b) Figure 9.31 shows down feather that is found close to the body of birds. It looks very different from the outer feathers. Suggest the function of the down feather and explain how it achieves its purpose.

Thought Process

(a) The ant has a silvery body. Silvery surface is slow in emitting and absorbing radiation.

(b) The down feather is fluffy and can trap air.

Answer

(a) The ant lives in a very sunny and hot environment. Its silvery body is effective at reflecting radiation from the sun to keep itself cool.

(b) The down feather has numerous sub-branches, making it fluffy and effective in trapping small pockets of air to act as a good insulating layer and reduces body heat to the surroundings by conduction. Thus, it helps to keep the bird warm in cold environments.

Let's Practise 9.3

Describe and identify how the energy transfer processes are relevant in each of these daily situations:

(a) Using a hair dryer to produce hot air
(b) Cooking a pot of soup
(c) Using a blanket to keep warm

Link

Theory Workbook
Worksheet 9C
Let's Assess
Let's Reflect

Problem-based Learning Application

Practical Workbook
Problem-based Learning: STEM Project

Problem-based Learning Activity

You are an engineer in the Housing Development Board (HDB) committee in charge of planning for a new town in Singapore. Your team receives a report on the uses of electricity in Singapore households in 2017 (Figure 9.32).

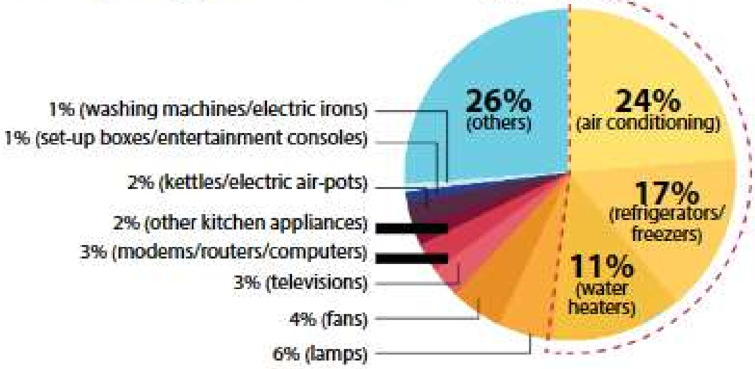


Figure 9.32 Uses of electricity in a typical household in Singapore

From the report, your team realises that more than half of the average household's use of electricity is on appliances that involve energy transfer processes (see segment highlighted by red dotted lines in Figure 9.32).

In order to build a green and sustainable town, your team is tasked to propose how the HDB flats in the new town can reduce the use of electricity for space cooling. Use the following questions to guide you in coming up with your proposal. You may do a search on the Internet to find the answers.

- What factors could cause a rise in the use of electricity for space cooling in the future?
- What are some technologies currently used for space cooling?
- How can we improve the efficiency of these technologies?

Cool Career

Architectural Engineer

Architectural engineers work very closely with architects and construction teams in the design and building process of buildings. The engineer focuses more on the mechanical, electrical and structural elements of the buildings.

With the growing concern on global warming, energy management has become an important consideration in the design of buildings. Hence, the engineer's knowledge of energy transfer processes can help to create buildings that are more environmentally friendly (Figure 9.33).

Figure 9.33 Architectural engineers take thermal processes into account when designing buildings.

Let's Map It

Thermal Transfer Processes

is the

Net transfer of energy from a region of higher temperature to a region of lower temperature until thermal equilibrium is reached

through

Conduction

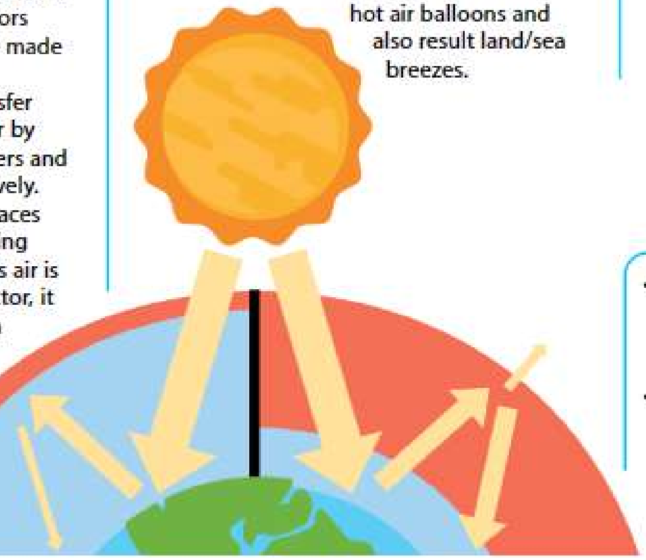
- Through physical contact between two surfaces
- Requires a medium
- In non-metals, by the vibration of particles
- In metals, by the vibration of particles and lattice vibration and movement of electrons

- Pots and pans are made from good thermal conductors while their handles are made from insulators.
- Heating elements transfer energy to air and water by conduction in hair dryers and water heaters respectively.
- Air trapped in small spaces is restricted from forming convection currents. As air is a poor thermal conductor, it acts as good insulation in thermal wear and double-glazed/ triple-glazed windows.

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

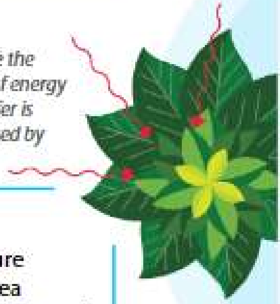
- Convection currents transfer energy from the hotter to the cooler regions in kettles, hot air balloons and also result land/sea breezes.



Radiation

- Through transfer of energy in the form of electromagnetic radiation
- Does not require a medium
- Absorbed and emitted by all objects

where the rate of energy transfer is affected by



- Surface temperature
- Surface area
- Surface colour and texture

- Greenhouses are kept warm as they allow solar radiation to enter but trap the re-radiated infrared radiation with longer wavelengths.
- Space blanket keeps a person warm as it reflects infrared radiation back to the person.

Let's Review

Section A: Multiple-choice Questions

1 At which of the following temperatures will a substance have least energy in its kinetic store?

○ A −100 °C
○ B 0 °C
○ C 10 °C
○ D 100 °C

2 According to the kinetic theory of matter, energy is transferred from the hot end of a glass rod to the cold end when the molecules at the hot end ________.

○ A emit infrared radiation to the cold end
○ B move to the cold end
○ C move around and transfer energy to molecules at the colder end by collision
○ D vibrate more vigorously and transfer energy to the neighbouring molecules

3 Equal volumes of hot water were poured into containers P and Q on a table (Figure 9.34).

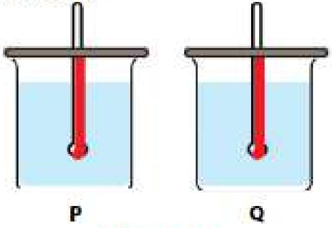


Figure 9.34

Initially, the water in P and Q had the same temperature. After an hour, the temperature of water in P was found to be lower than that of Q. Which of the following could have contributed to the outcome?

○ A P has a shiny surface.
○ B P is made of a better conductor.
○ C Q has a rough surface.
○ D The cover of Q has some holes.

4 A hot object is cooling on a cork mat in an open space at room temperature. Which of the following statements about how the hot object loses energy is **incorrect**?

○ A Loss of energy by conduction is inefficient because air is a poor thermal conductor.
○ B Loss of energy by radiation is most effective when the temperature difference between the object and the surrounding is small.
○ C The processes of convection, conduction and radiation are in operation.
○ D The rate at which the object loses energy by radiation depends on its surface colour and texture.

5 A person sits in front of a campfire. What is/are the main thermal process(es) by which energy is transferred to the person?

○ A conduction and radiation only
○ B conduction, convection and radiation
○ C convection and radiation only
○ D radiation only

Section B: Structured Questions

1 Four similar cups contain the same volume of water at 100 °C and allowed to cool at room temperature (Figure 9.35).

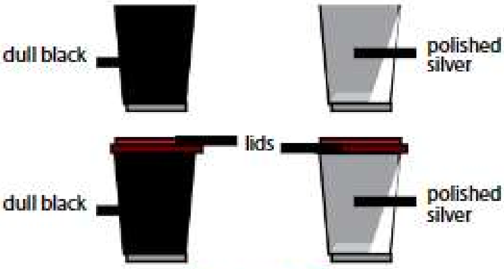


Figure 9.35

Identify the cup that will be the hottest after five minutes. Explain your answer in terms of thermal processes.

2 A cup of hot tea is left on a table. Explain how energy escapes from the tea by:
  (a) conduction;
  (b) convection; and
  (c) radiation.

3 In cold countries, houses are kept warm with an inner wall and an outer wall. The gap between the walls could be filled with air or a polymer foam.
  (a) Which thermal processes are the two insulation methods restricting?
  (b) Compare the effectiveness of the two insulation methods.

4 A metal straw inserted into a cup of cold drink soon had condensation droplets on its top end. A student claimed that the "cold" from the cold drink had travelled up the straw and caused the top end of the straw to be cold. Explain whether you agree with the student's account.

5 (a) A piece of aluminium foil is used to wrap food for barbequing. One side of the foil is shiny, while the other side is dull. Which side of the foil should be on the outside and why?
  (b) Homes experiencing winter often have electric heaters. Explain why there are highly reflective surfaces behind the heating rods in the heater and why such heaters are usually placed on the floor.

Section C: Free-response Questions

1 (a) With reference to the mechanism of energy transfer in solids, explain why copper is a good thermal conductor but wood is a poor thermal conductor.
  (b) Briefly describe how an electric kettle heats water.
  (c) (i) Why are spacesuits and firefighting suits covered with a shiny metallic surface?
    (ii) Car radiators and motorcycle engines are fitted with cooling fins that are painted dull black and have a zigzag structure. Explain why.

2 80% of the housing in Singapore comprises Housing Development Board (HDB) flats. As Singapore is very hot and humid, it is important that the flats are able to remain comfortably cool.
  (a) The HDB rooftops consist of two layers of concrete tiles, with a gap between the layers. Suggest a reason how this can help the top floor units stay cool.
  (b) Tom suggests to install double glazed windows to further improve the cooling of the HDB flats. Discuss if his suggestion is suitable.
  (c) Explain the colour you would choose for your block to help keep it cool.

CHAPTER

10

Thermal Properties of Matter

What You Will Learn

- How is internal energy related to heat capacity?
- What are the processes that involve a change of state?
- What is latent heat?

Have you walked barefoot on the sand at the beach on a hot day? Did you notice how warm the dry sand is compared to the wet sand next to the edge of the water? As you wade into the water, your feet will feel cooler.

Singapore is at the equator, yet we rarely experience extreme temperatures beyond 40 °C unlike some places that are further from the equator. This is because our island is surrounded by seawater that keeps it cool despite the hot sun!

The land and the seawater are both heated by the sun but why do they have different temperatures?

10.1 How Is Internal Energy Related to Heat Capacity?

Learning Outcomes

- Describe internal energy as an energy store that is made up of the total kinetic energy associated with the random motion of the particles and the total potential energy between the particles in the system.
- Define *heat capacity* and *specific heat capacity*.
- Recall and apply the relationship *energy transfer (by heating) = mass × specific heat capacity × change in temperature* to new situations or to solve related problems.

In Chapter 9, we learnt that during the day the air above the land heats up and rises. The cooler air above the sea moves towards the land, setting up a convection current, creating sea breeze. The reverse is true for land breeze.

The convection currents are caused by temperature differences between the land and the seawater. Why does the land heat up and cool down faster than seawater?

To find the answer, we need to understand the concepts of *heat capacity* and *specific heat capacity*. As internal energy is closely linked to both concepts, let us first review what internal energy is.

Disciplinary Idea

Matter and energy make up the Universe

A macroscopic amount of matter has energy in the internal store, which comprises microscopic kinetic energy and potential energy.

Internal Energy

In the kinetic particle model, the particles have kinetic energy due to their random motion. The particles also have potential energy due to the forces between them.

Internal energy is an energy store that is made up of the total kinetic energy associated with the random motion of the particles and the total potential energy between the particles in the system.

Heat Capacity and Specific Heat Capacity

Different bodies or objects have different capacities to store internal energy. With the help of the kinetic particle model (Figure 10.1), we can see that this capacity depends on the following.

1. Number of particles
   - When there are more particles, more energy can be stored. Thus, larger objects tend to have larger heat capacities.
2. Nature and strength of the intermolecular forces
   - A stiffer spring (which represents a stronger force between particles) allows more energy to be stored for the same extension or compression. Thus, for the same volume, solids and liquids tend to have larger heat capacities than gases.

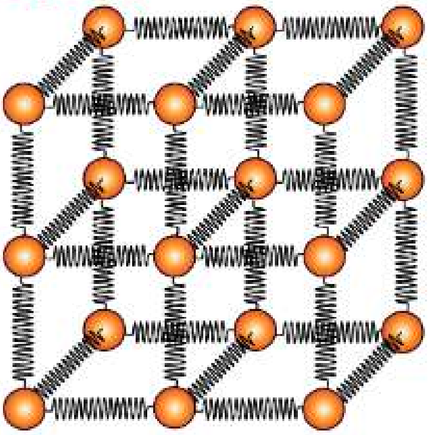


Figure 10.1 Model of matter consisting of particles exerting forces on each other

Link

Recall from Chapter 8: Temperature rises with the average kinetic energy of the particles in a body and vice versa.

Heat capacity C of an object is the change of its internal energy per unit change in its temperature.

$$C = \frac{Q}{\Delta\theta}$$

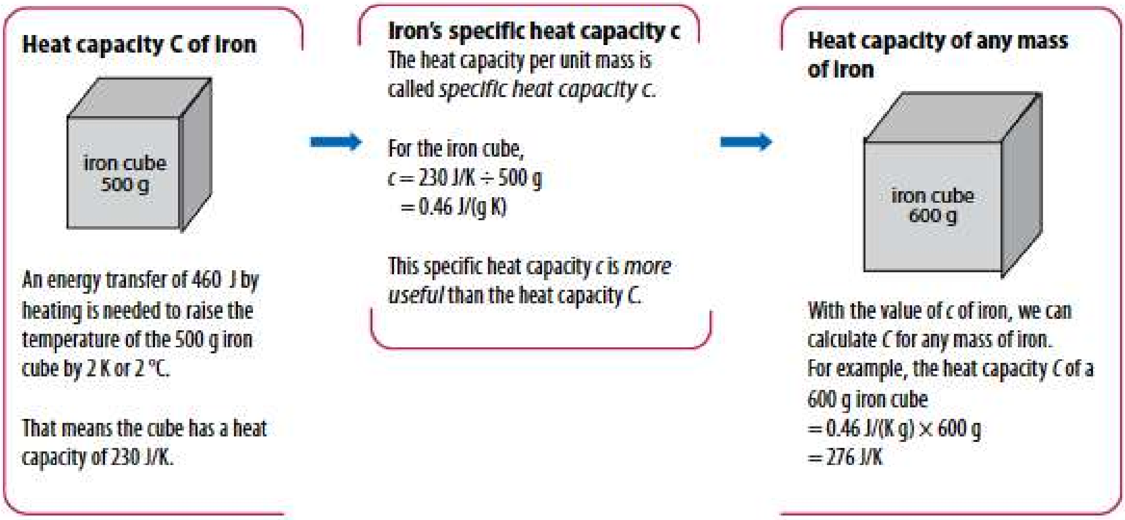
where Q = change in internal energy (J) by energy transfer
$\Delta\theta$ = change in temperature (K or °C)

Helpful Note

θ is a Greek alphabet known as the theta. Scientists and mathematicians commonly use Greek alphabets to represent quantities.

The SI unit of heat capacity is **Joule per Kelvin (J/K)** or **Joule per degree Celsius (J/°C)**.

Consider Figure 10.2.



Heat capacity C of iron

An energy transfer of 460 J by heating is needed to raise the temperature of the 500 g iron cube by 2 K or 2 °C.

That means the cube has a heat capacity of 230 J/K.

Iron's specific heat capacity c

The heat capacity per unit mass is called *specific heat capacity c*.

For the iron cube,
$c = 230 \text{ J/K} \div 500 \text{ g}$
$= 0.46 \text{ J/(g K)}$

This specific heat capacity c is *more useful* than the heat capacity C.

Heat capacity of any mass of iron

With the value of c of iron, we can calculate C for any mass of iron.
For example, the heat capacity C of a 600 g iron cube
$= 0.46 \text{ J/(K g)} \times 600 \text{ g}$
$= 276 \text{ J/K}$

Figure 10.2 Calculating heat capacities of iron cubes

Since values of specific heat capacity are more useful, scientists and engineers have carefully measured and compiled such values for future reference.

Specific heat capacity c of a material is the change of its internal energy per unit mass for each unit change in its temperature.

$$c = \frac{C}{m} = \left(\frac{Q}{m\Delta\theta}\right)$$

where C = heat capacity (J/K or J/°C)
Q = change in internal energy (J) by energy transfer
m = mass of substance (kg)
$\Delta\theta$ = change in temperature (K or °C)

Helpful Note

The word "specific" is linked to "per unit mass".

The SI unit of specific heat capacity is **Joule per kilogram per Kelvin (J/(kg K))** or **Joule per kilogram per degree Celsius (J/(kg °C))**. Another common unit is joule per gram per Kelvin (J/(g K)).

Heat capacity is seen as a property of an *object* that can consist of parts made of different materials. On the other hand, specific heat capacity is seen as the property of a *uniform material*.

Table 10.1 shows the specific heat capacity of some common substances. The specific heat capacity of water is 4200 J/(kg K). This means that 4200 J of energy is required to raise the temperature of 1 kg of water by 1 K.

Table 10.1 Specific heat capacity of some substances

Substance	*Specific Heat Capacity / J/(kg K)
gold	129
tungsten	132
brass (alloy of copper and zinc)	380
ordinary glass	670
sand	830
soil	800–1500
wood	1300–2500
ice (at 0 °C)	2100
alcohol	2400–2500
seawater	3900
water	4200
hydrogen	14 000
dry air at sea level	1005

*Values vary with environmental conditions like temperature.

Worked Example 10A

(a) On a sunny day, the dry sand feels hot while the seawater feels cool. Explain why the dry sand feels hot while the seawater stays cool even though both receive energy at the same rate from the sun.

(b) At night, a land breeze develops due to the seawater being warmer than the land. Why does the land's temperature drop faster than the seawater?

Thought Process

Different materials have different specific heat capacities — the amounts of energy required to change the temperature of a unit mass of different materials by 1 K are different.

Answer

(a) The specific heat capacity of sand is lower than that of the seawater (see Table 10.1). Hence, the temperature of sand increases faster than the seawater even though they both receive energy at the same rate from the Sun.

(b) At night, without the sun's radiation, the land and the seawater transfer energy to the surroundings by conduction, convection and radiation. The land cools faster than the seawater because it has a lower specific heat capacity. In addition, the land has a higher temperature difference with the surroundings as compared to the seawater at sunset. Hence, energy is transferred from the land to the surroundings faster than from the seawater to the surroundings.

Calculations Involving Heat Capacity and Specific Heat Capacity

We can rewrite the formulae for heat capacity and specific heat capacity. Thus, the energy Q transferred by heating to an object of heat capacity C so that the object has a temperature change $\Delta\theta$, is:

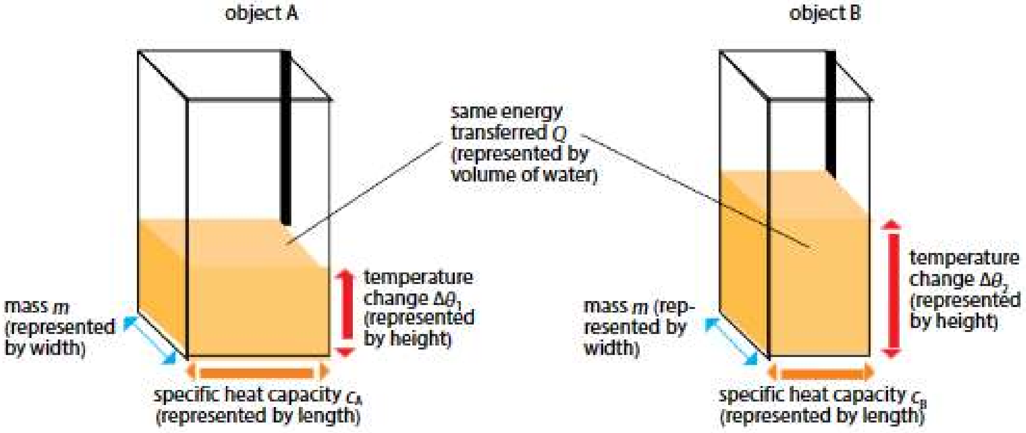
$$Q = C\Delta\theta$$

For a substance made of a uniform material of mass m, specific heat capacity c, and a temperature change $\Delta\theta$, the energy Q transferred by heating is:

$$Q = mc\Delta\theta$$

A useful way to understand the formula, $Q = mc\Delta\theta$, is by modelling it visually. For example, we have two objects of the same mass. The objects have different specific heat capacities and the same amount of energy is transferred into them. We want to know which object will have a larger temperature rise.

We can use two rectangular containers to represent objects A and B (Figure 10.3). Each dimension of the container represents a component of the formula. When the same volume of liquid (representing the energy transferred by heating) is added to each container, object B has a greater rise in temperature. Hence, we can see that the object with the lower specific heat capacity will show a greater rise in temperature.



Note:
- The base area of the containers represents the heat capacity of the objects ($m \times$ specific heat capacity). Mass m is the same. Specific heat capacity c_A is higher than specific heat capacity c_B.
- The size of each cuboid does not represent the actual size of the object.
- Energy is a property of an object and not a substance.

Figure 10.3 When the same amount of energy Q is transferred to two objects of the same mass, the temperature rise will depend on the specific heat capacity.

Let's Investigate 10A

Aim
To determine the specific heat capacity of steel and glass

Procedure

1. Prepare the calorimeter (Figure 10.4).
2. Fill the can with 250 g of tap water. Record the temperature T_i.
3. Prepare one steel sphere of about 3 cm in diameter.
4. Measure and record the mass of the metal sphere m_m.
5. Place the sphere in a beaker of water and boil the water so that its temperature is 100 °C.
6. Using a pair of tongs, transfer the sphere into the can.
7. Gently stir the water and record the maximum stable temperature T_m of water.
8. Repeat steps 1 to 7 using a glass sphere instead of a steel sphere.
9. Determine the specific heat capacity of the spheres.

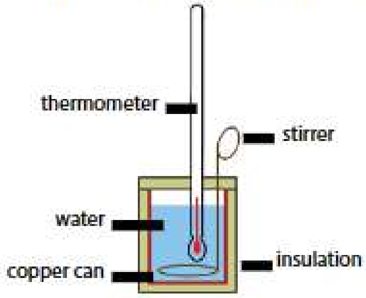


Figure 10.4

Calculation
Temperature change of the water = $(T_m - T_i)$ °C
Temperature change of the sphere = $(100 - T_m)$ °C

Using the known specific heat capacity of water (4200 J/(kg °C)) and the data collected, the specific heat capacity c of the spheres can be calculated.

Energy transferred out of the sphere = Energy transferred into the water

$$m_m \text{ kg} \times c \text{ J/(kg °C)} \times (100 - T_m) \text{ °C} = 0.250 \text{ kg} \times 4200 \text{ J/(kg °C)} \times (T_m - T_i) \text{ °C}$$

Questions

1. Why is it best to use a can that is not too large compared to the size of the sphere?
2. What is the purpose of stirring the water in the calorimeter?
3. A metal sphere and a glass sphere of the same mass are used. The final stable temperature of the water in the calorimeter is higher when the glass sphere is added. Which material, metal or glass, has a higher specific heat capacity? Explain.

Link
Practical Workbook
Experiment 10A
Experiment 10B

Worked Example 10B

During a baking session, a 25 g steel spoon was accidentally left in the oven and heated to 150 °C. Jenny placed the spoon in a ceramic container and added 300 g of tap water at 24 °C to cool it down.

Assuming that energy is transferred only from the spoon to the water, calculate the final temperature of the spoon and water.
(The specific heat capacity of steel is 460 J/(kg °C) and the specific heat capacity of water is 4200 J/(kg °C).)

Answer
Let the final common temperature be θ_f.
Energy transferred to the water = Energy transferred out of spoon

$$m_w c_w \Delta\theta_w = m_s c_s \Delta\theta_s$$

$$m_w c_w(\theta_f - 24\,°\text{C}) = m_s c_s(150\,°\text{C} - \theta_f)$$

$$0.3\text{ kg} \times 4200\text{ J/(kg °C)} \times (\theta_f - 24\,°\text{C}) = 0.025\text{ kg} \times 460\text{ J/(kg °C)} \times (150\,°\text{C} - \theta_f)$$

$$1260\text{ J/°C} \times (\theta_f - 24\,°\text{C}) = 11.5\text{ J/°C} \times (150\,°\text{C} - \theta_f)$$

$$1260\text{ J/°C} \times \theta_f + 11.5\text{ J/°C} \times \theta_f = 11.5\text{ J/°C} \times 150\,°\text{C} + 1260\text{ J/°C} \times 24\,°\text{C}$$

$$(1260\text{ J/°C} + 11.5\text{ J/°C}) \times \theta_f = 31\,965\text{ J}$$

$$\theta_f = 31\,965\text{ J} \div 1271.5\text{ J/°C}$$

$$\theta_f = 25.1\,°\text{C}$$

Let's Practise 10.1

1 Between heat capacity and specific heat capacity:
  (a) which is dependent on the mass of the object; and
  (b) which is applicable only to uniform materials?

2 Table 10.2 shows information about two objects.

Table 10.2

Property	Object X	Object Y
mass / kg	1	3
specific heat capacity / J/(kg K)	800	400

  (a) Which object, X or Y, requires more energy to increase its temperature by 2 K?
  (b) Which object, X or Y, has a larger heat capacity?
  (c) In which object, X or Y, will the temperature rise faster if energy were transferred to both objects at the same rate?

Link
Theory Workbook
Worksheet 10A

10.2 What Are the Processes that Involve a Change of State?

Learning Outcomes

- Describe melting/solidification and boiling/condensation as processes of energy transfer without a change in temperature.
- Explain the difference between boiling and evaporation.

Figure 10.5 Food cooks faster under a high pressure.

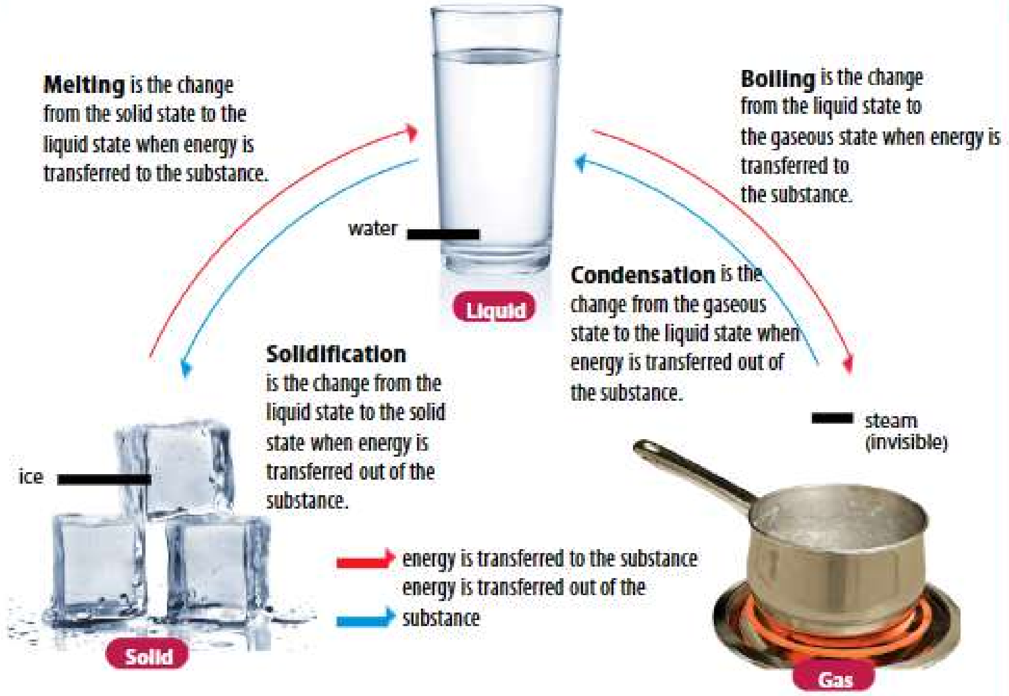
At its boiling point, the temperature of water cannot increase further. This is because the rate at which energy is transferred away with the steam equals the rate at which energy is supplied to the water. Do you know that water does not always boil at 100 °C?

The atmospheric pressure is lower at higher altitudes. This results in a lower boiling point of water. An increased pressure above the hot water surface will make it more difficult for steam to form and escape. This will raise the boiling point of water. Thus, food in a pressure cooker will be cooked faster (Figure 10.5).

Besides boiling, what are other changes of state around us? Why do some changes of state occur at a fixed temperature?

Changes of State

Matter changes state when they gain or lose energy (Figure 10.6).



Note: During the process that involves a change of state, the temperature of a pure substance remains constant.

Figure 10.6 Processes taking place during changes of state involve energy transfers at a constant temperature (for a pure substance)

The temperature at which:

- a solid melts is called its **melting point**;
- a liquid solidifies or freezes is called its **freezing point**;
- a liquid boils is called its **boiling point**; and
- a gas condenses is called its **condensation point**.

We will learn why the temperature of a pure substance remains constant when it is melting, solidifying and boiling in Section 10.3.

Link

Chemistry

In Chemistry, we learn that matter can change from one state to another when it gains or loses energy. The particles of solids, liquids and gases have different amounts of kinetic energy.

Link

Recall from Chapter 8: Matter can exist in three different states. The properties of the states of matter are different due to the arrangement and motion of particles in each state.

Past to Present

People have different ways to preserve food. Food is preserved by drying, adding salt, fermentation and freezing. Modern technology now offers another method called freeze-drying. The method works by freezing the food and creating a low-pressure partial vacuum. The frozen water in the food will directly turn into vapour (in a process called sublimation) and be removed from the food. The nutritional values of the food remain unchanged.

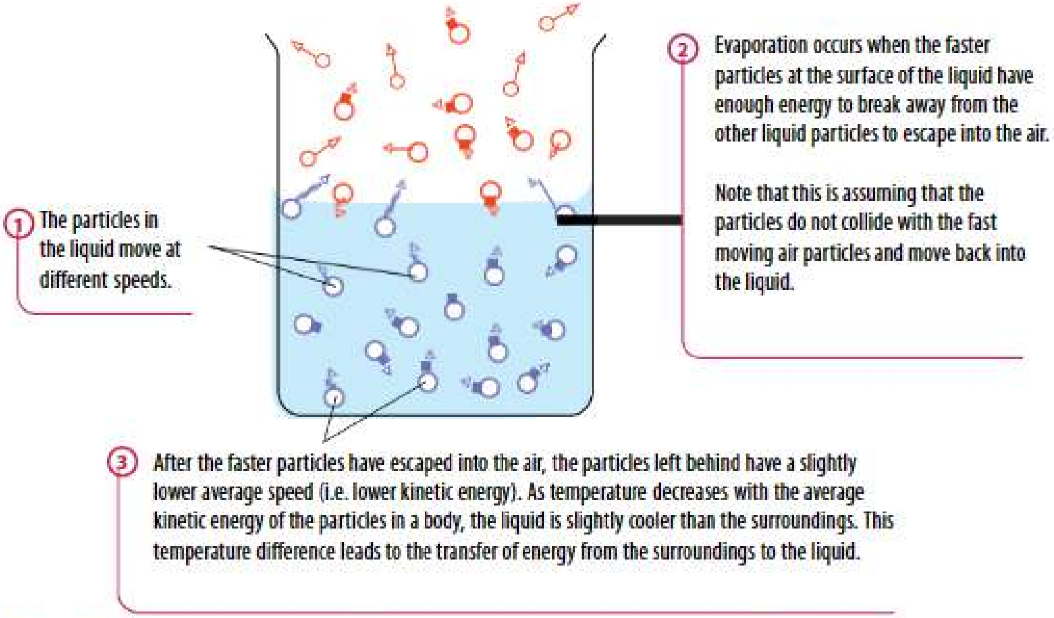
Figure 10.7 shows some freeze-dried fruits and berries. They can be eaten in their dried and crunchy state or be soaked in water to return them almost fully to their original juicy state. Freeze-dried foods have several advantages such as being long-lasting, easier to store and easier to transport (smaller mass and volume). They are ideal for adventurers such as astronauts, who need to travel light.

Figure 10.7 Freeze drying helps retain the nutritional values of the food while making it last longer.

Boiling and Evaporation

Both boiling and evaporation involves vaporisation (change from a liquid to a gas). During boiling, bubbles are seen throughout the liquid. The boiling point remains constant assuming that there is no change in the atmospheric pressure.

Evaporation of a liquid takes place only at the *surface* of the liquid exposed to the air. Figure 10.8 shows how cooling by evaporation occurs.



① The particles in the liquid move at different speeds.

② Evaporation occurs when the faster particles at the surface of the liquid have enough energy to break away from the other liquid particles to escape into the air.

Note that this is assuming that the particles do not collide with the fast moving air particles and move back into the liquid.

③ After the faster particles have escaped into the air, the particles left behind have a slightly lower average speed (i.e. lower kinetic energy). As temperature decreases with the average kinetic energy of the particles in a body, the liquid is slightly cooler than the surroundings. This temperature difference leads to the transfer of energy from the surroundings to the liquid.

Figure 10.8 Evaporation occurs when faster particles escape from the surface of the liquid leading to a lower average speed of the remaining liquid particles.

Although boiling and evaporation both involve the change of state from a liquid to a gas, they have their differences (Table 10.3).

Table 10.3 Differences between boiling and evaporation

	Boiling	Evaporation
1	needs a heat source	does not need a heat source
2	vaporisation takes place throughout the liquid	vaporisation takes place only at the liquid surface
3	rate of vaporisation is faster	rate of vaporisation is slower
4	happens only at the boiling point	happens at temperatures below the boiling point
5	liquid temperature remains constant	liquid temperature tends to drop

Figure 10.9 shows the factors that affect the rate of evaporation.

Factors affecting the rate of evaporation

Pressure
When the pressure is higher, the rate of evaporation is lower. At a higher pressure, liquid molecules escape into the air less quickly.

Humidity of air
Humidity is a measure of the amount of water vapour in the air. When the humidity is high, there is a lot of water vapour in the air and the rate of evaporation is lower.

Surface area of liquid
When the exposed surface area of the liquid is higher, the rate of evaporation is higher. This is because more molecules can escape from the surface of the liquid.

Temperature
When the temperature is higher, the rate of evaporation is higher. At a higher temperature, the average kinetic energy of the liquid molecules is higher. More liquid particles can escape into the air.

Wind speed
Wind (moving air) removes the molecules that have just escaped into the air. Thus, the air surrounding the liquid is drier. Hence, when the wind speed is higher, the rate of evaporation is higher.

Boiling point of the liquid
A liquid with a lower boiling point evaporates more quickly than one with a higher boiling point under similar conditions. This is because the attractive forces between the particles of the liquid with a lower boiling point are weaker.

Figure 10.9 Factors affecting the rate of evaporation

Worked Example 10C

While walking on a beach on a sunny day, we can feel that the wet sand is less warm than the dry sand. Explain how evaporation and the presence of wind cool the wet sand.

Answer
During evaporation of water from the wet sand, the faster water molecules escape into the air. This results in a lower average speed and kinetic energy of the remaining water molecules in the sand. Since temperature decreases with lower average kinetic energy of the molecules, the water in the wet sand is cooler. Energy is transferred from the sand to the water. Thus, evaporation cools the sand.

In the presence of wind, evaporation of water happens more quickly as wind removes the water molecules that escaped into the air. The air near the sand is drier and this leads to a higher rate of evaporation and further cooling.

Let's Practise 10.2

For each of these processes, state whether energy is transferred into or out of the substance.

(a) Boiling (b) Solidification (c) Condensation (d) Melting

Link
Theory Workbook
Worksheet 10B

10.3 What Is Latent Heat?

Learning Outcomes

- Define *latent heat* and *specific latent heat*.
- Recall and apply the relationship *energy transfer (by heating for a change of state) = mass × specific latent heat* to new situations or to solve related problems.
- Explain latent heat in terms of behaviour of particles in a body.
- Sketch and interpret a cooling curve.

Figure 10.10
A water mist system is able to produce a jet of very fine mist for fire-fighting.

The idea of using water mist to put out fire started about 80 years ago. Since then, many improvements to the method and equipment have been made.

The modern water mist system produces large jets of very fine mist using high pressure (Figure 10.10). The water droplets are less than 0.2 mm in diameter. The combined surface area of all the droplets is so large that energy is transferred very quickly from the air to the droplets.

The energy transferred to the droplets causes the water droplets to vaporise into water vapour. This cools the surrounding air and the water vapour displaces the air (including oxygen). The resulting cooling of the air and reduced amount of oxygen in the air prevent the the fire from spreading further. What makes water a suitable substance for the mist system?

Water has a high specific heat capacity. Thus, more energy can be transferred to water before its temperature increases. In addition, more energy is absorbed from the surroundings when water changes from liquid to gas at a constant temperature. The energy needed for this change of state from a liquid to a gas is known as the **latent** heat of vaporisation.

In this section, we will learn about:

- the energy transfer during changes of state; and
- what happens during changes of state.

Word Alert

Latent: hidden; used to indicate that energy released or absorbed during a change of state does not result in a temperature change

Latent Heat and Specific Latent Heat

Latent heat L is the energy released or absorbed to change the state of a substance, at constant temperature.

There are two types of latent heat. For melting and solidification, there is the latent heat of *fusion*. For boiling and condensation, there is the latent heat of *vaporisation*.

The SI unit of latent heat is the **joule (J).**

Latent Heat of Fusion

When a substance is melting, energy is transferred to the substance through work done against the attractive forces between the particles. There is an increase in the potential energy of the particles but the kinetic energy of the particles remains unchanged. When solidifying, energy is transferred out of the substance which leads to a decrease in the potential energy of the particles but the kinetic energy of the particles remains unchanged. Hence, there is no temperature change when a substance is melting or solidifying.

Latent heat of fusion L_f is the amount of energy transferred to change a substance between the solid and liquid states, at constant temperature.

Specific Latent Heat of Fusion

The mass of a substance affects the latent heat. A large cup of ice cream has a greater mass and takes a longer time to melt than a small cup of ice cream. We say that the large cup of ice cream has a higher latent heat of fusion than the small cup of ice cream (Figure 10.11).

Figure 10.11 More energy is required to melt the large cup of ice cream.

In Section 10.1, we saw that specific heat capacity is more useful than heat capacity. Similarly, the amount of energy required to change the state of a *unit mass* of a substance (i.e. specific latent heat) is also more useful for calculations.

Specific latent heat of fusion l_f is the amount of energy transferred per unit mass of a substance to change between the solid and liquid states, at constant temperature.

$L_f = l_f m$ where L_f = latent heat of fusion (J)

l_f = specific latent heat of fusion (J/kg)

m = mass of substance (kg)

Latent Heat of Vaporisation

When a substance is boiling, energy is transferred to the substance through work done against the attractive forces between the particles. There is an increase in the potential energy of the particles but the kinetic energy of the particles remains unchanged.

Latent heat of vaporisation L_v is the amount of energy transferred to change a substance between the liquid and gaseous states, at constant temperature.

Tech Connect

A thermoelectric generator (TEG) is a small semiconductor device that can generate an electric current when energy is conducted through it. Also, if a reversed current passes through it, the direction of energy transfer will be reversed. Can you think of a possible use of the TEG in our hot climate?

- TEGs can generate electricity when non-useful energy such as the internal energy of a car's engine is transferred to them.
- In recent years, scientists have begun building TEGs that are thin, flexible and wearable. The purpose of these TEGs is to power electronic devices such as watches when energy from our body's internal store is transferred to the TEGs due to a temperature difference (Figure 10.12).

Figure 10.12 A TEG on a glove

Specific Latent Heat of Vaporisation

▶ **Specific latent heat of vaporisation** l_v is the amount of energy transferred per unit mass of a substance to change it between the liquid and gaseous states, at constant temperature.

▶ $L_v = l_v m$ where L_v = latent heat of vaporisation (J)
l_v = specific latent heat of vaporisation (J/kg)
m = mass of substance (kg)

Helpful Note

l_v is generally higher than l_f because changing from a liquid to a gas involves a much larger increase in volume than changing from a solid to a liquid. Hence, more energy is transferred to the substance as there is greater work done against the forces of attraction between the particles.

Worked Example 10D

Figure 10.13 shows a set-up used to find the specific latent heat of fusion of water. When the ice cubes start to melt, the heater is turned on and the reading on the electronic balance is 30.0 g. After two minutes, the reading on the weighing scale is 68.0 g. The heater supplies energy at a rate of 100 W.

(a) Why must the ice be melting before starting the measurement?

(b) Find the specific latent heat of fusion of ice.

(c) Other than the heater, state another source that transfers energy to the ice cubes.

(d) Explain how the measurements can be made more accurate.

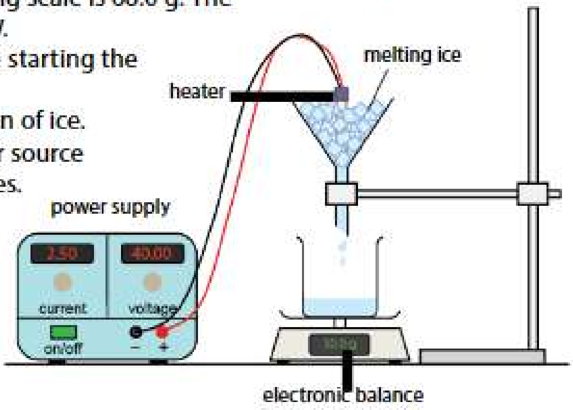


Figure 10.13

Thought Process
Specific latent heat of fusion is related to the processes of changing between solid and liquid states.

Answer

(a) When the ice cubes are just taken out of a freezer, their temperature is below 0 °C and thus has not reached the melting point. The ice needs to be melting when measuring the specific latent heat of fusion.

(b) Given: mass of ice cubes m = 30.0 g
Let the specific latent heat of fusion of water be l_f.
Assume that the energy transferred to melt the ice comes only from the heater:

$$\text{Energy from the heater} = m \times l_f$$
$$\text{Power} \times \text{Time} = (0.068\text{ kg} - 0.030\text{ kg}) \times l_f$$
$$100\text{ W} \times (2 \times 60)\text{ s} = 0.038 \times l_f$$
$$l_f = 316\text{ kJ/kg}$$

(c) The surrounding warm air

(d) The ice cubes can be crushed so that there is a greater surface area in contact with the heater. This will reduce the amount of energy transferred to the air instead of the ice cubes. In addition, the top of the funnel can be covered with a plastic sheet to reduce the energy transfer from the heater to the air. The sides of the funnel can be wrapped with an insulating material to reduce energy transfer from the surroundings to the ice cubes by conduction.

Link

Chemistry
In Chemistry, we learn that matter can change from one state to another when it gains or loses energy. The particles of solids, liquids and gases have different amounts of kinetic energy and potential energy.

Link

Practical Workbook
Experiment 10C

What Happens During Heating and Cooling?

Figure 10.14 is useful in bringing many related concepts together to showcase various key concepts.

Looking at Figure 10.14 from the left to the right, we have a **heating curve**. It is a graph showing how temperature changes with time when a substance undergoes heating.

Looking at Figure 10.14 from the right to the left, we have a **cooling curve**. It is a graph showing how temperature changes with time when a substance is cooled.

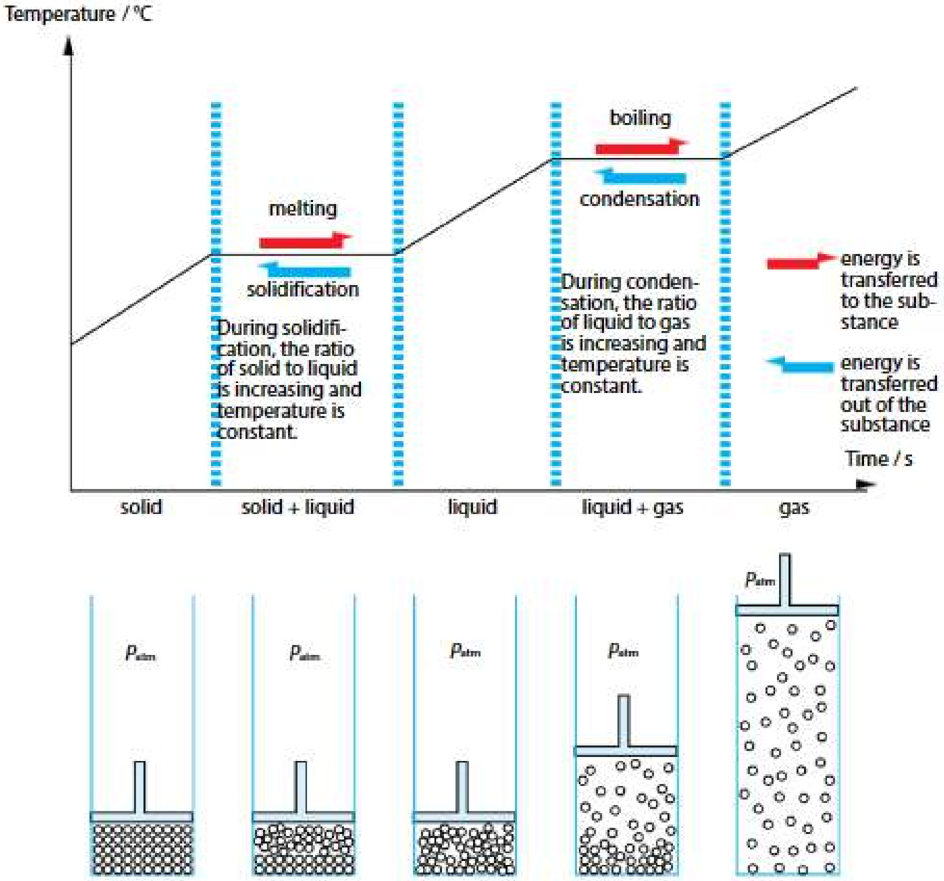


Figure 10.14 How the temperature of a substance and its arrangement of particles change during heating or cooling

Disciplinary Idea

Microscopic models can explain macroscopic phenomena.

The temperature of a body rises with the average kinetic energy of the particles in the body and vice versa.

When a body changes state at a constant temperature, latent heat is absorbed or released. This is linked to changes in the forces of attraction between the particles. Kinetic energy of the particles remains the same.

The state of the body is dependent on the forces between the particles, how far apart they are, and the motion of the particles.

Helpful Note

The temperature of a body rises with the average kinetic energy of the particles in the body and vice versa.

The potential energy of the particles increases with average particle separation. (Think of the *stretched* springs between particles in the kinetic model in Figure 10.1)

Disciplinary Idea

Conservation laws constrain the changes in systems.

Internal energy changes when energy is transferred in or out of a system. There may be a change in temperature or a change of state.

The extent of the change in temperature or a change of state depends on the amount of energy transfer involved.

Heating Curve

Figure 10.15 shows the changes in the kinetic energy and potential energy of the particles when the substance is heated.

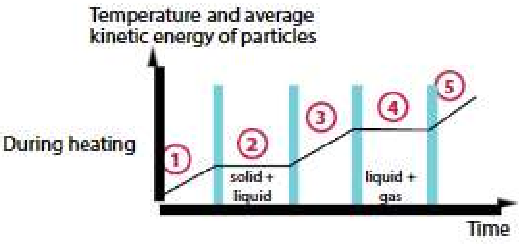


Figure 10.15 Changes in the kinetic energy of the particles of the substance when energy is transferred to the substance (The graphs only show general trends. Actual variation with time is affected by the specific conditions.)

①, ③ and ⑤

- During heating, energy transferred to the substance allows the particles to move faster and there is an increase in their kinetic energy.
- Temperature increases with the average kinetic energy, so the temperature increases.
- The potential energy of the particles increases with the increase in average separation of the particles.

② and ④

- During melting and boiling, energy transferred to the substance results in work done against the attractive intermolecular forces. The average separation of the particles increases and so the potential energy increases.
- However, the kinetic energy and temperature remain constant.

Cooling Curve

During cooling, the reverse happens. Figure 10.16 shows the changes in the kinetic energy and potential energy of the particles when the substance is cooled.

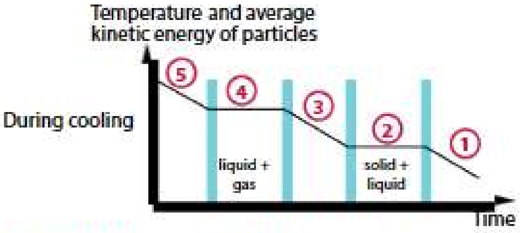


Figure 10.16 Changes in the kinetic energy of the particles of the substance when energy is transferred out of the substance (The graphs only show general trends. Actual variation with time is affected by the specific conditions.)

⑤, ③ and ①

- During cooling, energy is transferred out of the substance and the particles move slower. There is a decrease in their kinetic energy.
- The temperature of the substance decreases.
- The potential energy of the particles decreases as the average separation of the particles decreases.

④ and ②

- During condensation and solidification, energy is transferred out of the substance. The average separation of the particles decreases and so the potential energy decreases.
- However, the kinetic energy and temperature remain constant.

Internal energy = Total kinetic energy of particles (increases with temperature) + Total potential energy of particles (increases with distance between the particles)

The internal energy of the substance *increases* when it is heated.
The internal energy of the substance *decreases* when it is cooled.

Let's Practise 10.3

1 A hot gas is kept inside a container fitted with a frictionless piston (Figure 10.17).

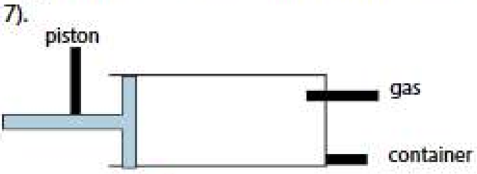


Figure 10.17

As the gas is cooled, it condenses into a liquid. Upon further cooling, it eventually turns into a solid.

(a) Draw a graph to show how the temperature of the substance in the container changes with time as it changes from a gas to a solid.
(b) Label the portions of the graph where the substance is in the solid, liquid and gaseous states.
(c) Label the portion of the graph where the substance is a mixture of solid and liquid.

2 Material X has specific latent heat of fusion of 500 J/g. Material Y has specific latent heat of fusion of 400 J/g. Assume that both materials have the same melting point of −2 °C and their other thermal properties are the same.
Which material is better for making ice packs to keep food fresh? Explain your choice.

Link

Theory Workbook
Worksheet 10C
Let's Assess
Let's Reflect

Cool Career

Thermal Engineer

A thermal engineer specialises in systems that involve the transfer of energy by heating. The job could include designing, constructing, maintaining and operating such systems. These systems can be as large as a power generation plant. They can also be smaller systems such as a combustion engine, a household air conditioning system or the heat management components in a mobile phone.

Depending on the type of system, the thermal engineer will also have to master software and hardware tools for measuring and tracking a system's performance. They need to have good knowledge of the thermal properties of materials (Figure 10.18). For very large systems, they may have to work with engineers and people from other fields of work.

Figure 10.18 A thermal engineer needs to understand the systems that control the transfer of energy by heating and the thermal properties of materials.

Let's Map It

Thermal Properties of Matter

is linked to the

Internal energy Q

is defined as The sum of the total kinetic energy and total potential energy of particles in the system.

is related to

Heat capacity C

$Q = C\Delta\theta$
where
$\Delta\theta$ = change in temperature

Specific heat capacity c

$Q = mc\Delta\theta$
where
m = mass of substance
$\Delta\theta$ = change in temperature

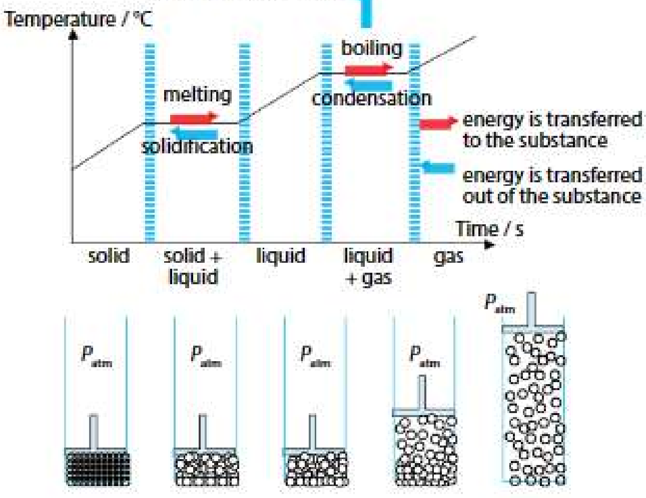
is different in

Different states of matter

Changes of state

Solid ← Solidification / Melting → **Liquid** ← Condensation / Boiling / Evaporation → **Gas**

can be shown using heating or cooling curves



depends on

Latent heat and specific latent heat

for changes from solid state to liquid state

Latent heat of fusion
$L_f = m\ell_f$
where
L_f = latent heat of fusion
m = mass of substance
ℓ_f = specific latent heat of fusion

for changes from liquid state to gaseous state

Latent heat of vaporisation
$L_v = m\ell_v$
where
L_v = latent heat of vaporisation
m = mass of substance
ℓ_v = specific latent heat of vaporisation

Let's Review

Section A: Multiple-choice Questions

1 Which of the following correctly describes what happens during a change of state?

○ **A** The average kinetic energy of the particles changes.
○ **B** The average potential energy of the particles is constant.
○ **C** The substance is in a mixture of two states.
○ **D** The temperature changes.

2 Which properties of a material make it ideal as a cold pack to keep food cold?

	Specific Heat Capacity	Specific Latent Heat of Fusion
○ **A**	high	high
○ **B**	high	low
○ **C**	low	low
○ **D**	low	high

3 Which of the following correctly describes the evaporation of a puddle of water?

○ **A** The average kinetic energy of the particles in the liquid increases.
○ **B** The process does not require energy transfer to the liquid.
○ **C** The process is faster when the air has higher humidity.
○ **D** The process is faster when the atmospheric pressure is higher.

4 Under the same environmental conditions, a substance with a higher latent heat of fusion ________

○ **A** requires a higher temperature to melt
○ **B** requires less energy transfer to change its state
○ **C** requires more energy transfer to change its temperature
○ **D** will melt slower

Section B: Structured Questions

For questions 1 to 4, you may use the following data:

- Specific heat capacity of ice = 2.1 J/(g K)
- Specific heat capacity of water = 4.2 J/(g K)
- Specific latent heat of fusion of water = 334 J/g
- Specific latent heat of vaporisation of water = 2260 J/g

1 A steam generator transfers energy to water by heating to produce steam at 100 °C for ironing clothes. If 250 g of water at an initial temperature of 25 °C was turned into steam:

(a) calculate the energy transferred to the water; and
(b) calculate the increase in the energy in the internal store when 250 g of water at 100 °C is changed into the gaseous state.

2 A paper cup contains 200 g of water at 30 °C. 40 g of ice cubes at –10 °C are added to the water. Assume that all energy transfers are between the ice and the water only. Determine the final temperature of the water after all the ice has melted.

3 A water heater transfers energy to the water at a rate of 3.5 kW. If cold water enters and leaves the heater at a rate of 90 g per second, calculate the increase in temperature of the water.

4 1 g of steam at 100 °C condenses on a 250 g steel plate at a temperature of 30 °C. The specific heat capacity of steel is 0.46 J/(g K). Assume that all energy transfers are between the steam and plate only.

(a) Calculate the energy transferred to the plate when the steam has fully condensed.
(b) Calculate the final temperature of the plate when the condensed water reaches thermal equilibrium with the plate.

(c) Calculate the ratio of energy contributed by the steam to that contributed by the hot condensed water in heating the plate.

(d) Based on your answer in (c), compare the dangers of coming into contact with 1 g of boiling water and 1 g of steam.

5 As a substance is heated, it goes through five stages, P, Q, R, S and T, as shown in Figure 10.19.

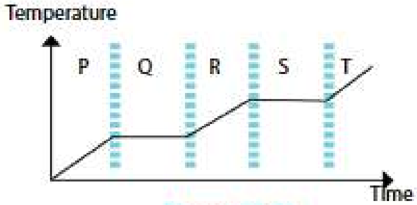


Figure 10.19

(a) Identify the stage(s) when the energy in the kinetic store of the particles is constant.

(b) State whether the internal energy is increasing, decreasing or constant in each of the five stages.

(c) Identify **three** stages when the substance is not in a mixture of different states.

(d) Identify the stage when the substance undergoes the largest increase in volume.

Section C: Free-response Questions

1 A liquid is split equally into two beakers. The first beaker is left on a table to evaporate while the liquid in the second beaker is brought to a boil.

(a) Describe how the molecules in the first beaker escaped from the liquid.

(b) State **three** differences between evaporation and boiling.

(c) Suggest **one** way to increase:

(i) the rate of evaporation; and

(ii) the rate of boiling.

2 Many cultures around the world have firewalking rituals. Participants would walk barefoot across hot coals.

(a) Participants gathered around the patch of coal will become sweaty. Explain how this helps to protect their feet from the heat of the coals.

(b) Explain how the conductivity of air plays a part in protecting the feet of the participants.

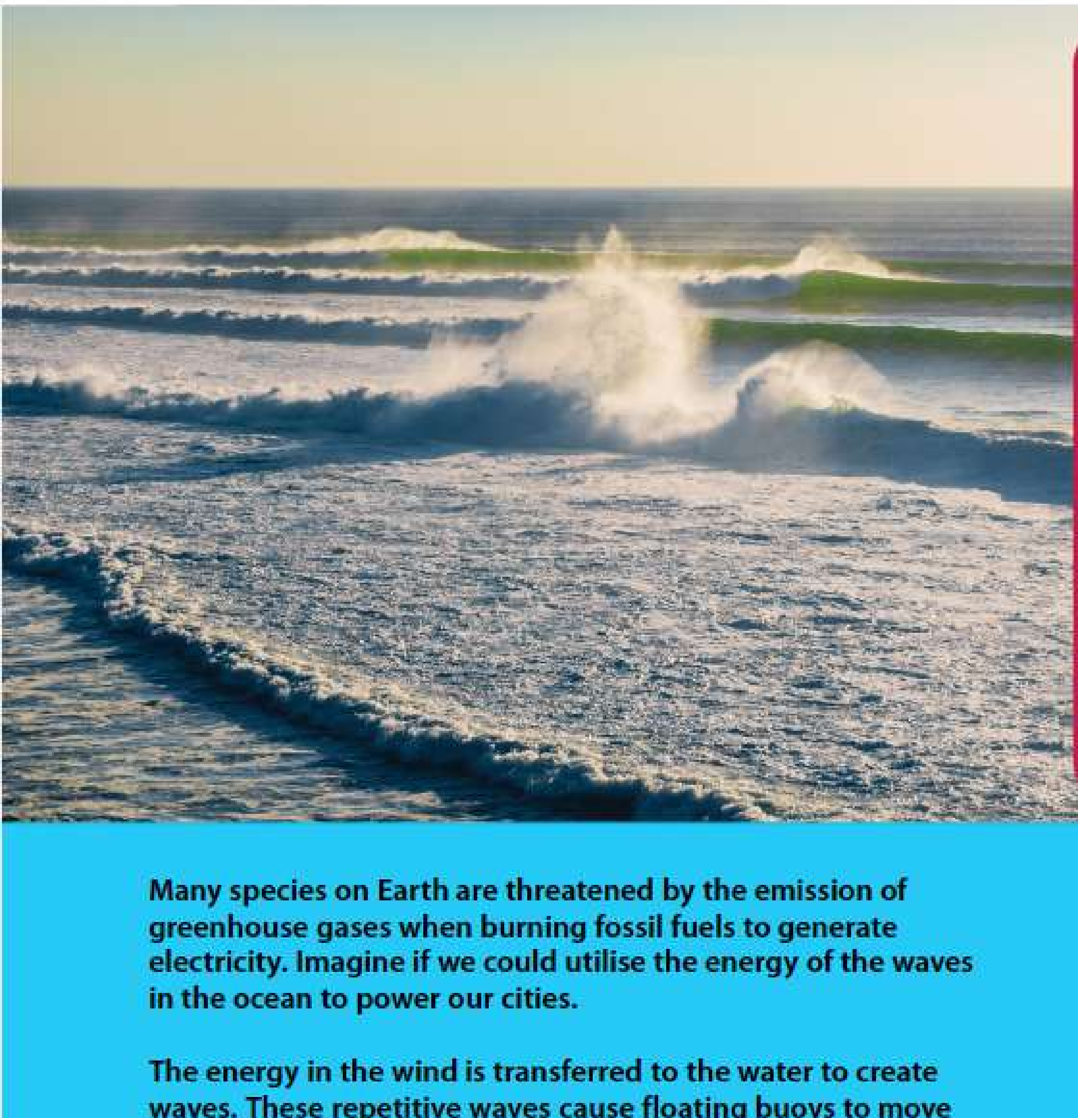
Link

Theory Workbook
Revision Worksheet 3

CHAPTER

11

General Wave Properties I: Introduction



What You Will Learn

- How can we describe wave motion?
- How can we describe the characteristics of waves?

Many species on Earth are threatened by the emission of greenhouse gases when burning fossil fuels to generate electricity. Imagine if we could utilise the energy of the waves in the ocean to power our cities.

The energy in the wind is transferred to the water to create waves. These repetitive waves cause floating buoys to move up and down with the waves. The energy from the up and down motion of the buoys can then be transferred to a rotating turbine to produce electricity.

How does the up-and-down motion of the buoys transfer energy to drive the turbine? What does this tell us about the properties of waves?

11.1 How Can We Describe Wave Motion?

Learning Outcomes

- Describe what is meant by wave motion as illustrated by vibrations in ropes and springs and by waves in a ripple tank (including use of the term wavefront).
- Show an understanding that waves transfer energy without transferring matter.

Waves are often used to explain physical phenomena, such as light and sound. On the previous page, we saw an example of a wave — water waves. Before we can understand complex water waves, we need to understand a basic family of waves called sinusoidal waves. One way to represent this is shown in Figure 11.1.

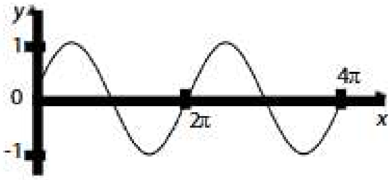
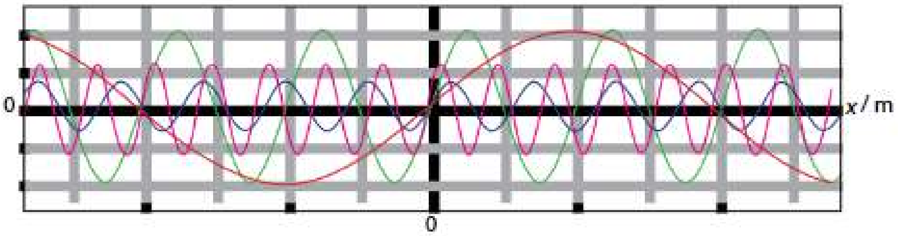


Figure 11.1 A sine wave

By adding simple sinusoidal waves, complex waves can be constructed (Figure 11.2).



The result of adding all the above waves:

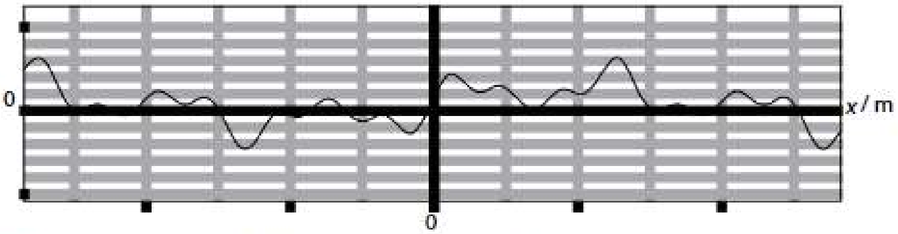


Figure 11.2 Complex waves created from adding many simple sine waves

An example in which simple waves are added to generate a complex wave occurs in a synthesiser. In a synthesiser, sound waves (covered in Chapter 12) are added in chosen proportions to create a new sound. Sinusoidal sound waves can also be combined to cancel each other out, such as in noise-cancelling headphones.

Word Alert

Waves: refers to many cycles of wave motion or just a single cycle

Tech Connect

To pick up a small bead, we usually need a tool such as a pair of tweezers. Now scientists are able to use sound waves to levitate and move small objects like a bead or a small screw (Figure 11.3).

This new capability is not just for amusement as it has practical applications. For example, the technology allows scientists to study the mixing of different chemical droplets without the constraint of a container. Engineers are also trying to use the technology for the assembly of tiny parts in a manufacturing process. Can you think of other uses for such technology?

Figure 11.3 A bead floats in air due to sound waves.

Examples of Waves

Water Waves

Waves can be produced in water using a ripple tank and a wave generator.

Figure 11.4 Water ripples are waves that can be created by dropping a small ball bearing onto a still water surface.

You may notice that the water waves or water ripples shown in Figure 11.4 are not equally spaced. For systematic studies, regular waves are needed. Regular waves are produced by a wave generator (Figure 11.5).
The electrically powered device has a dipper driven by a motor.

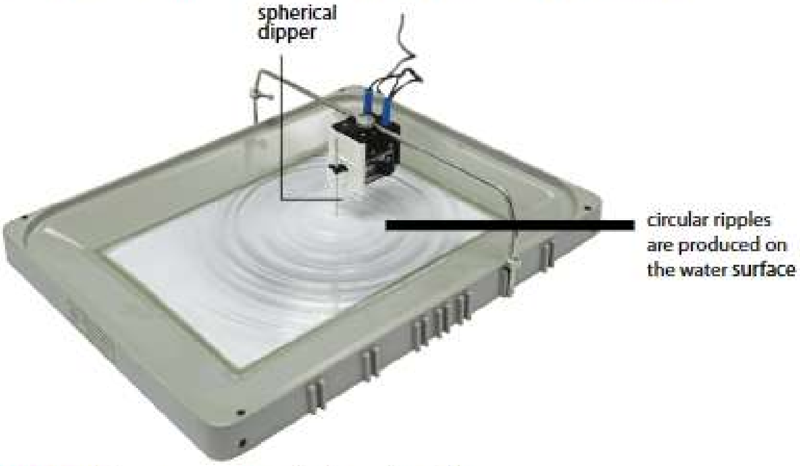


Figure 11.5 Using a wave generator to create water waves

Disciplinary Idea

Conservation laws constrain the changes in systems.

The total energy transfer by propagation of waves cannot exceed the energy input from the wave source.

Waves on a Rope

Waves can also be created using a rope. In Figure 11.6, one end of the rope is fixed to a wall. The other end is moved *repeatedly* and *regularly* in a direction that is perpendicular to the rope.

Figure 11.6 Wave on a rope with one end fixed a long distance away and the other end being moved repeatedly and regularly

The direction in which the wave shape (or wave profile) moves is the *direction of the wave*. In Figure 11.6, the wave's direction is towards the fixed end (i.e. moves towards the right). Within the wave, each particle's motion is perpendicular to the wave's direction. Here, the rope is the **medium** through which the wave moves.

Word Alert

Medium: the substance or material which carries the wave

The wave in Figure 11.6 will travel or propagate to the right just like how the disturbance on the water surface spreads away from the source. To create more regular waves, we use a wave generator (Figure 11.7).

Disciplinary Idea

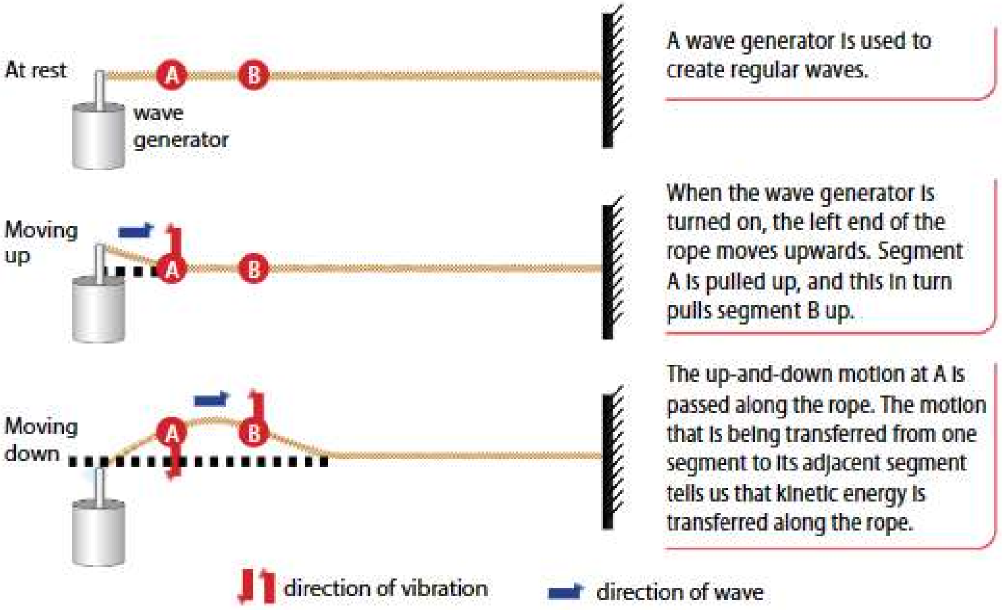
Matter and energy make up the Universe.

The waves created by the wave generator involve the motion of matter and possess kinetic and potential energy.

Disciplinary Idea

Waves can transfer energy without transferring matter.

In waves, energy is transferred in the direction which the wave travels in. Some waves travel through matter such as water and air. Electromagnetic waves travel through a vacuum.



A wave generator is used to create regular waves.

When the wave generator is turned on, the left end of the rope moves upwards. Segment A is pulled up, and this in turn pulls segment B up.

The up-and-down motion at A is passed along the rope. The motion that is being transferred from one segment to its adjacent segment tells us that kinetic energy is transferred along the rope.

Figure 11.7 Wave propagates along a rope because neighbouring segments are connected so there is transfer of energy from one particle on the rope to the next.

Note that segments A, B and all subsequent segments do not move along the rope. There is no transfer of matter along the rope. For any segment on the rope, its motion is described as cyclical or periodic because after moving up and down, it returns to its original position.

From our observations of the different types of waves, we can see that:

► A **wave** is a disturbance that propagates through space, transferring energy with it but not matter.

Waves on a Spring

A spring with a fixed end can be stretched on the floor. Besides moving the free end up and down like the wave on a rope, we can push and pull the free end of the spring rapidly, to create the waves in Figure 11.8. The waves travel along the spring and move towards the fixed end. The direction moved by the waves is parallel to the direction of the hand motion.

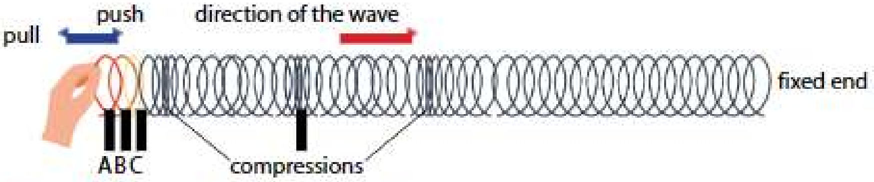


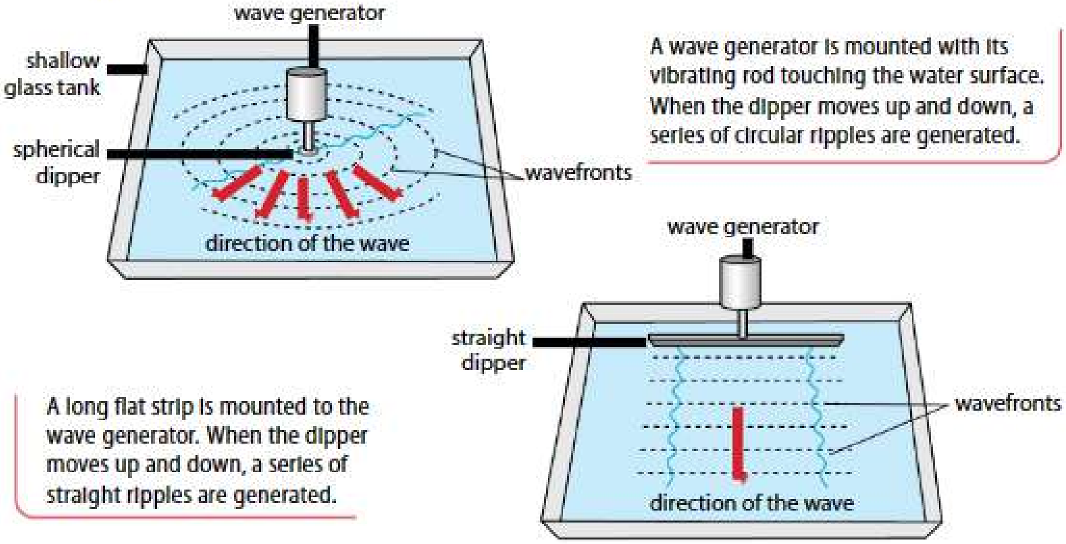
Figure 11.8 The periodic push and pull at one end creates compressions which travel along the spring.

If we focus on a single segment of the spring, for example, A, it is in a cyclical or periodic motion. This motion is transferred to the adjacent segments B, then C, and towards the fixed end.

While the waves in the rope and the spring do not have the same appearance, there are similarities between the waves. How is the cyclical or periodic motion of a segment in the spring similar to that of a segment in the rope?

Water Waves in a Ripple Tank

A ripple tank is a set-up to demonstrate the basic properties of water waves. A shallow glass tank of water is placed below a wave generator connected to a dipper (Figure 11.9). When the dipper touches the water surface, circular waves are produced. The imaginary line that joins all adjacent points on the wave that are in phase, such as the crests, is called a **wavefront**.



A wave generator is mounted with its vibrating rod touching the water surface. When the dipper moves up and down, a series of circular ripples are generated.

A long flat strip is mounted to the wave generator. When the dipper moves up and down, a series of straight ripples are generated.

Figure 11.9 A ripple tank set-up to produce circular and straight ripples

From the examples of waves on a rope, spring and in a ripple tank, we can observe that the motion of any selected point in a wave is periodic and repetitive. This motion is known as a **vibration** or **oscillation**.

Let's Practise 11.1

1 Fill in the blanks.
A small leaf on a water surface moves up and down as a wave passes. The leaf maintains the same distance from the source of the wave. This shows that waves can carry ________ but not ________.

2 The motion of a small segment of the medium is the same when a wave passes through a rope, water or along a spring. How would you describe this motion?

Word Alert

Vibration / Oscillation: periodic and repetitive motion.

Link

Theory Workbook
Worksheet 11A

11.2 How Can We Describe the Characteristics of Waves?

Learning Outcomes

- Compare transverse and longitudinal waves and give suitable examples of each.
- Define and use the terms *speed*, *frequency*, *wavelength*, *period* and *amplitude*, including graphical representation.
- Recall and apply the relationship *speed of wave* = *frequency* × *wavelength* to new situations or to solve related problems.

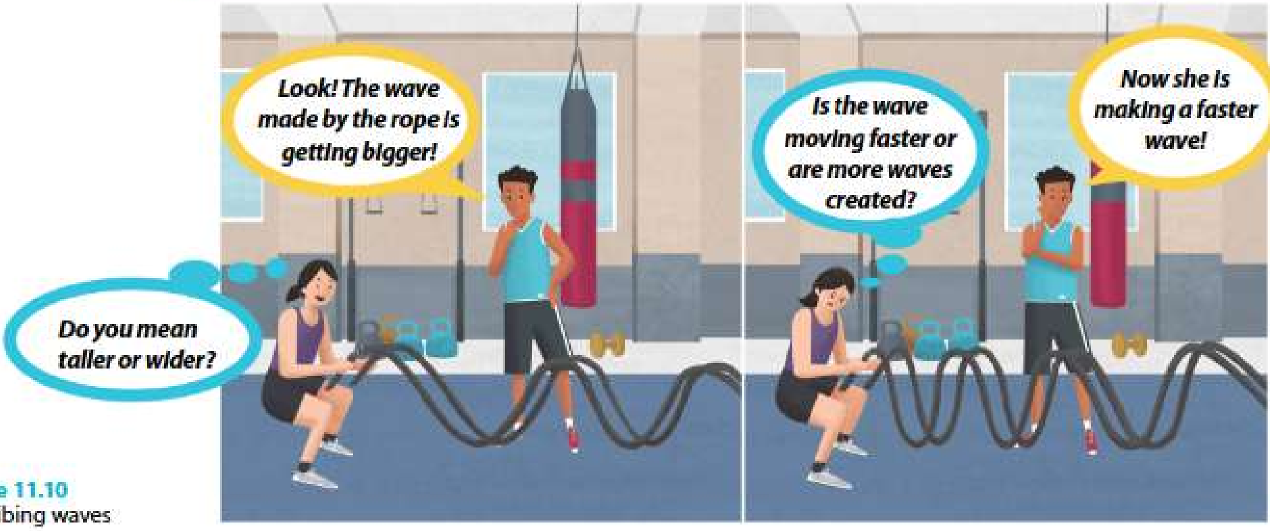


Figure 11.10 Describing waves

To avoid confusion when describing waves, we must use the correct terms to describe waves (Figure 11.10).

Types of Wave Motion

Waves can be described as transverse or longitudinal. Each of these has its own set of characteristics. We can illustrate these using a stretched spring.

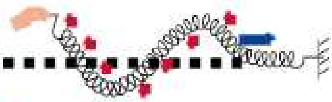


Figure 11.11 For a transverse wave, the vibration of the spring is perpendicular to the wave motion.

A **transverse** wave has a direction of vibration that is *perpendicular* to the direction of wave travel (Figure 11.11).

Some examples of transverse waves are light waves and a vibrating guitar string when plucked.

Figure 11.12 For a longitudinal wave, the vibration of the spring is parallel to the wave motion.

A **longitudinal** wave has a direction of vibration that is parallel to the direction of wave travel (Figure 11.12).

Some examples of longitudinal waves are sound waves and certain waves of an earthquake. Of the waves illustrated in Section 11.1, do you know which one is also a longitudinal wave?

Basic Characteristics of Waves

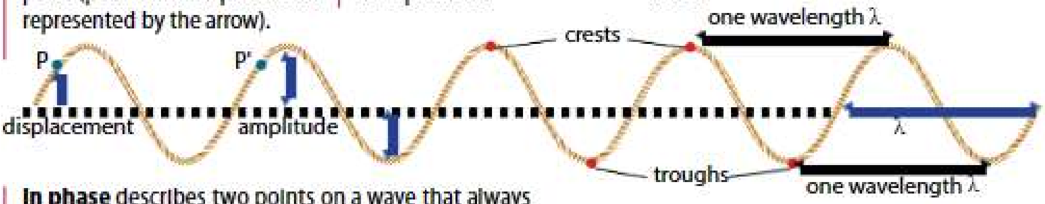
Figure 11.13 shows a transverse wave on a rope. The free end is moved up and down rapidly. We can fully describe the wave by defining the various characteristics of the wave.

Displacement of any point on the wave is a vector pointing from its rest position to the point (point P has displacement represented by the arrow).

Amplitude of a wave is its maximum magnitude of displacement from its rest position.

Crests are the highest points of a transverse wave.

Troughs are the lowest points of a transverse wave.



In phase describes two points on a wave that always have the same direction of motion (moving in step). For example, P and P' are in phase. All crests on a wave are always in phase. All troughs on a wave are always in phase.

Wavelength λ is the shortest distance between two successive crests or troughs.

Figure 11.13 Wave on a rope and some of its defining characteristics

Helpful Note

The wavelength can also be defined as the shortest distance between two **successive** crests or two **successive** troughs.

The dotted line indicates the rope's resting position before the wave was created.

The shape of the wave is called the **waveform**.

Link

Recall from Chapter 2: Displacement is a vector quantity.

Two points along a wave are said to be in phase if they are at the same stage in a cycle. This implies that they always have the same direction of motion.

Let's take a look at the moon as an example. The moon goes through different phases in each cycle of 28 days (Figure 11.14). Similarly, for the wave on a rope in Figure 11.15, we can see that point 1 goes through different phases in each cycle of motion. Each phase in a cycle corresponds to a distinct combination of direction, speed and position.

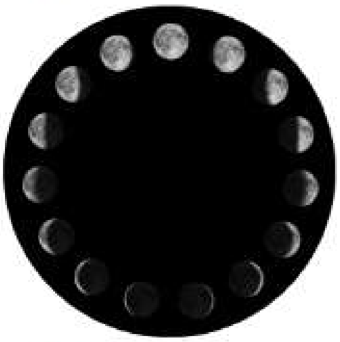


Figure 11.14 The different phases of the moon

As the wave travels to the right, we observe that points 1 and 3 will always be in the same phase. Points 1 and 3 are said to be moving in phase.

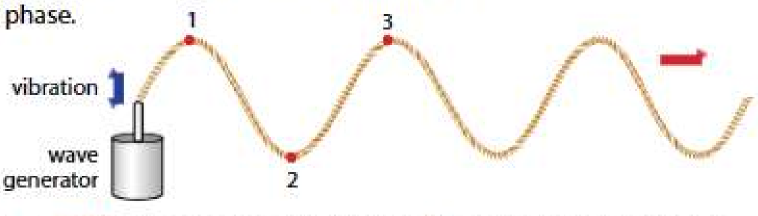


Figure 11.15 Points 1 and 2 are out of phase while points 1 and 3 are in phase.

Points 2 and 3, while taking the same time to complete each cycle, are always in opposite directions or completely out of step. Points 2 and 3 are said to be completely out of phase.

Displacement–Distance Graph

The illustration of a wave on a rope is an equivalent of a graph of displacement against the distance from the source (Figure 11.16). This graph describes the displacement of all particles relative to their rest position, at a particular instant in time.

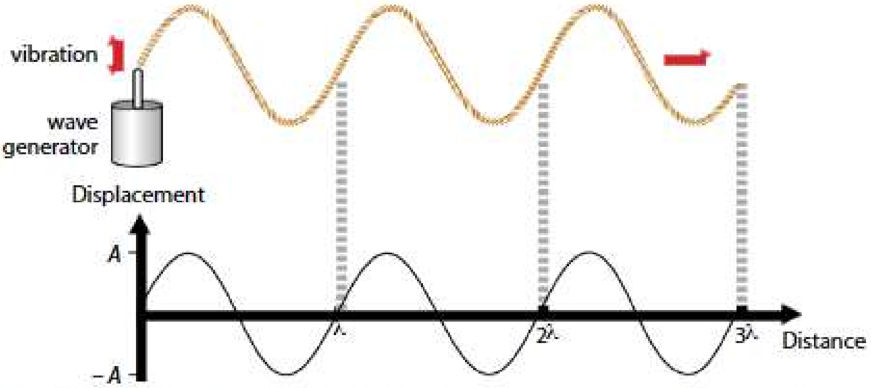


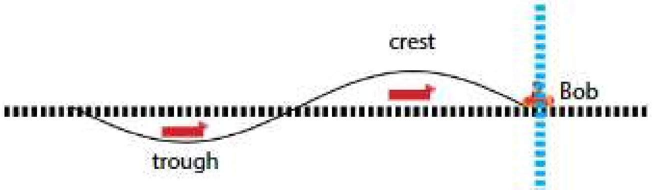
Figure 11.16 Displacement–distance graph of the rope wave at a particular instant in time

From the displacement–distance graph, we can deduce the displacement of each point, amplitude, the crests and troughs, and wavelength of the wave.

Displacement–Time Graph

Waves can also be described using displacement–time graphs.

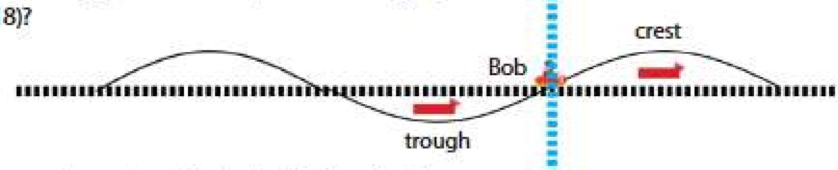
Imagine that Bob is on the surface of the sea when water waves move towards him from left to right (Figure 11.17). As the crest of the wave approaches Bob, is he moving up or down?



Note: Diagram is not drawn to scale.

Figure 11.17 Water wave at sea at an instant in time ($t = t_0$)

As the wave moves to the right, Bob will be moving up and down but not sideways. After the passing of the peak and as the bottom of the wave approaches Bob, is he moving up or down (Figure 11.18)?



Note: Diagram is not drawn to scale.

Figure 11.18 Water wave at sea at another instant in time ($t = t_1$)

As the wave propagates, we track Bob's vertical displacement at a fixed horizontal position. This allows us to describe how the wave's displacement varies with time.

From the moment Bob first met the water wave until the passing of two complete waves, his displacement–time graph is as shown in Figure 11.19.

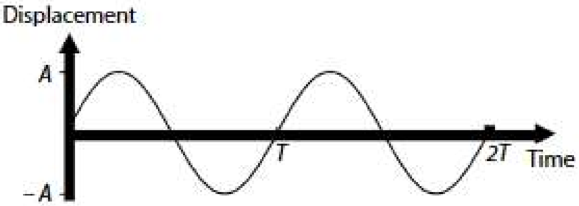


Figure 11.19 Displacement–time graph for a fixed point on the wave (in this case, Bob's location).

The displacement–time graph describes the displacement of Bob relative to his rest position over a time interval. From the displacement–time graph, we are able to deduce the period, and hence the frequency.

Relationship Between Period, Wave Speed, Frequency and Wavelength

▶ The **period T** is the time taken by each point on the wave to complete one oscillation.

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 one wavelength.

▶ The **frequency f** is the number of oscillations each point completes per second.

Its SI unit is the **hertz (Hz)**.

▶ The **wavelength λ** is the shortest distance between two successive crests or troughs.

Its SI unit is the **metre (m)**.

The frequency of a wave is also the number of crests (or troughs) that go past a point per second. Frequency and period are related by this equation:

▶ $f = \frac{1}{T}$

In Figure 11.20, three wave cycles are produced and move away from the source in 1 s.

Figure 11.20
Frequency $f = 3$ Hz
Period $T = \frac{1}{3}$ s.

▶ **Wave speed v** is the distance travelled by a wave per second.

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

Recall that speed $= \frac{\text{distance}}{\text{time}}$. Since every crest advances by one wavelength in one period T, the speed of the wave is given by:

▶ $v = \frac{\lambda}{T}$

where v = wave speed (m/s)
λ = wavelength (m)
T = period (s)

Since $f = \frac{1}{T}$, $v = f\lambda$.

In Figure 11.20, the wavelength of the wave is 0.5 m.
Wave speed $v = 0.5 \div (\frac{1}{3}) = 1.5$ m/s

To conclude, the relationship between v, f and λ is $v = f\lambda$.

Helpful Note

It is important to remember that the speed of waves is determined by the properties of the medium and not the frequency.

Link

You will learn that for the same medium, waves of different frequencies can have different speeds in Chapter 14.

The wave speed v is determined by the *properties of the medium*. For example, the wave speed on a rope is determined by factors like the tension and thickness of the rope. Therefore, for a wave that stays in the same medium, v is fixed. The equation $v = f\lambda$ tells us that if the frequency f of the wave generator is increased, λ will decrease.

Sometimes, a wave can travel into a different medium and its speed in the new medium can be higher or lower. However, the frequency of the wave will always remain the same as a wave travels from one medium to another. If the wave travels to a different medium such that v decreases, then λ will decrease since f remains the same.

Let's look at Figure 11.21 to understand why the frequency of the wave remains the same as a wave travels from one medium to another. In Figure 11.21, the wave is travelling along a rope made up of two sections of different materials.

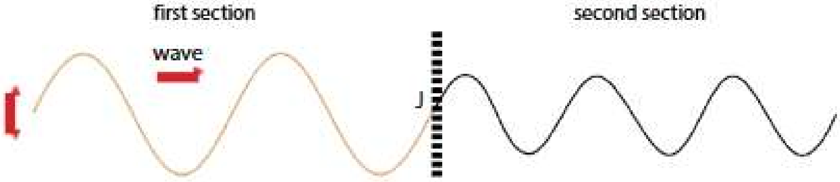


Figure 11.21 Wave traveling from one medium to another.

At point J where two sections of rope are joined, the oscillation of the first section is passed on to the next section. Hence, the frequency f of oscillation in the second rope must be the same as in the first rope.

Compare the wavelength in the second section to the first section and applying the formula $v = f\lambda$. Can you deduce whether the speed of the wave is smaller or greater in the second section?

Wavefronts

The speed of waves can also be deduced by observing the wavefronts.

A **wavefront** is an imaginary line joining all adjacent points that are in phase.

From the ripples produced in a ripple tank, the crests and troughs can be identified. Each continuous circle of a crest or trough forms a wavefront. By considering a particular point x on a crest and measuring how fast it travels away from the source, we can find the speed of the wave.

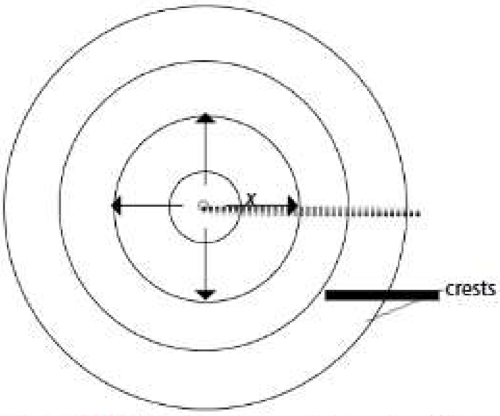


Figure 11.22 Wavefronts spreading outwards from the source

Let's Investigate 11A

Aim
To measure the speed of water waves

Procedure

1. Fill up a container with water until it is about half to three-quarters full (Figure 11.23). The length L of the container is from 30 cm to 50 cm.
2. When the water surface is still, dip a card into the water at one end of the container to create a single water wave.
3. Observe that a water wave is clearly visible as it is repeatedly reflected from sides B to A and from A to B of the container.
4. Start a stopwatch when the wave reaches side A of container. Record the time taken t for the wave to travel N times across the length L of the container. For instance, the wave will have travelled two times across the length L of the container if it travels from A to B, and from B to A.

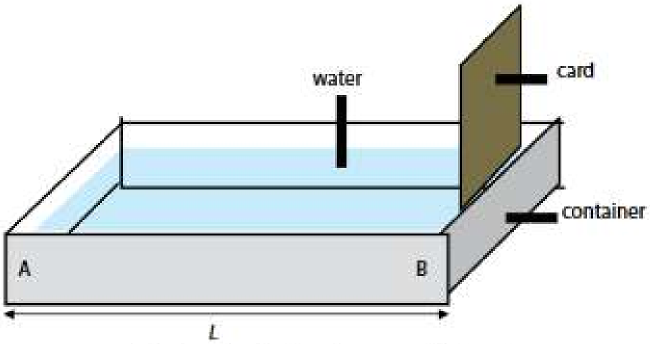


Figure 11.23 A set-up for finding the speed of a water wave

5. Calculate the speed v of the wave using the equation, $v = \frac{NL}{t}$.

Questions

1. Why is it a good practice to measure the time for multiple laps made by the wave?
2. How can you use the set-up to find out whether water waves travel faster in deeper water?

Link
Practical Workbook
Experiment 11A

Worked Example 11A

A source at a fixed location is producing a wave. The displacement of a particle on the wave varies with time as shown in Figure 11.24.

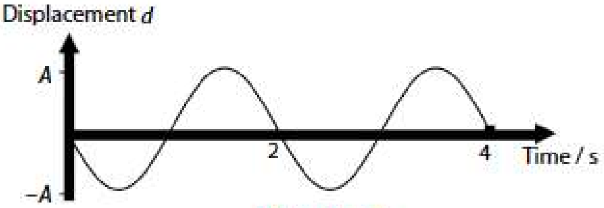
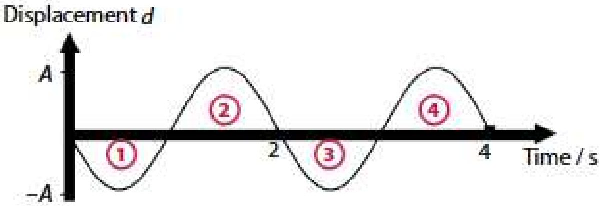


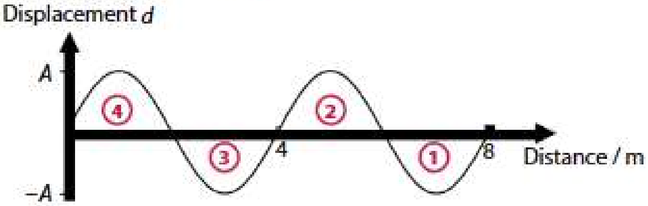
Figure 11.24

If the wave has a speed of 2 m/s, draw a graph of how the displacement of the particle varies with its distance from the source.

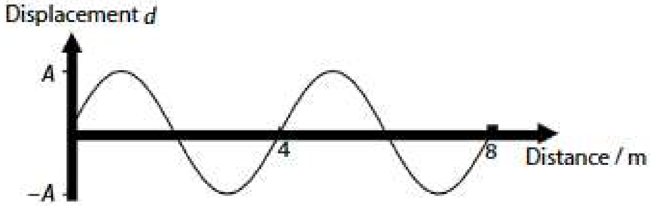
Thought Process
Step 1: Start with the known information — the wave speed is 2 m/s and has been travelling for 4 seconds.
Step 2: Make connections — the furthest that the wave has travelled must be speed × duration of wave generation = 8 m.
Step 3: Construct the graph — from the given graph, the wave started with increasing negative displacement then positive displacement and so on for two complete cycles.



Part ① is generated first, so it would have travelled the furthest from the source, followed by part ② and so on:



Answer



Worked Example 11B

The displacement–distance graph of a transverse wave moving to right is shown in Figure 11.25.

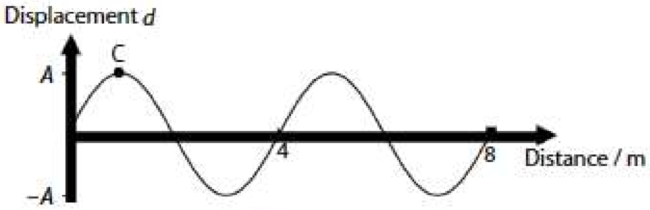


Figure 11.25

The speed of the wave is 0.50 m/s. For the given wave in Figure 11.26,

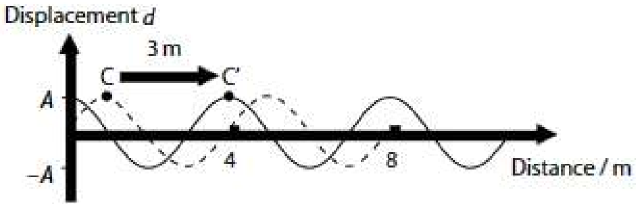
(a) find its frequency and period;
(b) draw its displacement–distance graph 6.0 s later; and
(c) draw the displacement–time graph for a particle at crest C in the next 6.0 s.

Answer

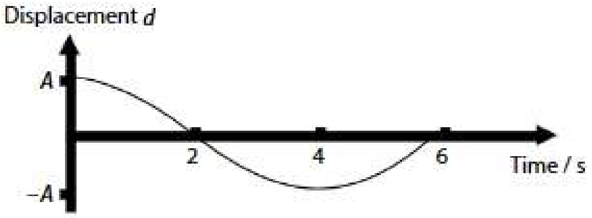
(a) Use $v = f\lambda$
Given $v = 0.50$ m/s and $\lambda = 4.0$ m from the graph,
$0.50 = f(4)$
$f = 0.125$ Hz

Period $T = \frac{1}{f}$
$T = \frac{1}{0.125}$
$T = 8.0$ s

(b) In 6.0 s, the wave will move to the right by a distance
$= vt$
$= (0.50)(6.0)$
$= 3.0$ m
That means that the crest C will now be at C'.



(c) As the wave moves to the right, the crest C will move down then up to the peak again in 8.0 s (1 cycle), but the graph should only show the displacement over 6.0 s.
That means only $\frac{3}{4}$ cycle:



Worked Example 11C

An earthquake at the ocean floor typically causes surface waves of a few metres (Figure 11.26). Big boats and ships at sea are not in danger. Given that the speed of water waves decreases with water depth,

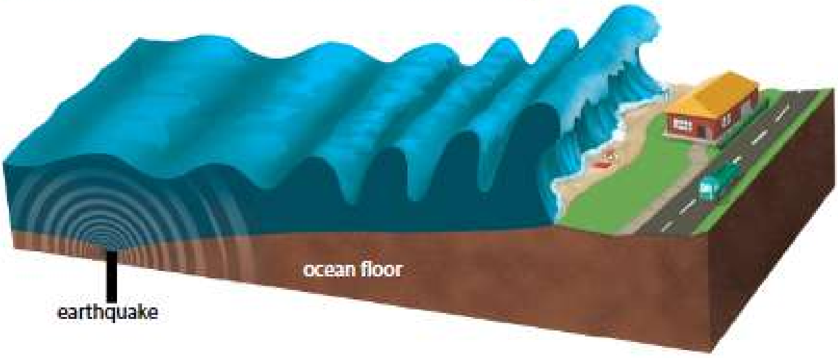


Figure 11.26

(a) explain what happens to the wavelength as the waves reach the shore.

(b) explain why the height of the waves increases as they reach the shore.

Answer

(a) Using $v = f\lambda$ and the fact that the frequency of a wave does not change from one medium to another, the wavelength must decrease as the waves approach the shore.

(b) The smaller wavelength means that the waves are "squeezed" as shown in Figure 11.26. Hence, the water and crests get pushed up higher. In terms of energy carried by the waves, the more closely packed waves are, the more energy is packed into a smaller area. Therefore, giant waves or tsunami waves are more destructive.

Note that surface waves are different from the water current, which is the movement of water due to wind and differences in water density due to temperature variations.

Helpful Note

Notice that explanations are often based on the following:

- Key concepts e.g. wavelength
- Equations or formulas
- Laws
- Facts e.g. constant f

Past to Present

In 1924, a scientist recorded brain waves using sensors attached to the scalp. The electromagnetic brain waves arise from electrical signals in the brain's neurons. As research continued, scientists discovered that different wave frequencies are associated with different mental states.

Ongoing research today and advancements in artificial intelligence have enabled scientists to more accurately associate different brain wave patterns to different mental states and thoughts. Consequently, they are able to read a person's brain waves to direct a robot to carry out some desired actions.

Let's Practise 11.2

1 Bob is on a float. When he meets a giant wave moving from left to right, his displacement–time graph is as shown in Figure 11.28.

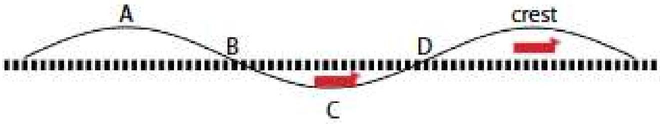


Figure 11.27

Which of the four positions **A**, **B**, **C** or **D** is Bob's starting position that corresponds to the graph in Figure 11.27?

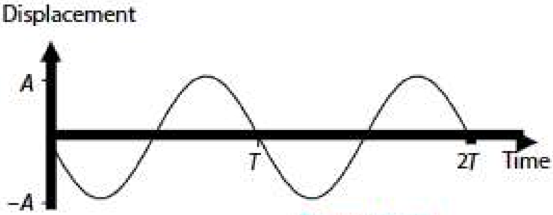


Figure 11.28

2 Figure 11.29 shows circular ripples created by a wave generator. Which of the distances 1, 2, 3 or 4 gives the wavelength?

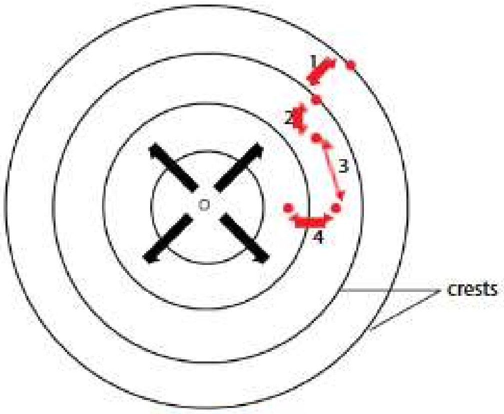
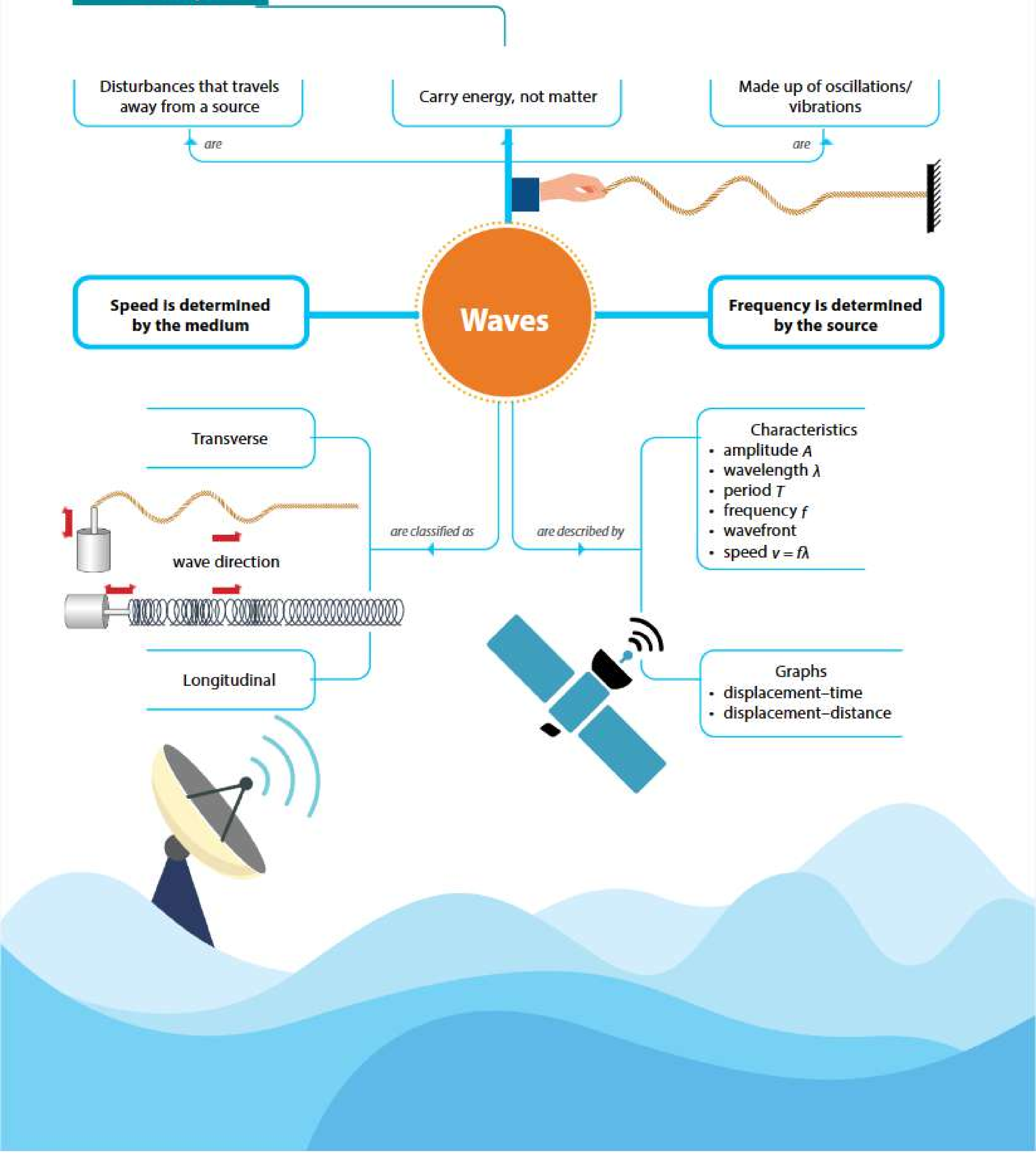


Figure 11.29

Link

Theory Workbook
Worksheet 11B
Let's Assess
Let's Reflect

Let's Map It



Waves

- *are* Disturbances that travels away from a source
- Carry energy, not matter
- *are* Made up of oscillations/ vibrations

Speed is determined by the medium

Frequency is determined by the source

are classified as

- Transverse
- Longitudinal

are described by

Characteristics
- amplitude A
- wavelength λ
- period T
- frequency f
- wavefront
- speed $v = f\lambda$

Graphs
- displacement–time
- displacement–distance

Let's Review

Section A: Multiple-choice Questions

1 For a wave with speed v, period T and wavelength λ, which of the following sets of values is correct?

	v / m/s	T / s	λ / m
○ **A**	30	0.1	3
○ **B**	9	3	20
○ **C**	5	2	8
○ **D**	2	1	4

2 For a wave with speed v, frequency f and wavelength λ, which of the following statements is correct?

○ **A** v is always proportional to f.
○ **B** v is always proportional to λ.
○ **C** v is inversely proportional to $\frac{1}{T}$.
○ **D** v is determined by the properties of the medium.

3 Figure 11.30 shows a graph of a wave.

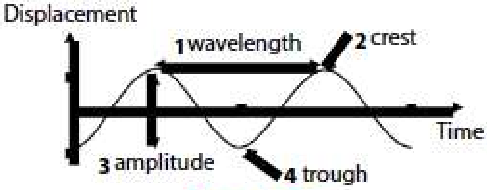


Figure 11.30

Which label(s) is/are correct?

○ **A** 1 and 3 only
B 2 and 4 only ○
○ **C** 1, 2 and 4 only
D All are correct. ○

4 Which of the following is **incorrect**?

○ **A** Amplitude is the distance between a crest and the rest position.
○ **B** In one period, a crest will move a distance of one wavelength.
○ **C** When the speed of a wave increases, its frequency must increase.
○ **D** A transverse wave has oscillations perpendicular to the wave direction.

5 Which of the following statements is **incorrect**?

○ **A** "In phase" describes two vibrations or oscillations that always have the same direction.
○ **B** A wavefront is an imaginary line joining all adjacent points that are in phase.
○ **C** A longitudinal wave has a direction of vibration that is parallel to the direction of wave travel.
○ **D** The particles making up the wave motion sometimes get transported away from the source.

Section B: Structured Questions

1 For each oscillation, a wave advances by 15 m in 3 s. Find:
(a) the wavelength;
(b) the speed of the wave; and
(c) the frequency of the wave.

2 A point in a wave has a displacement–time graph as shown in Figure 11.31.

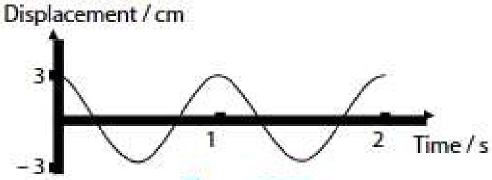


Figure 11.31

(a) If the speed of the wave is 0.50 m/s, draw the corresponding displacement–distance graph.
(b) Draw the displacement–time graph if the frequency of the wave is doubled.

3 The displacement–distance graph of a wave is shown in Figure 11.32.

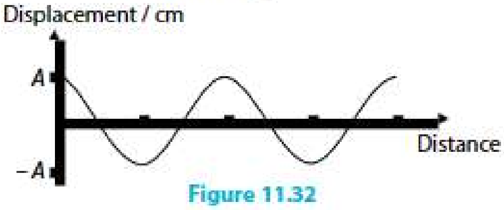


Figure 11.32

Draw its waveform $\frac{3}{4}$ of a period later.

4 (a) Describe what a wave motion is.
(b) Describe the difference between a transverse wave and a longitudinal wave.

5 A series of regularly spaced, outward spreading wavefronts is created by dipping the tip of a rod in and out of a water surface (Figure 11.33).

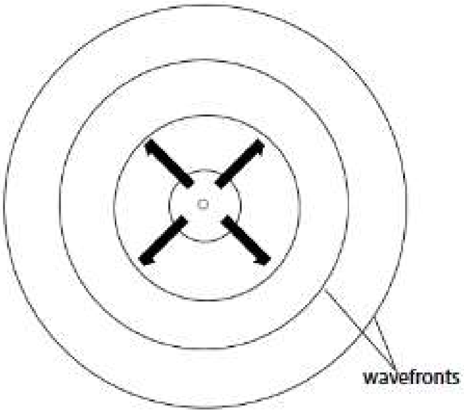


Figure 11.33

(a) Explain what a wavefront is.
(b) What is the shortest distance between two consecutive wavefronts known as?

Section C: Free-response Questions

1 In the two scenarios below, explain why each student's statement is **incorrect** and how you would rephrase it to be more accurate.
(a) A student states that a wavelength is the shortest distance between two crests.
(b) Another student states that a wave's amplitude is half the distance between a crest and a trough.

2 A wave travels to the right as shown in Figure 11.34.

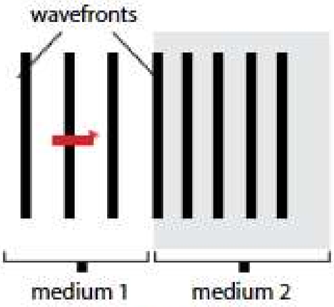


Figure 11.34

As the wave enters the second medium, state what happens to its:
(a) wavelength;
(b) frequency; and
(c) speed.

CHAPTER

12 General Wave Properties II: Sound

What You Will Learn

- What is sound?
- How do we relate loudness to amplitude and pitch to frequency?
- How is sound useful?

You may have seen the structure shown above on some rooftops. Do you know what it is?

This structure is a set of loudspeakers mounted on a pole. It is part of the Public Warning System from the Singapore Civil Defence Force. They can be found in various locations all over our island and serve a very important function. In case of an air raid or shelling, the speakers will sound an alarm signal so that we can be warned quickly to take refuge in shelters.

The speakers can produce three different sound signals — "alarm signal", "all clear signal" and "important message signal". By identifying the signal, we can take appropriate actions. This is one example of how sound is useful for communication. Can you think of what else sound is useful for?

12.1 What Is Sound?

Learning Outcomes

- Show an understanding that sound can be produced by vibrating sources and a medium is required for the transmission of sound.
- Describe the longitudinal nature of sound waves in terms of the processes of compression and rarefaction.

Disciplinary Idea

Waves can transfer energy without transferring matter.

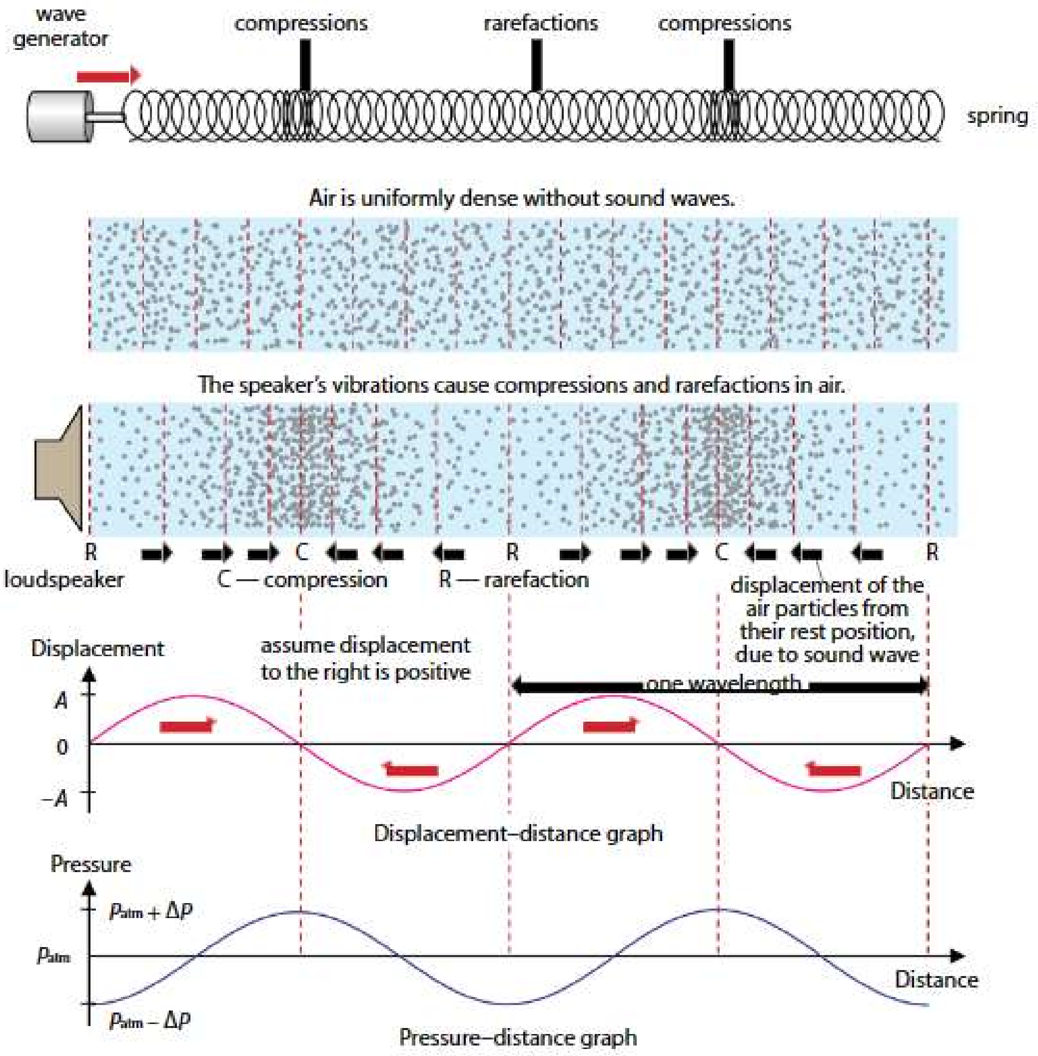
Longitudinal and transverse waves differ in the way that particles in the material medium vibrate in relation to direction of wave travel.

Disciplinary Idea

Matter interacts through forces and fields.

In mechanical waves, the oscillations of particles are due to forces of interaction between the particles.

Sound is a longitudinal wave travelling in the air, created by a vibrating source. The source of sound can be a person's voice box or a loudspeaker. A vibrating loudspeaker has a surface that is driven by a fluctuating electric current. Its forward and backward vibration is passed on to the air particles like how a spring is pushed and pulled repeatedly. This causes alternate regions of the air particles to be compressed and extended. The compressed regions are called **compressions** and the extended regions are called **rarefactions** (Figure 12.1).



A	is amplitude	Δp	means a pressure difference
p_{atm}	is atmospheric pressure	$p_{atm} - \Delta p$	is slightly lower than p_{atm}
$p_{atm} + \Delta p$	is slightly higher than p_{atm}		

Figure 12.1 Particulate view of a sound wave and its corresponding graphical representations

Link

Recall from Chapter 11: The speed of a wave is determined only by the medium's properties.

Having seen how sound waves travel through air, do you think sound waves can travel through other media such as water, the ground, rocks, and a vacuum?

Since a sound wave relies on the passing on of motion from a group of molecules to another group through collisions, it cannot propagate in a vacuum.

Worked Example 12A

The vertical lines in Figure 12.2(a) show a uniform mean spacing of the air particles without a sound wave. Figure 12.2(b) shows the varying spacing of the air particles when a sound wave is travelling through. Figure 12.2(c) shows the displacement-distance axes. The displacement d of layer x of air is shown in Figure 12.2(b).

(a) In Figure 12.2(b), label the regions of rarefactions with **R**.

(b) How does the air pressure at **R** compare to the atmospheric pressure?

(c) In Figure 12.2(c) using the axes provided, draw the displacement–distance graph corresponding to the sound wave in Figure 12.2(b). Specify which direction is taken to be the positive direction.

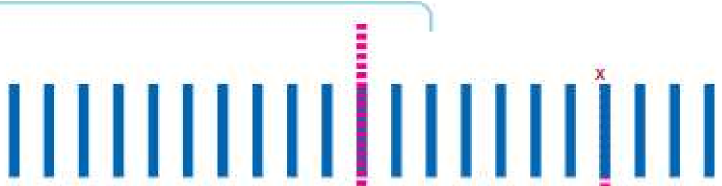


Figure 12.2(a) Mean spacing of air particles before the sound wave travels through

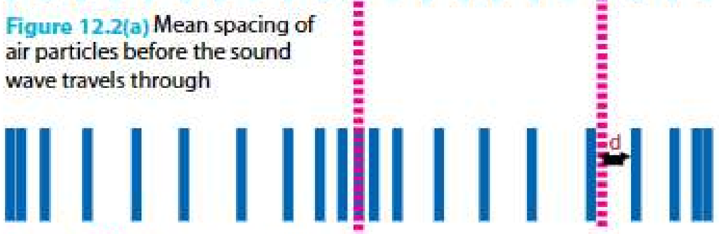


Figure 12.2(b) Mean spacing of air particles when the sound wave travels through

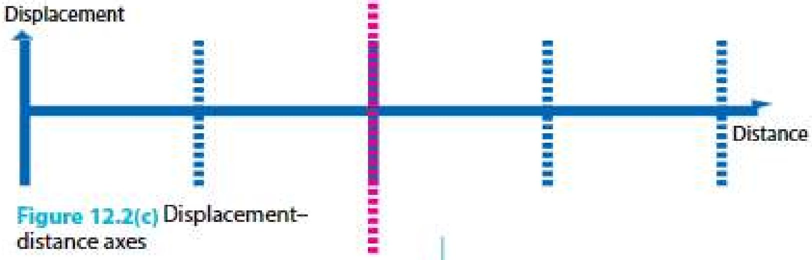
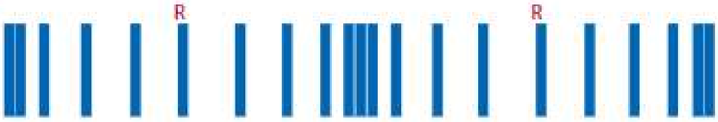


Figure 12.2(c) Displacement–distance axes

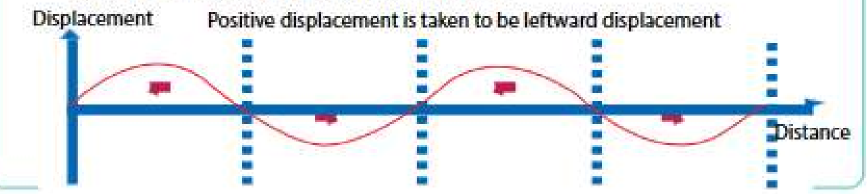
Answer

(a)



(b) The air pressure at **R** is slightly lower than normal atmospheric pressure.

(c) Note: To produce a rarefaction, the air particles must move further apart as indicated by the arrows below.



Worked Example 12B

An oscilloscope is a device that can display a displacement–time graph of the sound wave (Figure 12.3).

① Sound waves are directed to the microphone.

② Sound waves are translated to corresponding electrical signals by the microphone.

③ The waveform is displayed on the oscilloscope screen as a displacement–time graph.

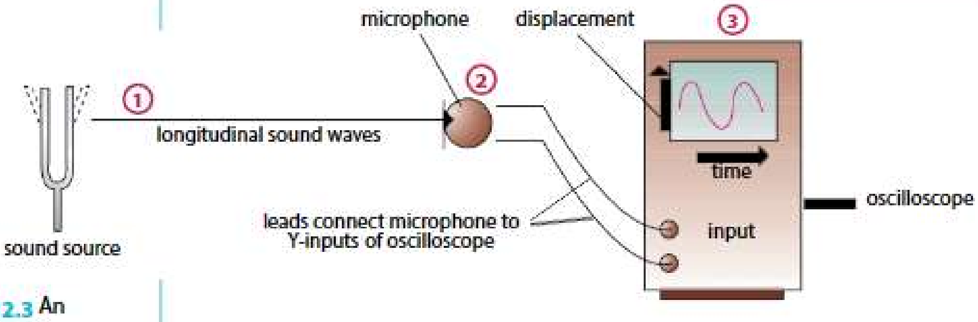


Figure 12.3 An oscilloscope is commonly used to track the variation of a quantity with time.

For a particular tuning fork, the displacement–time graph on the screen is shown in Figure 12.4.

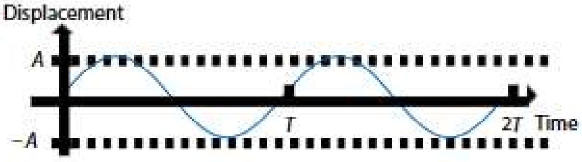


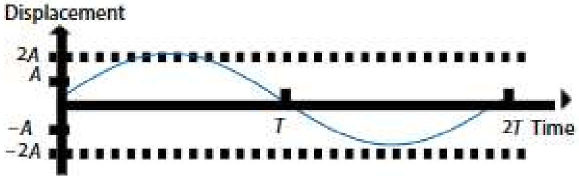
Figure 12.4 Displacement–time graph

Draw a new displacement–time graph to show the sound from the tuning fork with its amplitude doubled and its frequency halved.

Answer

Since $T = \frac{1}{f}$, halving the frequency doubles the period.

Hence the new graph is:



Link

Theory Workbook
Worksheet 12A

Let's Practise 12.1

1 In a sound wave:
 (a) what wave property describes the shortest distance from one compression to the next compression;
 (b) what are the regions which are at pressures slightly above the atmospheric pressure called?

12.2 How Do We Relate Loudness to Amplitude and Pitch to Frequency?

Learning Outcome

- Relate loudness of a sound wave to its amplitude and pitch to its frequency.

If two people were asked separately to rate a speaker's loudness on a scale of 1 to 10, the values would likely be different. To the human ears, the loudness of a sound is **subjective**. We need a standardised way to measure the loudness of a sound.

Loudness and Amplitude

A device that gives an **objective** number indicating loudness is called a sound level meter. With sound level meters, scientists have found that as people age, their sense of hearing generally declines due to biological changes.

Word Alert

Subjective: dependent on a person

Objective: not dependent on a person, dependent only on the object

Audible: able to be heard

A sound level meter also gives a standardised reading when exposed to sound waves of the same amplitude. Loudness is generally related to the amplitude of a sound wave. The larger the amplitude, the louder the sound.

Pitch and Frequency

Similarly, pitch refers to a human's perception of sound. Humans often describe sound as high-pitched or low-pitched. The higher the frequency, the higher the pitch. While pitch and frequency are related, only frequency is a measurable physical quantity. Again, it is found that as people age, they are less able to hear sounds with high frequencies.

Link

Recall from Chapter 11: Amplitude of a wave is its maximum magnitude of displacement from its rest position. The frequency f is the number of oscillations each particle on the wave completes per second.

Audible and Inaudible Sounds

The human ears can hear sounds of frequency from 20 Hz to 20 000 Hz (20 kHz). This is known as our **audible** range. Frequencies below 20 Hz are called infrasound and frequencies above 20 000 Hz are called ultrasound.

Figure 12.5 shows the audible range of some organisms and the frequency of sounds produced by some objects.

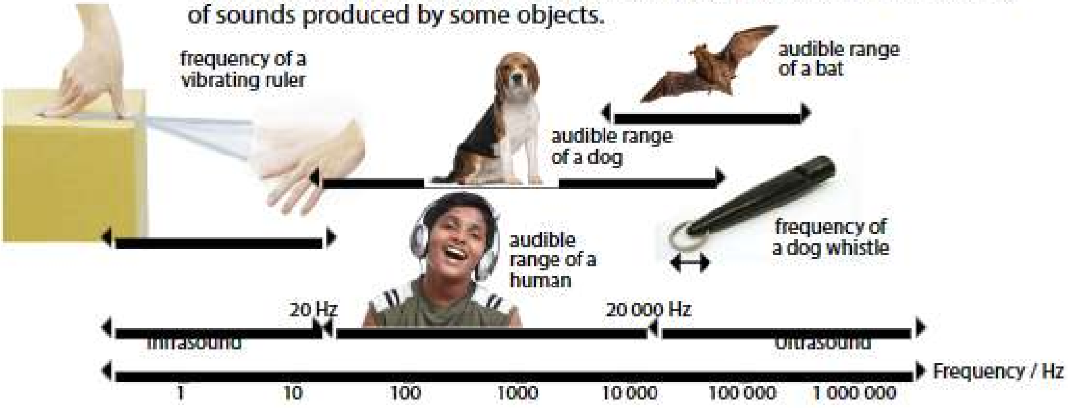


Figure 12.5 Spectrum of different sound frequencies

12.3 How Is Sound Useful?

Learning Outcomes

- Describe how the reflection of sound may produce an echo, and how this may be used for measuring distance.
- Describe and explain how ultrasound is used, e.g. in sonar and medical scanning of soft tissue.

Figure 12.6 How do echoes help bats to hunt for prey?

Reflection of Sound

When you clap your hands, you will hear the sound of your clap immediately. If there is a tall wall some distance in front of you, you will hear a softer second clap due to the reflected sound of your clap. The reflected sound is called an **echo.**

Do you know how some animals use echoes to detect obstacles and find their prey (Figure 12.6)? Before we look at how they are able to achieve that, let's investigate how we can use echoes to find the speed of sound in air.

Measuring the Speed of Sound in Air

Let's Investigate 12A

Aim

To investigate how fast sound travels in air

Procedure

1 Stand facing a big wall about 100 m to 150 m away.
2 Measure and record your distance *d* from the wall with the help of a friend.
3 Hit two wooden blocks against each other repeatedly such that each hit coincides with the echo from the previous hit. (When you can consistently achieve that, the time interval between hits is the time taken for the sound to travel to the wall and back to you.)
4 Get a friend to measure and record the time *t* for 15 intervals using a stopwatch.
5 Calculate the speed *v* of sound in air. $v = \frac{\text{total distance travelled}}{\text{time}} = \frac{15 \times 2d}{t}$

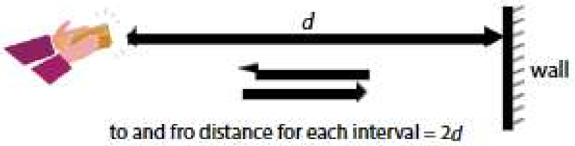


Figure 12.7 A set-up to measure the speed of sound

Questions

1 The human reaction time is about 0.2 s and the speed of sound in air is around 340 m/s. Why is it not a good idea to just clap once and measure *t* for the echo to return?
2 Why is it not a good idea to use a distance *d* of 20 m?
3 After we have found the speed of sound in air, how can it help us find the distance between us and a different wall?

Helpful Note

Generally, speeds of sound vary this way: $v_{\text{solid}} > v_{\text{liquid}} > v_{\text{air}}$

Echolocation

With the speed of sound, a computer-controlled sound emitter and sound sensor, the distance from the emitter to the reflecting surface can be easily calculated. This is called **echolocation**.

Animals such as bats and dolphins are able to use echoes to locate objects and prey around them (Figure 12.8). This ability is very useful when dolphins are deep in the water where there is very little light.

Though humans do not naturally have the ability to echolocate, we have built electronic devices that can do so. An example of such a device is commonly installed at the rear bumper of cars such that the closer a reversing car gets to an object behind, the faster the beeping sound from the device.

Figure 12.8 Bats navigate by emitting high frequency sounds that humans cannot hear.

Ultrasound

Ultrasound is sound with frequencies above the upper limit of the human range of audibility. As we have learnt in Section 12.2, ultrasonic frequencies are frequencies above 20 kHz. Some of the technologies which make use of ultrasound are discussed in this section.

Sonar Technologies

Commercial fishing boats often use sonar (**So**und **N**avigation **A**nd **R**anging), which emits an ultrasound pulse into the water and listens for the reflected pulse. In the case of the fishing boat in Figure 12.9, reflected pulses will come from the shoal of fish and the sea floor. The strength of the reflected pulses will differ according to the distance and characteristics of the reflecting objects. After the reflected signals are processed by a computer, the location is presented on the user's screen.

Helpful Note

Ultrasound has better penetrating power than normal sound. Hence, it can travel deeper into the water.

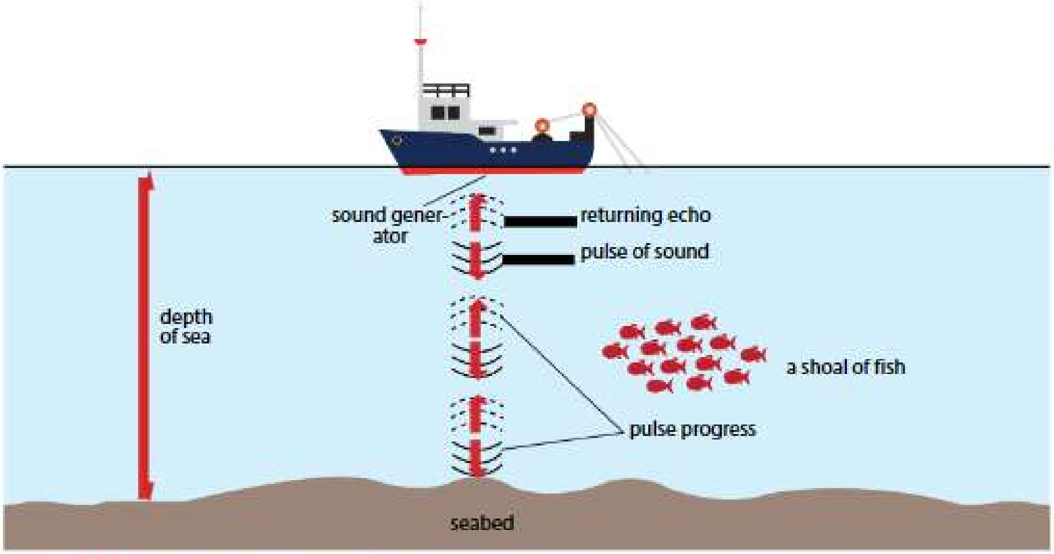


Figure 12.9 Sonar being used to find fish

With the help of sonar, fishermen are able to catch fish more easily. Is this good or bad? Will there be a problem of overfishing, leading to a decline in fish population and hence lower yields for fishermen? How would the decline in fish population impact the ecosystem?

Tech Connect

Traditional speakers produce sound that spreads across a wide angle. A new kind of speaker is able to produce a narrow ultrasound beam similar to a narrow laser beam. The sound can be heard only when a person blocks the path of the beam. People who are nearby but not in the path of the beam cannot hear the sound. One use of this technology is in some museums to beam narration to a person standing in front of an exhibit.

What is the advantage of this narrow sound beam compared to sound from normal speakers? Can you think of other applications of this kind of sound beams?

For Imaging Internal Organs

Ultrasound has many medical applications. The basic principles are similar to its usage in finding fish in the sea. By detecting the strength, direction and timing of the reflected pulses, a computer can process the data very quickly to generate an image of the internal organs. Unlike low frequency sound, higher frequency ultrasound can also be manipulated into thin beams, just like laser beams.

This common handheld scanner (Figure 12.10) can emit and detect reflected waves. In the scanner, many emitters placed in a row each sends out a pulse of ultrasound at the same time. From the reflected pulses in each path, the computer can work out the kind of tissues (e.g. fats, muscles, bones) encountered in a thin slice through the body and construct an image of the slice.

Figure 12.10 A handheld ultrasound scanner

Ultrasound is also commonly used in prenatal scanning, where pulses are sent into the womb of a pregnant woman via a transmitter. The strength, direction and timing of each reflected pulse are measured, allowing for the reflecting surface within the womb to be mapped. This forms an image of the unborn baby (Figure 12.11).

Figure 12.11 Ultrasound image of an unborn baby

For Breaking Up Kidney Stones and Cancer Treatment

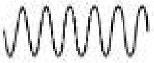
When an ultrasound beam is focused onto a kidney stone, its high intensity vibrations can break the stone up into smaller pieces so that they can be naturally expelled in the urine.

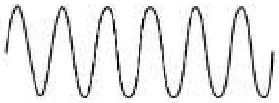
High intensity focused ultrasound can also be used to kill cancer or tumour cells. An advantage of this is that it is a safe and non-invasive method compared to surgery and other methods.

Let's Practise 12.2 and 12.3

1 The displacement–time graphs of four sound waves of different amplitudes and frequencies are shown.

A


B


C


D


(a) Which sound wave has the highest pitch?
(b) Which objective wave property determines the pitch?
(c) Which sound wave is loudest?
(d) Which objective wave property determines the loudness?

2 A fishing boat's sonar emits ultrasound that travels at a speed of 1500 m/s. A shoal of fish below the boat reflects some of the sound back to the boat. The time between emission and reception of the pulse reflected by the shoal of fish is 0.40 s. Calculate the depth of the shoal of fish.

3 State **two** examples of the medical use of ultrasound.

Link

Theory Workbook
Worksheet 12B
Let's Assess
Let's Reflect

Past to Present

In the 17th century, "ear trumpets" were used to concentrate and direct the sound into the ear, helping the hearing impaired hear better (Figure 12.12).

Modern hearing aids are much smaller and less visible. Some models can be completely hidden in the ear canal (Figure 12.13). The advanced digital models can be paired wirelessly with a mobile phone. The user is able to select different modes to suit the different sound environments such as a noisy public place, a concert or a conversation setting.

Figure 12.12 Ear trumpets

Figure 12.13 Modern hearing aids can be placed inside the ear.

Problem-based Learning Activity

Some research has shown that noise can have a negative impact on our mental and physical health without us consciously knowing it. Excessive exposure to noise has been linked to stress, poor concentration, hypertension and hearing problems. Table 12.1 shows the loudness of the sounds in some common settings.

Table 12.1 Loudness of sounds in various settings

Setting	Loudness in Decibels	Comment
ambulance siren	130	more harmful as exposure duration increases
thunder	120	
construction site piling work	110	
power tools	90	
hair dryer	80	loud
road traffic	70	
normal conversation	60	moderate
office environment	50	
library	40	soft

Some of us may have experienced days of continual loud noise from the usage of jackhammers in our neighbours' home renovation work. The operator of the jackhammer must also tolerate the high noise level at work. Loud noise is very disruptive, especially when we are trying to work on our assignments.

To improve the well-being of everyone, your team is tasked to propose solutions to reduce the noise level around you. Use the following questions to guide you in coming up with a proposal.

- What is a suitable tool for measuring noise level?
- What are some of the strategies, measures and/or materials that are useful for noise control?
- How can we improve the ways to reduce the noise level?

Link

Theory Workbook
Problem-based Learning: Application

Practical Workbook
Problem-based Learning: STEM Project

Cool Career

Sound Engineer

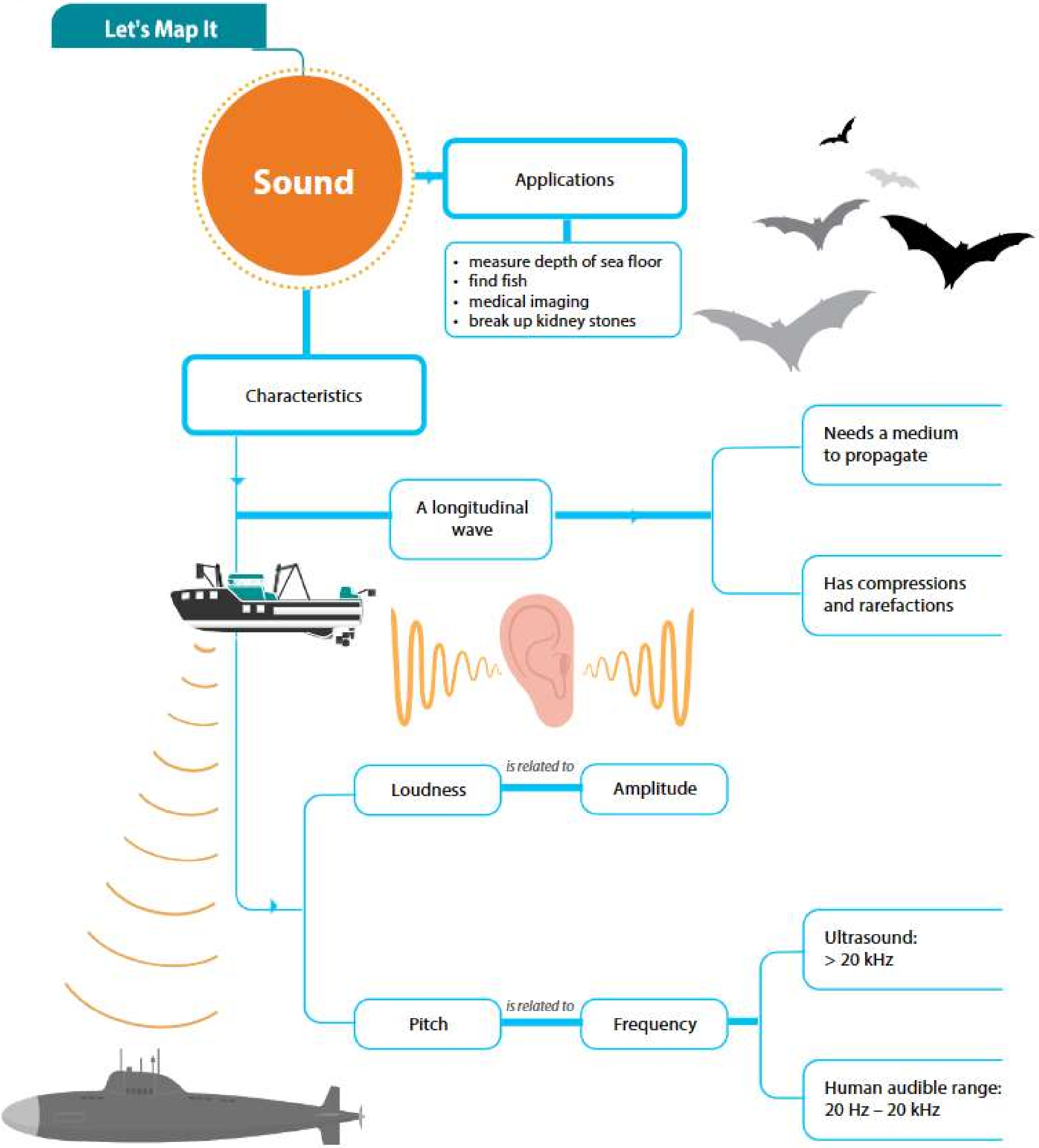
Music is a daily enjoyment for millions of people around the world. Sound engineers play a crucial role to make that possible.

Figure 12.14 A sound engineer at work

Sound engineers' understanding of the behaviour of sound allows them to effectively control and manipulate sound (Figure 12.14). For example, they need to understand how to manage echoes so that they do not interfere with the desired soundscape. They also need to be aware of many other variables affecting sound quality such as the positioning of different types of speakers, the effect of wall lining materials, the interior architecture of a venue and so on. They play crucial roles in the music production industry, concert hall designing, tailoring sound systems for development of sound equipment.

There are many pathways to becoming a sound engineer — from learning on the job to getting started with a diploma or degree. Other than good technical knowledge, sound engineers need to have a discerning ear for sound.

Let's Map It



Sound

Applications

- measure depth of sea floor
- find fish
- medical imaging
- break up kidney stones

Characteristics

A longitudinal wave

Needs a medium to propagate

Has compressions and rarefactions

Loudness *is related to* Amplitude

Pitch *is related to* Frequency

Ultrasound: > 20 kHz

Human audible range: 20 Hz – 20 kHz

Let's Review

Section A: Multiple-choice Questions

1 Which of the following is correct about sound waves?

○ **A** Ultrasound waves can be used for communication in space.

○ **B** The inaudible frequency range for humans is much greater than the audible range.

○ **C** In an earthquake, one type of wave with vibration that is perpendicular to the direction of wave travel is a sound wave.

○ **D** Sound waves are safe regardless of the frequency or amplitude.

2 Which of the following statements about sound is correct?

○ **A** Sound with a higher frequency travels faster.

○ **B** Sound with a higher pitch has larger amplitude.

○ **C** Sound with a larger amplitude is louder.

○ **D** Sound with a larger wavelength travels faster.

3 In which of the following materials is sound most likely to travel fastest?

○ **A** rubber ○ **B** air

○ **C** water ○ **D** aluminium

4 A sound wave travelling to the right has a displacement–distance graph as shown in Figure 12.15.

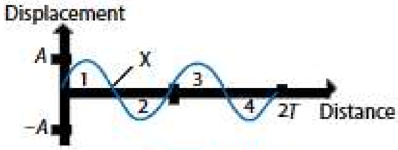


Figure 12.15

Given that point X is a rarefaction, what are the directions of particle movement in the regions 1, 2, 3 and 4?

	1	2	3	4
○ **A**	→	←	→	←
○ **B**	←	→	←	→
○ **C**	↑	↓	↑	↓
○ **D**	↓	↑	↓	↑

Section B: Structured Questions

1 A person standing near a cliff lets out a loud shout. After a while, he hears two echoes.

Figure 12.16

(a) Draw **two** likely paths taken by the echoes to return to the person in Figure 12.16.

(b) The intervals between the shout and the return of the two echoes are 2.8 s and 3.6 s. Assuming the speed of sound is 300 m/s, find the distances of the two reflecting surfaces from the person.

2 A speaker produces sound waves that travel to the right. Figure 12.17 shows the displacement–distance graph at a particular instant, assuming displacement to the right is positive.

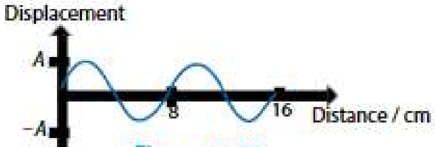


Figure 12.17

(a) Mark the two points on the distance axis where the compressions are.

(b) What is the distance from a compression to the next rarefaction?

3 A sound wave is modelled using a spring (Figure 12.18).

Figure 12.18

The wave is traveling to the right.

(a) Based on the oscillation direction with respect to the wave direction, what type of wave is it?

(b) At this moment, what is the direction of motion of the segments between
  (i) P and Q; and
  (ii) Q and R.

(c) Assume the rightward direction to be positive. Draw the displacement–time graph for the point Q using the axes in Figure 12.19.

Figure 12.19

4 Echolocation is a very useful application of sound waves. However, in some scenarios, echoes can be a problem. Explain the problem caused by echoes in a very big concert hall when a speech is delivered.

Section C: Free-response Questions

1 An ultrasound device emits a pulse and detects the reflected pulse (Figure 12.20).

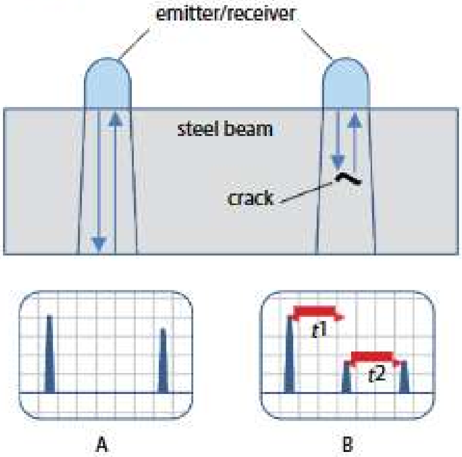


Figure 12.20

Both the emitted and reflected pulses are shown on the screen of an oscilloscope. Screen A is shown when there is no fault in the steel beam. When there is a crack in the beam, screen B is shown with the time intervals t_1 and t_2 between the pulses.

(a) Explain why the second pulse in A is slightly weaker than the emitted pulse.

(b) Explain what causes the second pulse in B.

(c) Explain what causes the third pulse.

(d) If the speed of sound in steel is v, how would you calculate the depth of the crack?

CHAPTER

13 Electromagnetic Waves

What You Will Learn

- What are electromagnetic waves?
- What are the uses and dangers of electromagnetic waves?

Watching a video on your mobile phone, using a microwave oven to heat up food and turning on the television with a remote control are activities many of us do daily. These are made possible because mankind has learnt to harness electromagnetic waves.

Singapore and many other countries have recognised the fifth generation (5G) of wireless communication technology as a great economic growth enabler. 5G technology uses electromagnetic waves in the GHz range, instead of in the MHz frequency range. Thus, 5G technology can transfer data about a thousand times faster than 4G technology.

Can you think of other modern conveniences enabled by the usage of electromagnetic waves?

13.1 What Are Electromagnetic Waves?

Learning Outcomes

- State that all electromagnetic waves are transverse waves that travel with the same speed in vacuum.
- Describe the main regions of the electromagnetic spectrum in order of wavelength and frequency.

Nature of Electromagnetic Waves

We have learnt that sunlight can be split into a continuous spectrum of colours. The rainbow spectrum is just one small section on the spectrum of electromagnetic waves. In this chapter, we will learn that the continuous **electromagnetic wave spectrum** covers a large range of wavelengths and frequencies. Figure 13.1 shows the arrangement of electromagnetic (EM) waves in order of frequency and wavelength.

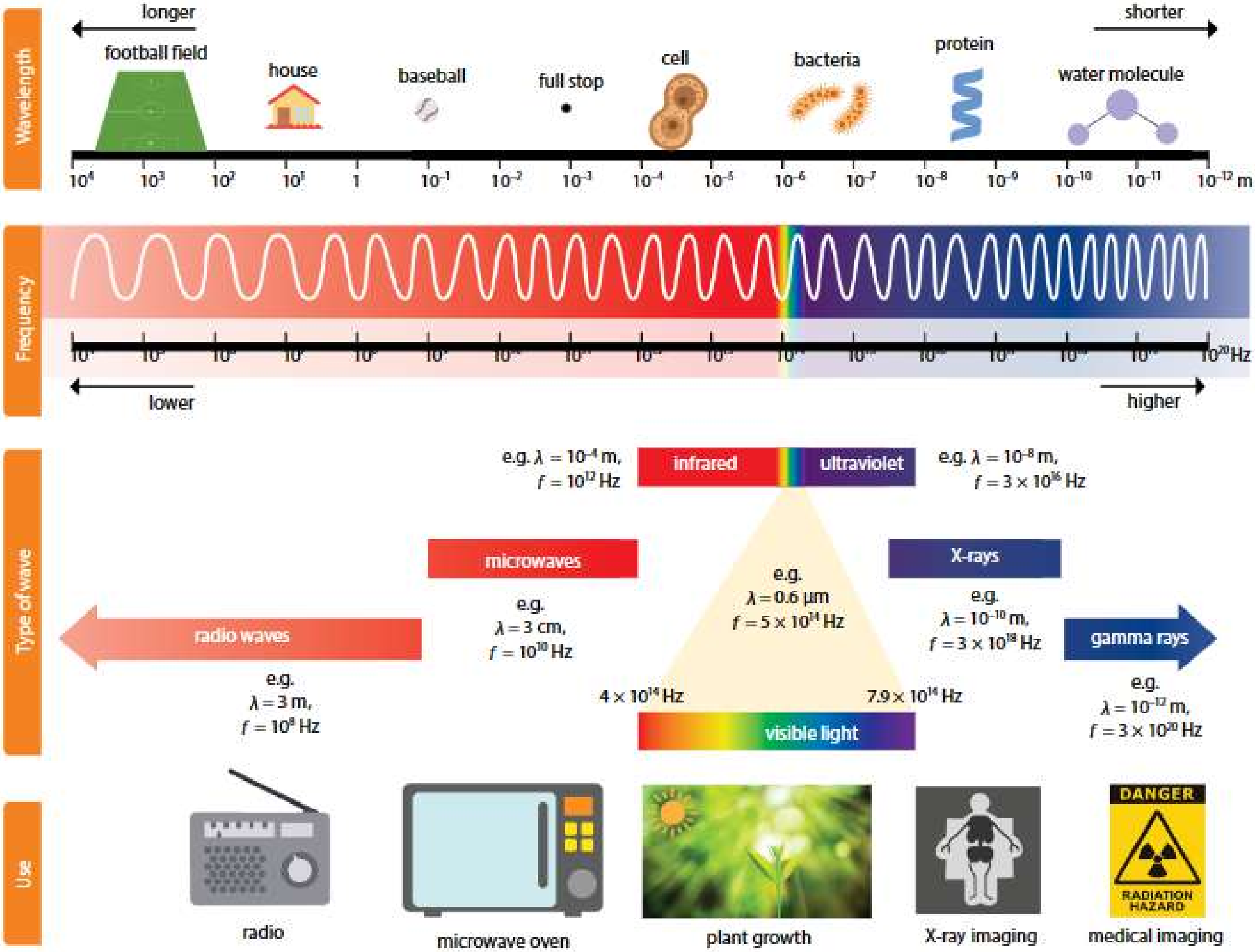


Figure 13.1 The electromagnetic spectrum and its components

The following lists some facts about electromagnetic waves.

1 All electromagnetic waves are **transverse** waves.

2 Electromagnetic waves are made up of oscillating electric and magnetic fields (Figure 13.2). They do not carry electric charges.

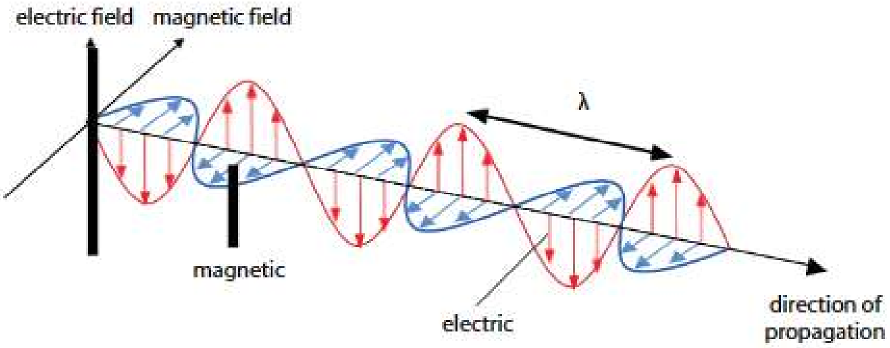


Figure 13.2 Electromagnetic wave with oscillating electric and magnetic fields

3 All electromagnetic waves can travel without a medium, with the same speed of **3×10^8 m/s in a vacuum.**

4 The **wave speed** equation, $v = f\lambda$, applies to all electromagnetic waves.

5 When an electromagnetic wave travels from a vacuum to other media, the wave speed and wavelength decrease. The decrease in speed is different for different frequencies. However, the **frequency stays the same as at the source** when the wave goes into a different medium.

6 Electromagnetic waves undergo reflections and refractions.

7 Electromagnetic waves transfer energy.

8 **Ionising waves** are those with higher frequencies and hence higher energies. They can eject electrons from atoms and molecules to create ions. The ions can cause harm by disrupting cell functions and even killing them.

9 All material bodies emit a range of electromagnetic waves. In general, higher temperature bodies tend to emit more and higher frequency electromagnetic waves.

Disciplinary Idea

Waves can transfer energy without transferring matter.

Electromagnetic waves can be transmitted through a vacuum without involving any material medium.

Disciplinary Idea

Matter interacts through forces and fields.

Electromagnetic waves can be established in the absence of matter. The magnetic and electric fields oscillate perpendicularly to each other and to the direction of movement of the waves (Figure 13.2).

In electromagnetic waves, the oscillating magnetic and electric fields can interact with charges in matter.

Link

Recall from Chapter 11: The speed of a wave depends on the medium's properties. However, the frequency of a wave remains the same when the wave goes into a different medium.

Link

You will learn about reflection and refraction in Chapter 14.

Worked Example 13A

GPS satellites are about 20 000 km above the ground and they communicate using 1.5 GHz electromagnetic waves (Figure 13.3).

Figure 13.3 GPS satellite transmits a signal that is carried by electromagnetic waves.

(a) What is the shortest time it takes for the signals to travel from a GPS satellite to a receiver on the ground?
(b) Which part of the electromagnetic spectrum does the wave belong to?

Answer

(a) Shortest time for a receiver directly below the satellite

$$= \text{height} \div \text{speed}$$
$$= 2 \times 10^7 \div (3 \times 10^8)$$
$$= 0.067\text{ s}$$

(b) 1.5 GHz = 1.5×10^9 Hz
Looking up the spectrum of frequencies in the electromagnetic spectrum, the signals belong to the microwave band.

Worked Example 13B

(a) Describe the direction of oscillation of electromagnetic waves with respect to their direction of travel.
(b) State what happens to the speed, wavelength and frequency of electromagnetic waves when they travel from a vacuum to a material such as glass.

Answer

(a) The oscillations are perpendicular to the direction of travel.
(b) The speed and the wavelength are reduced while the frequency is unchanged.

Let's Practise 13.1

1 As an electromagnetic wave passes from one medium into another, its wavelength increases from 5.0 mm to 6.0 mm.
  (a) Did the speed of the wave increase or decrease? Explain.
  (b) What is the ratio of the wave speed in the second medium to the speed in the first medium?

2 Arrange the following types of electromagnetic waves in order of increasing frequency.
visible light, gamma rays, microwaves, ultraviolet, X-rays, radio waves, infrared.

Link
Theory Workbook
Worksheet 13A

13.2 What Are the Uses and Dangers of Electromagnetic Waves?

Learning Outcomes

- State examples of typical uses of the different regions of the electromagnetic spectrum.
- Describe how over-exposure to electromagnetic waves can have hazardous effects on living cells and tissue.

Figure 13.4 Are electromagnetic waves dangerous?

What are some of the uses and dangers of electromagnetic waves? Are all electromagnetic waves harmful? Is there a need to actively cut down on equipment that emit these electromagnetic waves (Figure 13.4)?

Uses of Electromagnetic Waves

Radio Waves

From its name, can you guess one application of radio waves? When you tune in to a radio station, sound is transmitted through the air to your radio set via radio waves (Figure 13.5).

Figure 13.5 A radio set that receives both AM and FM transmissions

Information in radio waves can be transmitted by two methods. The first is called amplitude modulation (AM) as information is conveyed by varying the wave amplitude. The second is called frequency modulation (FM) as information is conveyed by varying the frequency. Interestingly, radio waves in the 3 to 30 MHz range can be reflected repeatedly off the ionosphere (part of Earth's upper atmosphere) and the ground to reach places thousands of kilometres away. This makes it very useful for long distance communication.

Figure 13.6 Radio telescopes can be connected to give higher resolution images

Stars, galaxies, and other celestial objects can produce electromagnetic waves of a wide range of frequencies. For example, the sun produces mainly visible light, ultraviolet and infrared. Knowledge about the frequencies and intensities of the waves allow astronomers to deduce the materials, temperatures and processes in the celestial objects.

Radio waves produced by some stars, quasars and galaxies can be detected with an array of radio-telescopes (Figure 13.6). The study of radio frequencies from outer space is called radio astronomy.

Figure 13.7 RFID tag

The Radio Frequency Identification (RFID) tag is a small and thin circuit that contains identification data (Figure 13.7). When a reader device sends a radio wave to the tag, the tag receives energy. This energy allows the tag to transmit its data by radio wave back to the reader. These tags are commonly used to tag library books, pets, items in warehouses and merchandise in shops.

Radio waves of different frequency bands are often set aside for special uses. Hence, the police force, the military, satellite communication, television signals have their allocated frequency bands.

Microwaves

While the usage of microwaves in microwave ovens is well known, do you know that wi-fi signals also fall under the microwave band? Does that mean that we can get cooked by wi-fi signals? Theoretically, that is possible, but in practice it would not happen because the power of a wi-fi signal is about a thousand times weaker than the power of a microwave oven.

Microwaves are used very extensively for communication. The best known example is in mobile phone communication where many transmitters and receivers relay information across the whole network. Other uses include the Global Positioning System (GPS) (Figure 13.8), satellite communication and radar. Beyond communications, microwaves can be used for cancer treatment.

Figure 13.8 Microwave signals received from at least three GPS satellites allow a receiving device such as a GPS device or a mobile phone to work out its location.

Infrared

When we stand near a fire or a hot object, we feel warm even though there is no contact with the hot object. This is because our skin has thermoreceptors that are sensitive to infrared waves.

Electrically heated rods in ovens give out infrared waves or radiation to cook food (Figure 13.10). A similar set-up to produce infrared radiation keeps people warm in cold places.

Infrared waves can also be used for data transfer between devices like mobile phones and laptops. Since higher frequency waves carry more data, infrared can typically transfer data faster than microwaves. More importantly, infrared waves are used in long distance fibre-optic cables for high-speed data transfer.

Other common uses of infrared are in remote controls, camera auto-focusing and thermometers that measure body temperature by sensing the emitted infrared radiation to produce a thermal image. These thermometers can also be enhanced to detect potential intruders at protected premises and sound alarms. In cold places, greenhouses made of glass are used to trap long-wavelength infrared to maintain a warm interior for plants to grow.

Tech Connect

Even as the world is focused on implementing 5G Wi-Fi, a newer and much faster system for communication called Li-Fi is on its way to eventually overtake Wi-Fi.

Instead of using microwaves, Li-Fi uses visible light and even ultraviolet light to transfer data about 100 times faster than Wi-Fi (Figure 13.9). Li-Fi can be used inside aircrafts and places that are sensitive to radio wave interference. It is also more secure because the light signals cannot pass through the walls.

Figure 13.9 Li-Fi uses light for transmission of data

Figure 13.10 Electric heater emits infrared waves.

Let's Investigate 13A

Aim

To investigate how well infrared radiation can pass through various materials

Procedure

1 Prepare a working television remote controller.
2 On a mobile phone, install a light detector meter application, e.g. Arduino Science Journal
3 Prepare the following items.
   - Aluminium foil
   - Paper
   - Cloth or towel
   - Glass pane of a few mm thick
   - Any other available materials that are able to cover the phone's camera completely.
4 Start the downloaded application and select "Light Meter".
5 The front facing camera will start measuring the amount of light, including some infrared. The application will show the amount of light measured.
6 Since we are only interested in measuring infrared, go to a dark room so that the camera's sensor will measure mostly the infrared.
7 Press the "on" button on the remote controller and aim it at the phone's camera that is a few centimetres away. Take note of the amount of light recorded on the phone.
8 Repeat step 7 using other materials to cover the phone's camera.

Questions

1 Which materials allowed the most infrared to pass through and which ones were most effective in blocking infrared?
2 Are you able to find a material that is good at blocking the infrared but allows visible light to pass through? Explain how such a material will be useful.

Visible Light

Taking a photograph on a mobile phone requires visible light. Visible light can also be used to transmit data directly through the air. During surgeries, optical fibres are very useful for transmitting light to illuminate internal organs.

Scientific research is ongoing to find out the role of differently coloured light in leaf growth, flowering and root formation. This will help farmers to effectively control the factors for ideal crop production using artificial light sources instead of relying on natural but unpredictable weather conditions (Figure 13.11). This could be crucial for feeding a growing world population.

Figure 13.11 Artificial light for plant growth

The soft material used by a dentist to fill up a treated tooth cavity needs to be cured with light so that it can be hardened. This chemical process is called polymerisation, where small molecular units called monomers link up to form a long chain. Over the years, different light sources have been used to trigger the process. Currently, blue light from a LED (light emitting diode) is used.

Link

You will learn more about specific applications of light in Chapter 14.

Another example of light induced chemical change is in photographic film. This has been largely replaced by electronic sensors in digital cameras. The film is coated with chemicals that react to visible light of different frequencies. This allows the film to record an image formed by a lens. These films respond to UV, X-rays and gamma rays too.

Ultraviolet

Ultraviolet (UV) light can be seen by some insects and animals thus giving them a keener sense of sight.

In Singapore's water treatment plants, UV plays an important role in disinfection and sterilisation as it can kill bacteria and viruses (Figure 13.12).

Figure 13.12 NEWater is produced from treated used water that is disinfected using UV and other processes in the water reclamation plants in Singapore.

Exposure to a suitable dose of UV light from the sun enables our body to produce vitamin D that is good for our bones, muscles and immune system. In places where there is little sunlight, people use sun-tanning beds to get a more tanned skin tone. However, users have to exercise caution and follow usage guidelines, as over exposure can have harmful effects, including skin cancer and premature aging.

Pigments that glow under UV light are also commonly used in anti-forgery features of printed notes as shown in Figure 13.13.

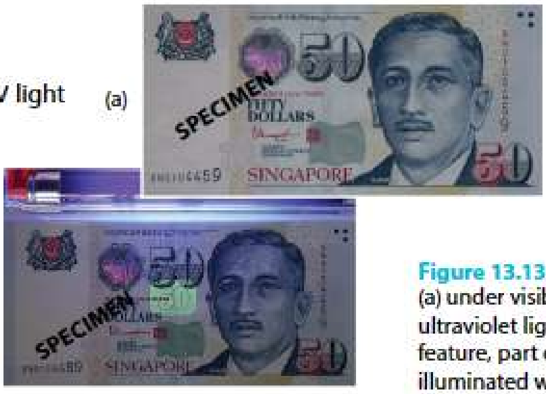


Figure 13.13 A Singapore bank note, (a) under visible light and (b) under ultraviolet light. As an anti-forgery feature, part of the note will glow when illuminated with ultraviolet light.

X-Rays

The intensity of X-rays passing through different tissue types varies. Parts of the body that absorb more X-rays appear brighter on the image (Figure 13.14). Thus, the different shades can reveal internal structures such as fractures and cancerous growths in the body.

A more advanced medical imaging technique is called Computed Tomography (CT). A rotating X-ray scanner collects data over a thin slice of a patient's body before moving on to do the same for the next adjacent slice. Data for each slice is processed by a computer to reconstruct the different types of tissue in that slice (Figure 13.15). Finally, all the slices are combined to form a 3D image of the scanned volume.

Figure 13.14 X-ray images are used to diagnose medical conditions such as fractures.

Figure 13.15 A Computed Tomography scan combines X-ray images taken at different angles to form a detailed image of the part of the body.

Energetic X-rays are also useful for killing cancer cells in radiotherapy. In addition, its high penetrative power makes it a useful tool to scan for manufacturing defects in metal parts and at airports to scan luggage for prohibited items.

Past to Present

In the past, only simple X-ray machines were available for doctors to produce internal images of our body. Now, with the more sophisticated Computed Tomography scanner and Magnetic Resonance Imaging (MRI) scanner, doctors have more tools for diagnosing medical conditions.

The MRI scanner may look quite similar to the CT scanner but it uses a very strong but safe magnetic field combined with radio waves to probe inside the body. Compared to the CT scanner, MRI is safer and it produces more detailed 3D images of soft tissues (Figure 13.16).

Figure 13.16 A MRI scan of the brain

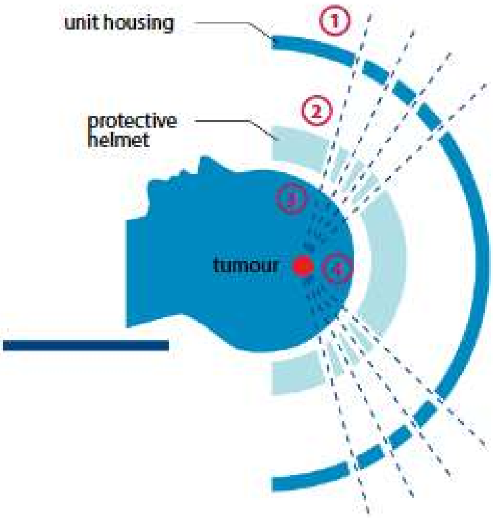
Gamma Rays

Gamma rays are the most energetic waves in the electromagnetic spectrum, making them very effective for killing germs in food and sterilising medical equipment. Like X-rays, gamma rays can be used for **radiotherapy** and detecting defects in manufacturing, including in metal objects. However, gamma rays are usually from a compact radioactive material while an X-ray machine tends to be bulky and require electrical power.

Word Alert

Radiotherapy: the use of ionising electromagnetic waves to kill cancer cells

Gamma rays have been used to treat cancer, in a procedure known as the Gamma Knife radio surgery. In the procedure, gamma rays are directed at brain tumours to kill cancer cells (Figure 13.17).



① Hundreds of radioactive gamma ray sources are positioned around a special helmet.

② The emitted gamma rays are aimed at a single target such as a tumour.

③ An individual beam from each source is not intense enough to kill the cells along its path.

④ However, when all the beams converge at the tumour, the high intensity of the ray is able to kill the cancer cells in the tumour.

Figure 13.17 Advantages of Gamma Knife treatment include high precision and fast recovery.

Harmful Effects of Electromagnetic Waves

Ionising Radiation

Ionising radiation can be high frequency electromagnetic waves or high energy particles. They come from outer space, natural radioactive materials in our environment or man-made sources. High energy electromagnetic waves can penetrate our body more easily than high energy particles.

Helpful Note

Recall that higher frequency electromagnetic waves have higher energy.

A large portion of our exposure to ionising radiation is from natural sources in our environment (Figure 13.18).

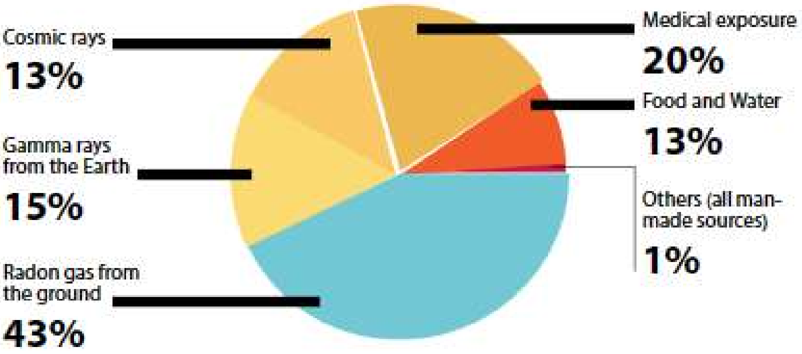


Figure 13.18 Our average exposure to ionising radiation from various sources

Link

You will learn more about the applications and hazards of radioactivity in Chapter 22.

Living things are made up of many types of cells such as nerve cells, skin cells and muscle cells. The cells are in turn made up of molecules and atoms. When a high frequency electromagnetic wave interacts with a particular atom or molecule and knocks an electron out from it, a charged ion is produced.

The charged ion will not behave in the same way as the original atom or molecule that was electrically neutral. Thus, the ion may hinder a certain chemical reaction which in turn affects a particular cell process. Depending on the scale of such disruptions and the specific biological system affected, the result could be cell death, mutations leading to diseases and organ failure.

Higher frequency electromagnetic waves can penetrate deep into the body more easily to create ions. High frequency electromagnetic waves are thus more harmful than high energy particles that do not penetrate as deep.

Link

Biology
In biology, we learn that mutation is a change in cellular genetic code or DNA. It can lead to cell death or abnormal outcomes such as cancerous growth or diseases.

Disciplinary Idea

Waves can transfer energy without transferring matter.

Absorption of electromagnetic waves may cause heating (e.g. microwave oven for cooking), ionisation and damage to living cells and tissues. Such behaviour can be harnessed in applications that maximise benefits while minimising harm.

Figure 13.19 Sunscreen protects us against UV rays.

Heating

The exposure to strong ionising electromagnetic radiation such as ultraviolet light causes heating effects. As mentioned, the over-exposure to ultraviolet light can have harmful effects such as skin cancer and premature aging. Thus, in Singapore where there is a high level of UV radiation all year round, we should protect ourselves against UV (Figure 13.19).

Let's Practise 13.2

1 Suggest **one** useful application for each of the following electromagnetic waves.
  (a) Microwaves
  (b) Infrared waves
  (c) Ultraviolet waves

2 (a) Many celestial objects emit X-rays and gamma rays. Why is it fortunate that Earth's atmosphere is thick enough to absorb these radiations?
  (b) Given that radio waves are used for communicating with satellites and for radio astronomy, what can you say about its ability to pass through the atmosphere?

Link

Theory Workbook
Worksheet 13B
Let's Assess
Let's Reflect

Cool Career

Wireless Network Engineer
A wireless network engineer is responsible for the maintenance and installation of the wireless network (Figure 13.20). There are many configuration settings that need to be correctly set for the network to work optimally. The engineers need to have up-to-date knowledge of all the network hardware components. They need to know how to use software tools to monitor network performance and security. The job requires good problem-solving and analytical skills in order to resolve network problems. Good communication skills and customer service skills are also crucial.

Figure 13.20 A wireless network engineer takes care of all aspects of the wireless network.

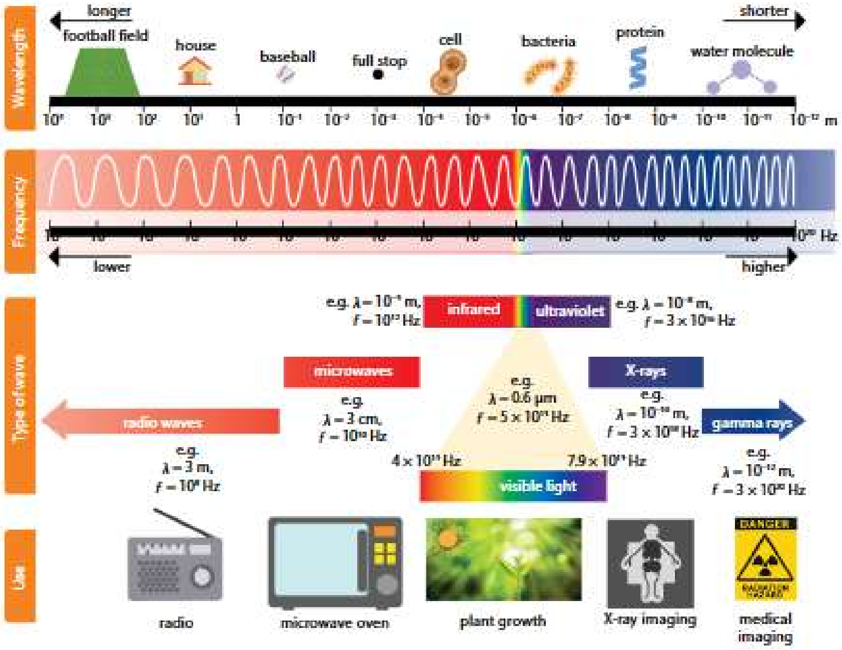
Let's Map It

Electromagnetic Waves

have

Common properties

- Transverse waves
- Oscillating electric and magnetic fields
- Speed of 3×10^8 m/s in a vacuum but slows down in physical media
- Frequency remains the same from one medium to another



form a

Continuous spectrum

Higher frequency

Non-Ionising

Ionising

have uses in

radio waves	radio and satellite communication, TV broadcast
microwaves	microwave oven, wi-fi signals, radar
infrared	heating, short range data transfer
visible light	artificial light for plants, data transfer in optical fibres
ultraviolet	sterilisation or killing bacteria and viruses
X-rays	medical imaging, find defects in manufactured parts
gamma-rays	radiotherapy, sterilisation

Let's Review

Section A: Multiple-choice Questions

1 Which of the following is **not** a property of electromagnetic waves?

○ A They travel at the same speed in all media.
○ B They can travel through a vacuum.
○ C They are transverse waves.
○ D They are made up of oscillating electric and magnetic fields.

2 Which of the following is **not** an ionising radiation?

○ A gamma rays ○ B ultraviolet
○ C infrared ○ D X-rays

3 Which two radiations have the highest and lowest frequencies in the electromagnetic spectrum?

○ A Radio waves and microwaves
○ B Ultraviolet and infrared
○ C X-rays and microwaves
○ D Gamma rays and radio waves

4 Which radiation is commonly used for killing germs and least harmful to humans if they are accidentally exposed to it?

○ A X-rays ○ B ultraviolet
○ C gamma rays ○ D radio waves

5 Which of the following statements about electromagnetic waves is **incorrect**?

○ A They have the same speed in a vacuum.
○ B They slow down when travelling from a vacuum to a physical medium.
○ C The wave frequency changes when going from one medium to another.
○ D Higher frequency waves are more energetic.

Section B: Structured Questions

1 Electromagnetic waves have many useful applications. Which part of the spectrum is:
(a) used for wi-fi and mobile phone communication;
(b) suitable for keeping people warm in cold places; and
(c) good for scanning metal objects for manufacturing defects?

2 When light travels from air to glass, its speed is reduced by 30%. What is the percentage decrease in the:
(a) frequency; and
(b) wavelength?

3 Electromagnetic waves have many uses. Identify **one** radiation suitable for:
(a) radars and telecommunications; and
(b) radiotherapy and scanning metal parts for defects.

4 Between sound waves and electromagnetic waves:
(a) what is their difference such that only one can be used for communicating with high altitude satellites;
(b) state whether it is possible for them to have the same frequency; and
(c) compare their directions of oscillation with respect to the direction of wave travel.

5 An autonomous car sends out a pulse of light in all directions. The time interval for light to be reflected back from each direction is used to determine the distance of the reflecting point.
(a) Approximately how many times is the speed of light faster than the speed of sound?
(b) Calculate how long it takes a light pulse to travel 1 km away and back. Hence what is the advantage compared to echolocation?
(c) Within the time calculated in (b), how far would an autonomous car move if it were travelling at 90 km/h?

Section C: Free-response Questions

1 The 2.4 GHz waves are able to pass through walls better than the 5 GHz waves. Your friend suggested that as electromagnetic wave frequency increases, the ability to pass through objects decreases. Explain whether your friend's conclusion is correct.

2 (a) Both ultrasound and X-rays can be used to detect cracks in materials. Suggest why in practice, ultrasound is preferred.
(b) Explain briefly the harmful effects of ionising radiation on humans.

CHAPTER

14 Light

What You Will Learn

- How does light enable us to see?
- How is light refracted?
- What is total internal reflection?
- How does a converging lens work?

At the centrepiece of Jewel Changi Airport is the 40 m tall Rain Vortex, which is the world's tallest indoor waterfall. At night, the waterfall becomes a screen where animated patterns are projected, accompanied by music. Several sessions of the light show are held every night for visitors from all around the world.

How does reflection enable us to see the patterns on the water screen? Laser beams travel from multiple projectors to reach the water screen. Some of the light is reflected off the screen into our eyes. The brain interprets the light as coming from the water screen. However, the light actually originates from the projectors. Why do we not see the light beams travelling from the projectors to the water screen?

14.1 How Does Light Enable Us to See?

Learning Outcomes

- Recall and use the terms *normal, angle of incidence* and *angle of reflection* to describe the reflection of light.
- State that, for reflection, the angle of incidence is equal to the angle of reflection and use this principle in constructions, measurements and calculations.

Reflection

Figure 14.1 What enables us to see?

We can see things around us when they emit light (luminous objects) (Figure 14.1). Non-luminous objects can be seen when they reflect light from a luminous object into our eyes (Figure 14.2).

Disciplinary Idea
Matter and energy make up the Universe.

Energy from a luminous object can be transferred to the surroundings as electromagnetic radiation in the form of visible light. Light can be reflected, absorbed or refracted.

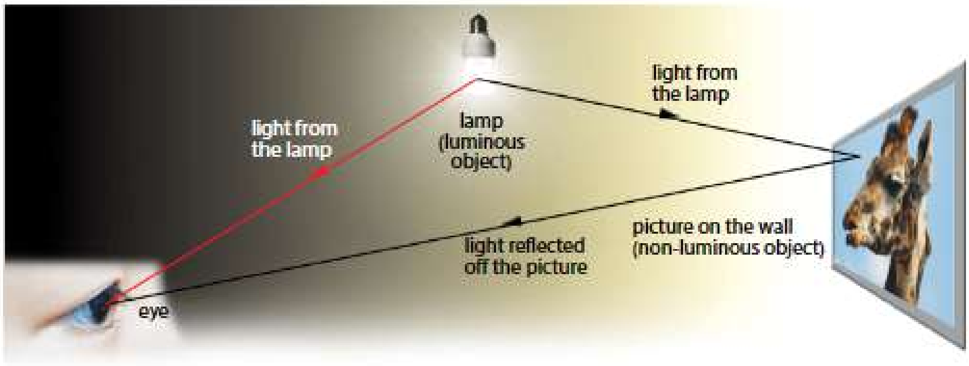


Figure 14.2 We are able to see objects because they either give out light or reflect light.

The presence of light does not guarantee the reflection of light. To show this, we take a look at a material called Vantablack (Figure 14.3).

Vantablack absorbs more than 99% of light falling on it. The black patch on the aluminium foil looks flat but it actually has creases. We cannot see the creases because too little light is reflected from the black coating to our eyes.

Figure 14.3 An aluminium foil with a part coated with Vantablack, which is one of the darkest substances known.

In the ray model of light, light is represented as straight lines with arrows to indicate the direction in which the light travels. Each of these lines is known as a light ray. A bundle of many **light rays** forms a **light beam**.

Laws of Reflection

Do you notice that when you wave your left hand in front of a mirror, the image in the mirror waves his or her right hand? When you walk further away from the mirror, the image of the person on the mirror also walks further away. What are the laws that govern the reflection of light?

When a light ray or light beam encounters a smooth surface, it is reflected as shown in Figure 14.4.

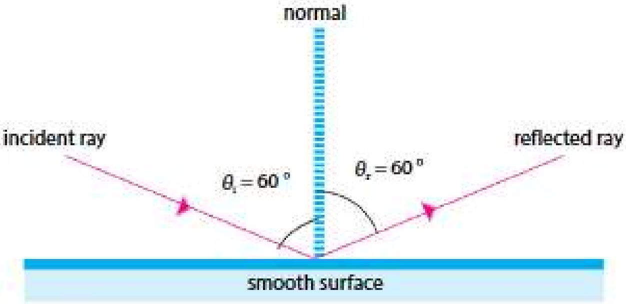


Figure 14.4 Incident ray, reflected ray and normal

- The light ray going towards the surface is called the **incident ray**.
- The light ray going away from the surface is called the **reflected ray**.
- The perpendicular line (90 °) to the surface at the point of incidence is called the **normal**.
- The angle between the incident ray and the normal is called the **angle of incidence (θ_i)**. The angle between the reflected ray and the normal is called the **angle of reflection (θ_r)**.

Past to Present

There is a legend that in 212 B.C., the Greek inventor, Archimedes, used mirrors to focus sunlight onto Roman ships attacking his home city. The sunlight concentrated on the ships set the ships on fire.

Now, some power stations use thousands of curved mirrors to concentrate sunlight onto a point in a tower, where water is turned into steam (Figure 14.5). The steam can then be used to drive a turbine to produce electricity.

Figure 14.5 Mirrors reflect sunlight to a point in the tower (in the middle of the mirrors).

By observing how light rays reflect, we can understand the characteristics of mirror images. They obey the laws of reflection.

- The **first law of reflection** states that the incident ray, reflected ray and the normal at the point of incidence lie in the same plane.
- The **second law of reflection** states that the angle of incidence θ_i is equal to the angle of reflection θ_r.

Types of Reflection

When a beam of light is reflected by a smooth surface, the reflected rays remain parallel to each other and maintain their spacing (Figure 14.6(a)). Thus, the reflection is described as regular (orderly) reflection.

In contrast, a rough surface gives rise to irregular (disorderly) reflection (Figure 14.6(b)). Irregular reflection is also known as diffuse reflection because after reflection, the rays spread out in different directions. Do the laws of reflection still apply in the case of diffuse reflection?

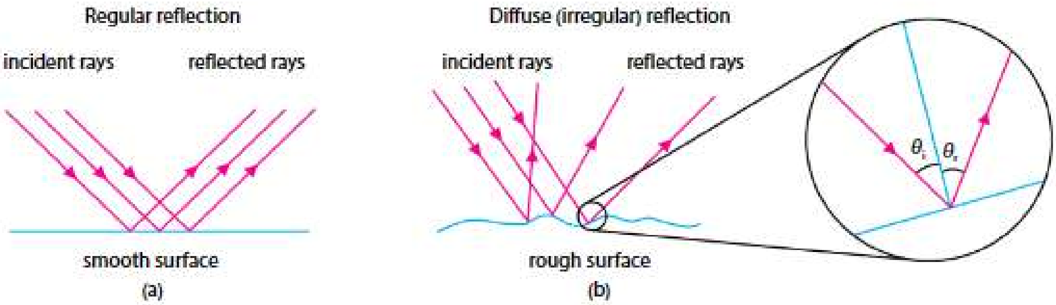


Figure 14.6 Comparing (a) regular and (b) irregular reflection

In both regular and diffuse reflection, the laws of reflection apply for each individual ray. In the case of regular reflection, the parallel incident rays are reflected in the same direction because the surface is smooth. All the rays have the same angles of incidence and reflection.

In the case of diffuse reflection, the parallel incident rays are reflected in different directions because the surface is uneven or rough. The normals at different points on the surface are not parallel to one another. Thus, the angles of incidence and reflection of one ray are different from that of the other rays.

Link

Practical Workbook
Experiment 14A

Characteristics of Mirror Images

Mirror Image and Object Are Equally Far from the Mirror

Consider the following scenario. In Figure 14.7, a point-like LED (Light Emitting Diode) emits light in all directions.

Light from the LED that is reflected at A reaches the eye. The nerves on the retina (area at the back of the eye) sense the light and transmit electrical signals to the brain. The brain interprets that the light comes from inside the mirror (see the black dashed lines in Figure 14.7).

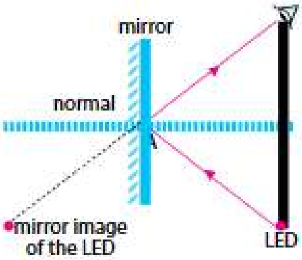


Figure 14.7 The apparent source of light (LED) appears behind the mirror

Do you think the ray shown in Figure 14.7 is the only ray that the eye can sense? As shown in Figure 14.8, the pupil is an extended opening that allows a bundle of rays to reach the retina. The two rays shown are the limits of the bundle of rays that can enter the pupil. Any ray from the LED that reaches the mirror between A and B will be received by the eye and sensed by the brain.

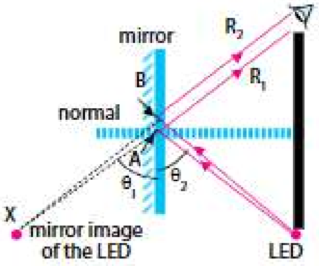


Figure 14.8 Locating the mirror image of a point object

To the brain, the rays reflected off the segment AB on the mirror to the eye seem to be coming from the intersection point X. Hence, the brain interprets that X seems to be where the LED is located. What we see in the mirror at X is called the mirror image of the LED.

Link

Biology

In Biology, we learn that nerves transmit information using electrical signals.

Can you show that $\theta_1 = \theta_2$? Can you go on to show that the perpendicular distance of X from the mirror is equal to the perpendicular distance of the LED from the mirror? After comparing the angles and the distances, the following important result about the positions of mirror images can be obtained.

▶ The image of a point object in a plane mirror is always as far behind the mirror as the object is in front of the mirror.

We shall see that this property is applicable to all points of an extended object (an object with length, width and height).

Light can be reflected off a piece of paper and a mirror. Why can we see an image of ourselves on a mirror but not on a piece of paper?

The surface of a piece of paper is uneven when viewed under a microscope. Let us consider Figure 14.9 where the segment between A and B of the piece of paper is not smooth or flat. The segment is made up of numerous tiny uneven surfaces.

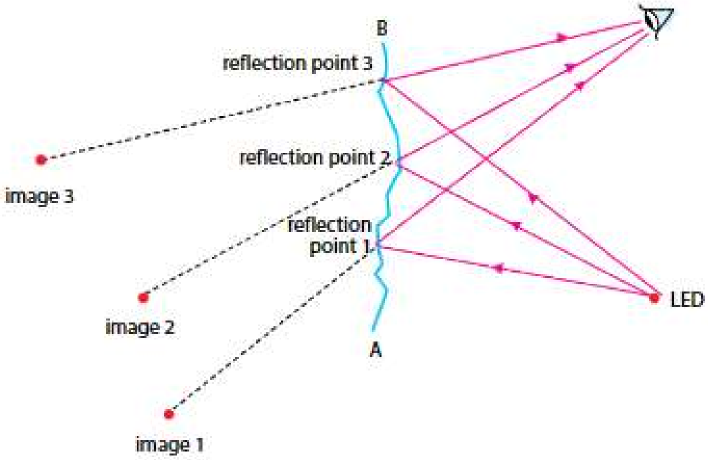


Figure 14.9 An uneven surface leads to an overall diffused image that is made up of many image points at different locations.

In Figure 14.9, three examples of reflections of rays from the LED are shown. Each reflection points to a different location where the LED seems to be at. The brain cannot interpret where the image is. The tiny point source of light looks like many point sources that are at different locations (images 1, 2 and 3) after reflection. There is a diffused reflection. Hence, a piece of paper with an uneven surface cannot form a mirror image.

Mirror Image is Virtual

A mirror image is often constructed geometrically on the two-dimensional plane of a piece of paper as shown in Figure 14.8. However, in real life, objects such as the wireframe shown in Figure 14.10 are three-dimensional.

In Figure 14.10, the four corners of the wireframe are as far in front of the mirror as their corresponding image points are behind the mirror. Every point on the frame will have a corresponding image point that is equally far away from the reflecting surface (mirror). Do all the image points behind the mirror actually exist?

The answer is "no", because light does not come from any point behind the mirror. The image in the mirror is made up of a set of imaginary points. Therefore, the mirror image is called a virtual image and it is a three-dimensional **virtual** object.

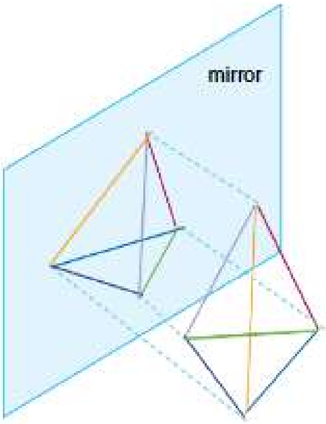


Figure 14.10 Each image point in the mirror is virtual. The distance of the image from the mirror equals the distance of the object from the mirror.

Mirror Image and Object Are of the Same Size

The virtual mirror image of an object refers to the set of imaginary points that are as far behind the mirror as the corresponding points of the object are in front of the mirror. Hence, the virtual mirror image is always the same size as the actual object, provided that the mirror is a plane mirror.

Note that the size of the image depends on the observer. The position of the observer looking at the image and object plays a part in the perception of the size of the virtual image.

The virtual mirror image is the same size as the actual object. Look at Figure 14.11. Why does the woman in the mirror look smaller than the actual woman?

When we look at two identical objects, they may not seem to be of the same size if they are placed at different distances away from us. An object that is further away looks smaller. Thus, in Figure 14.11 the mirror image seems smaller because the observer is further from the mirror image than the woman.

In Figure 14.12, the woman and the mirror image are identical in size because the observer is at the same distance from the mirror image and the woman.

Figure 14.11 The virtual mirror image of the woman seems smaller because it is further away from the observer.

Figure 14.12 The woman and her virtual image seem to be of the same size because they are equally far away from the observer.

Mirror Image Is Laterally Inverted and Upright

Consider the man and his mirror image in Figure 14.13. When the man's right hand is raised, the image's left hand is raised. The image is thus described as **laterally inverted**. The image is also **upright**.

Figure 14.13 The image in the mirror is laterally inverted and upright.

To summarise, the five characteristics of plane mirror images are:
- The image and object are equally far from the mirror.
- The image is virtual.
- The image and object have the same size.
- The image is laterally inverted.
- The image is upright.

Link
Practical Workbook
Experiment 14B

Steps for Drawing a Ray Diagram

For a given object, how do we accurately draw how its rays enter an observer's eye? Figure 14.14 shows a point object O in front of a plane mirror.

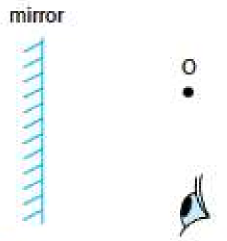
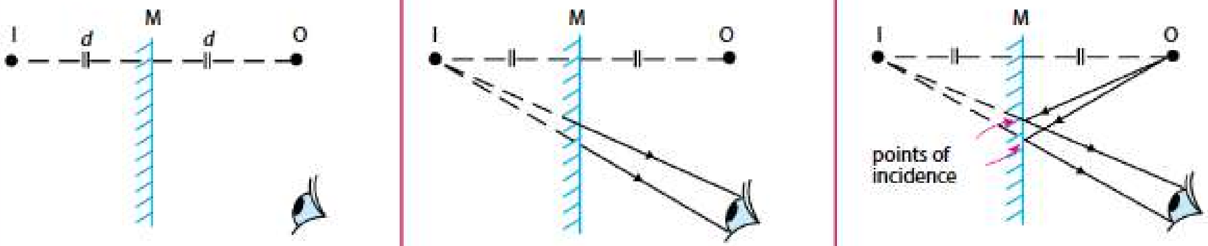


Figure 14.14 Object O in front of a plane mirror

The steps to draw a ray diagram for the point object O are shown in Figure 14.15.



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

- Draw a dashed line at 90 ° to the mirror, extending beyond the expected position of the image.
- Measure *d* and use it to locate the position of image I.

Step 2:
Draw the reflected rays.

- Draw lines to join I to the eye. Use dashed lines behind the mirror and solid lines for rays reflected into the eye.
- Insert arrowheads to indicate the direction at which the light travels.

Step 3:
Draw the incident rays.

- Draw solid lines from object O to the points of incidence on the mirror. These are the incident rays.
- Insert arrowheads to indicate the direction at which the light travels.

Figure 14.15 Steps for drawing a ray diagram

The resultant drawing in Figure 14.15 is known as a ray diagram. The steps will ensure that the angle of incidence is equal to the angle of reflection. For an extended object, the same three-step process needs to be repeated for key object points.

Worked Example 14A

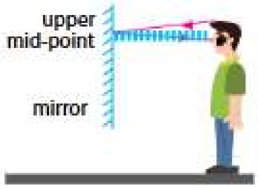
Tom, who is 1.5 m tall, wants to mount a mirror on a wall so that he can get a full view of himself. What is the minimum vertical length of the mirror that is needed?

Thought Process

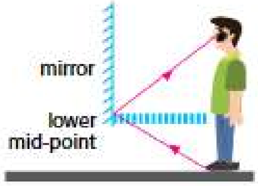
To get a full view of himself, Tom must be able to see the top of his head and bottom of his feet. The ray from the top of his head and the bottom of his feet must reflect off the mirror into his eyes. The laws of reflection should apply.

Answer

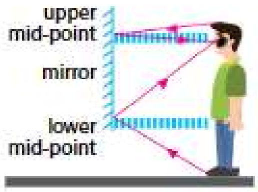
We use the second law of reflection (angle of incidence θ_i is equal to the angle of reflection θ_r) to guide us as we draw the ray diagram.



Draw a ray from the top of Tom's head to the mirror. In order to see his reflection, the incident ray from the top of his head must be reflected to his eye. Since the angle of incidence equals the angle of reflection, the highest point of the mirror should be at the mid-point between his eye and the top of his head.



Draw a ray from the bottom of Tom's feet to the mirror. In order to see his reflection, the incident ray from the bottom of his feet must be reflected to his eye. Since the angle of incidence equals the angle of reflection, the lowest point of the mirror should be at the mid-point between his eye and the bottom of his feet.



Notice that the distance between Tom and the mirror does not affect the upper and lower mid-points.

To see the top of his head, the point of reflection on the mirror is the mid-point between his eye and the top of his head (upper mid-point).
To see his feet, the point of reflection is the mid-point between his eye and his feet (lower mid-point).

Hence, the minimum vertical length of the mirror is half of his height.
Minimum vertical length of the mirror = $\frac{1.5\text{ m}}{2}$ = 0.75 m

Tech Connect

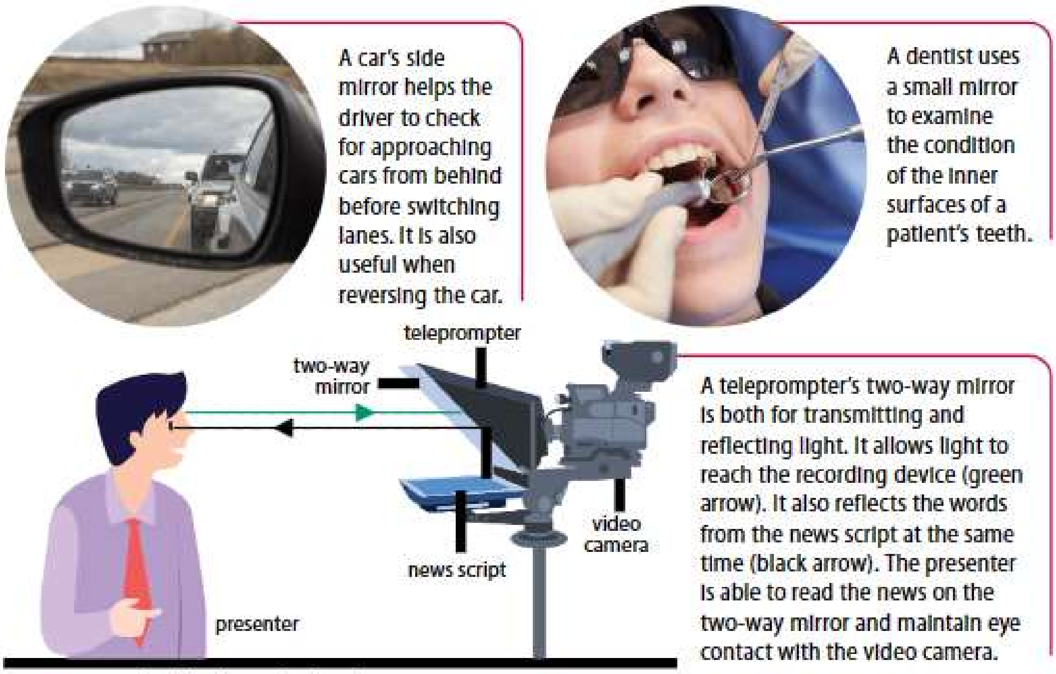
Fluorophores are molecules that emit low frequency light when illuminated with light of higher frequency. They can be manipulated to bind with specific protein molecules found in tumour cells.

In a surgery to remove cancerous tissues, these fluorophores can be made to glow. This helps the surgeon to achieve a thorough removal of cancerous tissues while minimising the removal of healthy tissues.

Some companies have also made use of fluorophores to tag SARS-CoV-2 viruses in samples so that they glow when activated by the light source from a smartphone. The smartphone's camera can then detect whether the virus is present in the samples.

Applications of Reflection

Figure 14.16 shows some applications of reflection.



A car's side mirror helps the driver to check for approaching cars from behind before switching lanes. It is also useful when reversing the car.

A dentist uses a small mirror to examine the condition of the inner surfaces of a patient's teeth.

A teleprompter's two-way mirror is both for transmitting and reflecting light. It allows light to reach the recording device (green arrow). It also reflects the words from the news script at the same time (black arrow). The presenter is able to read the news on the two-way mirror and maintain eye contact with the video camera.

Figure 14.16 Applications of reflection

Let's Practise 14.1

1 An observer and an L-shaped wire are in front of a mirror (Figure 14.17).

- (a) Draw solid lines with arrows to indicate how the light rays from the ends and corner of the wire reach the eye.
- (b) Does the observer need the full length of the mirror in order to see the entire wire? If not, indicate the shortest portion of the mirror that allows the observer to see the whole wire.
- (c) It is possible to block the rays from the longer section of the wire so that the observer will see only rays from the shorter section of the wire. Indicate the part of the rays that should be blocked.

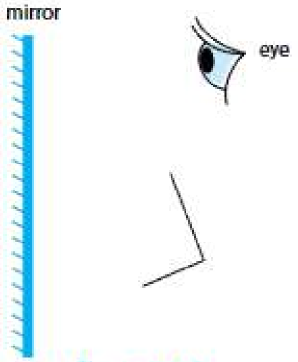


Figure 14.17

2 Perpendicular mirrors are placed next to two groups of printed letters (Figure 14.18).

Figure 14.18

- (a) Draw the mirror images of the letters in each mirror.
- (b) Will all the letters in the mirror be of the same size as those printed on the paper? If not, will the letters inside the mirror look smaller or bigger?

Link

Theory Workbook
Worksheet 14A

14.2 How Is Light Refracted?

Learning Outcomes

- Recall and use the terms *normal, angle of incidence* and *angle of refraction* to describe the refraction of light.
- Recall and apply the relationship *sin i / sin r = constant* to new situations or to solve related problems.
- Define *refractive index* of a medium in terms of the ratio of speed of light in vacuum and in the medium.

Figure 14.19 shows a mirage or illusion that the road is wet. On a very hot day, the layers of air progressively become cooler and denser as they get higher above the road surface. The varying density of the air layers progressively bend or refract the sky's blue light, leading to the illusion of water on the road.

Figure 14.19 Illusion of a wet road due to refraction of light

If a light ray is directed at a boundary between two materials, we will observe the bending of the rays (Figure 14.20). The bending of light is known as refraction.

▶ **Refraction** is the bending of light as it passes from one optical medium to another.

The **refracted ray** is the light ray that enters a medium and undergoes a change of direction. The angle of refraction is the angle between the refracted ray and the normal at the point of incidence. The incident angle is labelled *i* while the angle of refraction is labelled *r*.

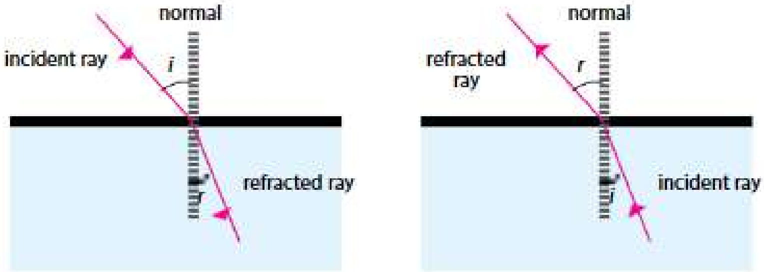


Figure 14.20 Refraction occurs at the boundary between two mediums of different optical densities.

Why does refraction take place? It occurs as light travels at different speeds in different media.

Helpful Note

Figure 14.21 shows light modeled as rays, while Figure 14.22 shows light modeled as a wave. While the ray model of light can be used to explain rectilinear propagation, the wave model of light is used to explain refraction and how the wavelength changes when waves travel from one medium to another.

Link

Recall from Chapter 11: A wavefront is an imaginary line joining all adjacent points of a wave that are in phase.

Consider a car travelling from the pavement (flat solid ground) to sand at an angle (Figure 14.21).

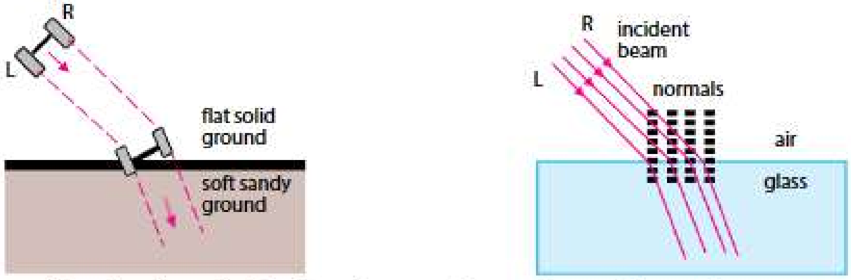


Figure 14.21 Using the change in direction of a toy car due to a decrease in speed to explain refraction of a light ray as it passes from air to glass

As wheel L goes onto the sand first, it sinks into the sand. This leads to a greater resistance than when it is on solid ground. In the meantime, wheel R is still on the solid ground and is travelling faster than wheel L. As a result, the pair of connected wheels turns towards the sandy ground.

Similarly, a light ray bends towards the normal when it travels from air (an optically less dense medium) to glass (an optically denser medium).

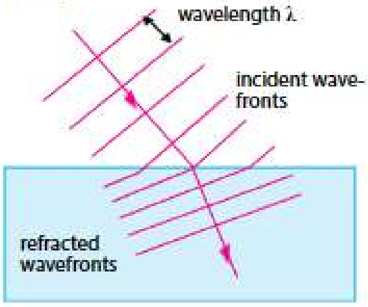


Figure 14.22 Bending of wavefronts

Instead of treating light as a bundle of rays, we can also see light as a wave. From this perspective, Figure 14.21 can be modified to show the wavefronts (Figure 14.22).

Just like reflection, refraction is governed by laws — the laws of refraction.

The **first law of refraction** states that the incident ray, refracted ray and the normal at the point of incidence all lie in the same plane.

The **second law of refraction** states that for two given media, the ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant, that is, $\frac{\sin i}{\sin r}$ = constant.

Refractive Index

The **refractive index *n*** of a medium is defined as the ratio of the speed of light in a vacuum to the speed of light in that medium.

$$n = \frac{c}{v}$$

where c = speed of light in a vacuum
v = speed of light in the medium

The speed of light in vacuum is constant over all frequencies. However, in different media, the speed of light varies with the frequency of light. Hence, the value of refractive index is different for different media.

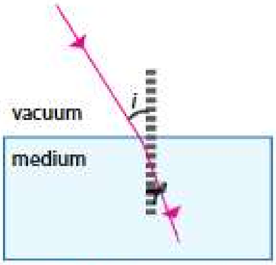


Figure 14.23 Refraction of light at a surface

For a light ray passing from a vacuum into a given medium, the refractive index n of the medium is also given by the ratio, $\frac{\sin i}{\sin r}$ (Figure 14.23).

$$n = \frac{\sin i}{\sin r}$$

where i = angle of incidence in a vacuum
r = angle of refraction in the medium

In a school laboratory, it is not practical to find the refractive index by measuring the speed of light. Hence, n is measured using the equation, $n = \frac{\sin i}{\sin r}$.

Another difficulty is that the angle of incidence i is in a *vacuum*. Since the speeds of light in a vacuum and air are almost the same, we can measure the angle i in air or a vacuum.

Most of the time, if we need to find the refractive index of a medium, we can refer to the tables of values measured and published by scientists and engineers.

Table 14.1 The refractive indices 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.

Materials with higher refractive indices (singular: index) cause light to slow down more. The angle of refraction r is smaller as the light bends more towards the normal. They are described as having higher "optical density". However, a higher "optical density" does not always mean that a material has a higher density.

Link
Practical Workbook
Experiment 14C

Principle of Reversibility of Rays

In Figure 14.24(a), a ray passes from A to the material and to B. In Figure 14.24(b), the light source is moved to B and a ray is sent in the opposite direction. It is found that the ray will reach A via the exact same path in Figure 14.24(a). There is no change in the angles x and y. This is called the principle of reversibility of light.

The **principle of reversibility of light rays** states that regardless of how many times a light ray has been reflected or refracted, it will follow the same path when its direction is reversed.

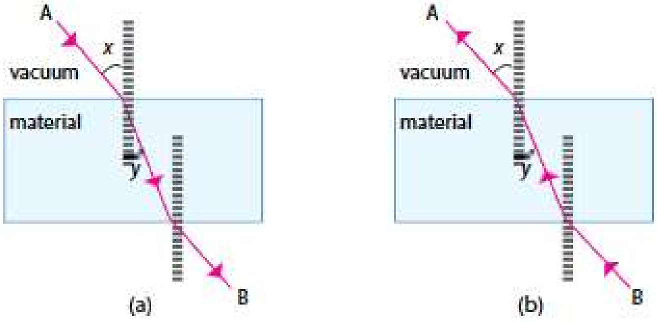


Figure 14.24 Set-ups to illustrate the principle of reversibility of light

Due to the principle of reversibility of rays, the refractive index of the material is always given by $n = \frac{\sin x}{\sin y}$ regardless of whether the ray goes from A to B or B to A.

A ray box contains a light source that emits a light ray or a beam of light (Figure 14.25). A ray box can be used to trace the path of light through a glass block as shown in Figure 14.26. The ray that emerges from the glass block is known as the **emergent ray**.

Figure 14.25 Ray box

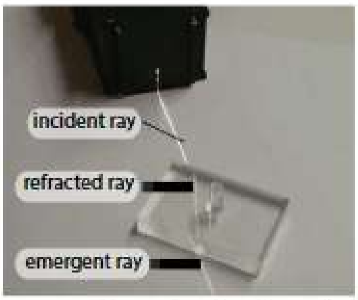


Figure 14.26 Set-up showing the path of ray through a block

Helpful Note

α is another Greek alphabet called alpha.

Let's Investigate 14A

Aim

To determine the refractive index of a glass block

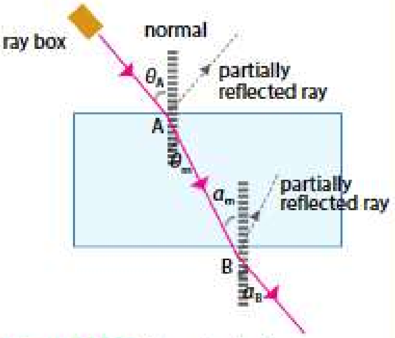


Figure 14.27 Set-up to find refractive index of a glass block

Procedure

1 Place a glass block on a piece of paper. Trace the outline of the glass block.
2 Use a ray box to shine a ray through the glass block (Figure 14.27).
3 Trace the path of the light ray outside the glass block.
4 Remove the glass block. Connect the entry point A and exit point B. Use a set-square to draw the two normals.
5 Measure the angles using a protractor. Calculate the refractive index using these equations, $n_A = \frac{\sin \theta_A}{\sin \theta_m}$ and $n_B = \frac{\sin \alpha_B}{\sin \alpha_m}$.

Discussion

n_A and n_B are equal as they are the refractive index of the same glass block.
Based on geometry:
$\theta_m = \alpha_m$
$\theta_A = \alpha_B$

In other words, the incident ray to the block and the emergent ray from the block are parallel to each other.

Helpful Note

It is useful to remember that when a ray enters and exits via two parallel sides of a uniform glass block, the incident and emergent rays are parallel.

Effects of Refraction

"Bent" Objects

Figure 14.28 shows a pencil placed vertically behind a glass block and seen by an observer from three positions.

Figure 14.29 shows what the observer sees when looking at the pencil through the glass block at the three positions. The pencil appears "bent" in positions 1 and 2. Why is this so?

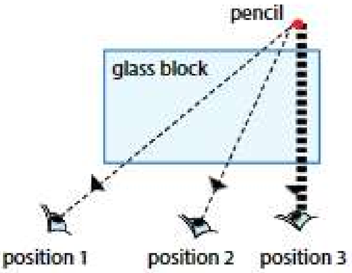


Figure 14.28 Pencil placed vertically behind a glass block and observed from three positions

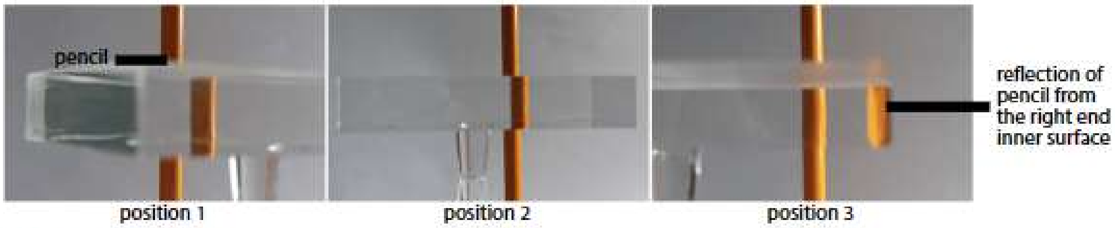


Figure 14.29 Views of the pencil through the glass block from different positions

The pencil appears "bent" due to refraction. Let us look at the ray diagrams when the observer is at positions 1 and 2.

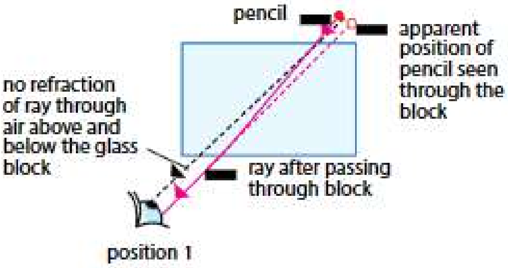


Figure 14.30 Ray diagram showing the apparent direction of a light ray through the block

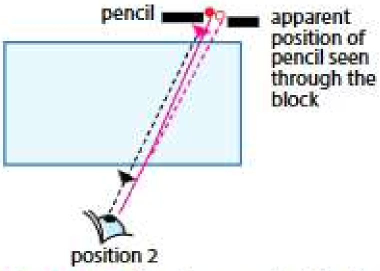


Figure 14.31 Ray diagram showing the apparent direction of a light ray through the block (with a smaller angle of refraction)

The pencil can be seen as it reflects light to the eyes of the observer. When the observer is at position 1, the reflected light ray from the pencil that passed through the block is refracted when it enters and exits the glass block (Figure 14.30).

The emergent ray is parallel to the incident ray and the ray through the air. The light ray as seen by the eye gives the impression that the part of the pencil seen through the glass block is at another position. This gives rise to the effect that the pencil is "bent" when seen through the block.

When the observer is at position 2, there is a smaller angle of incidence between the reflected light ray from the pencil and the normal when the ray enters the block (Figure 14.31). Since $n = \frac{\sin i}{\sin r}$, there is less refraction. The pencil appears to "bend less".

When the observer is at position 3, the reflected light ray from the pencil is perpendicular to the block. The ray enters the block without refraction. Thus, the pencil does not look "bent" from position 3.

We have just seen that after a light ray passes through a glass block, it will be parallel to the incoming ray when it exits the block. However, the ray is shifted from its original path. How would increasing the width of the glass block affect the amount shifted by the light ray?

Misperception of Depth

When the water in a swimming pool is very still, we can see the bottom of the pool very clearly. In such a scenario, the pool looks shallower than it actually is (Figure 14.32). Why is this so?

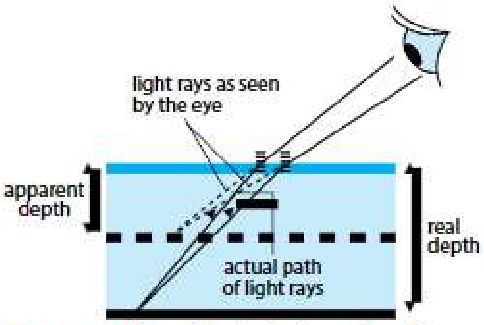


Figure 14.32 A pool looks shallower than it actually is.

Worked Example 14B

A student sees a fish below the water surface (Figure 14.33). With the help of appropriate construction lines, mark the apparent position of the fish with x. Using the principles of refraction, explain why the actual depth and the perceived depth are different.

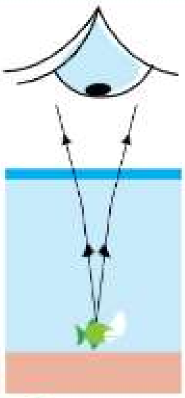
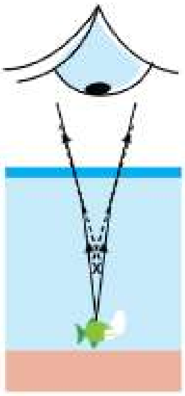


Figure 14.33

Answer

As shown in the diagram, when light rays from the fish exit from the water, they refract. To the eye, the light rays are perceived to be coming from the point x.



Let's Practise 14.2

Fill in the blanks.

1 The equation $n = \frac{c}{v}$ gives the refractive index n of any medium. If the medium is a vacuum, then the value of n for a vacuum must be = ______.
2 Since light travels fastest in a vacuum, the refractive index, $n = \frac{c}{v}$ of any material must always be greater than the number ______.
3 The greater the slow-down in speed when a light ray enters a medium from air or a vacuum, the ______ will be the n for the medium.

Link
Theory Workbook
Worksheet 14B

14.3 What Is Total Internal Reflection?

Learning Outcomes

- Explain the terms *critical angle* and *total internal reflection*.
- Apply total internal reflection to the use of optical fibres in telecommunication and medicine, stating the advantages of such use.

Figure 14.34 shows a reflected image of a fish underwater. This is due to a process called **total internal reflection** at the boundary between water and air.

To be able to see such a clear reflection, the water surface needs to be still. In this section, we will learn about the other conditions needed for total internal reflection.

Figure 14.34 Total internal reflection of a fish as seen underwater

Investigating Total Internal Reflection

Using a semi-circular glass block and a ray box, we can investigate the conditions needed for total internal reflection to occur.

To ensure that the ray entering the block from the curved surface does not bend, the light ray is always directed towards the centre of the glass block's diameter.

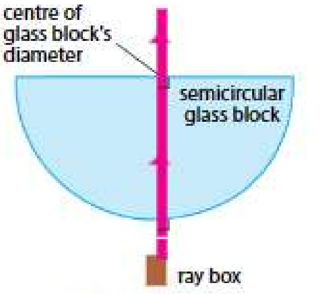


Figure 14.35

When a light ray crosses both boundaries perpendicularly, there is no change in the ray's direction (i.e. no refraction) (Figure 14.35).

Helpful Note

The radius of a circle is always perpendicular to the tangent to the circle.

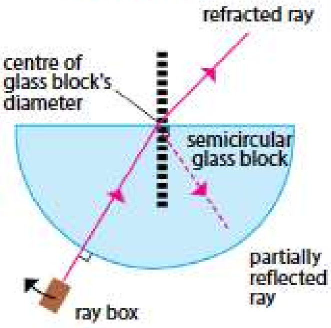


Figure 14.36

As the ray box is moved clockwise, there is refraction and partial reflection (Figure 14.36).

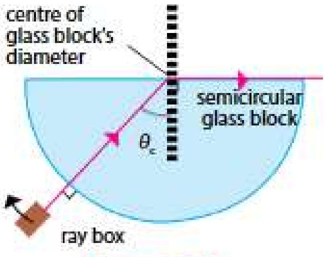


Figure 14.37

As the ray box continues to move clockwise, at a particular angle of incidence, θ_c, the angle of refraction becomes 90 ° (Figure 14.37).

θ_c is known as the *critical angle*.

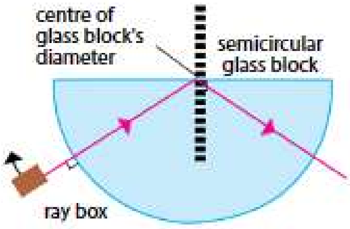


Figure 14.38

When an angle of incidence in the glass block is greater than θ_c, the ray will be reflected off the flat surface of the block (Figure 14.38). There is no refraction.

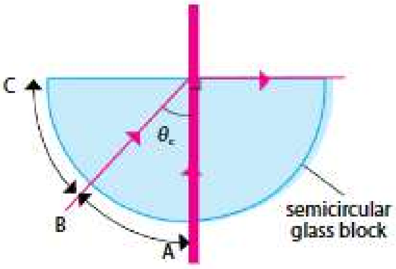


Figure 14.39

Using Figure 14.39, we can summarise that:

- between A and B, the ray undergoes refraction with some reflection;
- at B, the angle of refraction is 90 ° and the angle of incidence θ_c is known as the *critical angle*; and
- between B and C, the incident ray undergoes *total internal reflection*.

We can define **critical angle** and **total internal reflection** as follows.

▶ **Critical angle** θ_c is defined as the angle of incidence in an optically denser medium for which the angle of refraction in the less dense medium is 90 °.

▶ **Total internal reflection** is the *complete* reflection of a light ray in an optically denser medium at the boundary with an optically less dense medium.

Link
Practical Workbook
Experiment 14D

The two conditions for total internal reflection to occur:

- The incident ray must travel from an optically denser medium to an optically less dense medium.
- The angle of incidence must be greater than the critical angle.

There is a relationship between the critical angle θ_c and the refractive index n for a medium.

For a glass block surrounded by air, the formula for its refractive index n in terms of the critical angle θ_c can be derived as follows:

Recall that the formula for refractive index is $n = \frac{\sin i}{\sin r}$.

The angle of refraction is 90 ° when the angle of incidence in the glass block is θ_c. Applying the principle of reversibility:

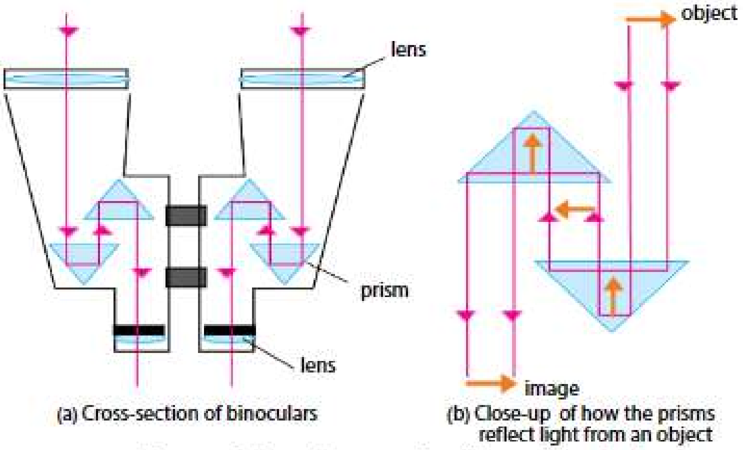
$$n = \frac{\sin i}{\sin r} = \frac{1}{\sin \theta_c}$$

Applications of Total Internal Reflection

Glass Prisms in Binoculars

Glass prisms are used to reflect light in binoculars (Figure 14.40(a)). Good-quality binoculars use prisms instead of mirrors as prisms are more durable and have better image quality.

After two total internal reflections due to the prisms, the resulting image is in the same orientation as the object (Figure 14.40(b)).



(a) Cross-section of binoculars

(b) Close-up of how the prisms reflect light from an object

Figure 14.40 The use of glass prisms to reflect light reduces the size of binoculars.

Optical Fibres

Optical fibres made from glass or plastic can carry information in the form of coded light pulses (Figure 14.41). The fibres rely on total internal reflection of light to transmit signals.

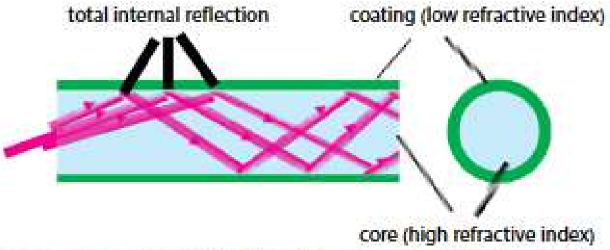


Figure 14.41 An optical fibre has a core of a high refractive index. It is coated with another material of a lower refractive index. Why are materials of different refractive index used?

Optical fibres are thin and flexible. They are used in telecommunications and medicine.

Telecommunications

For transmission of large amount of data, the optical fibres can be bundled to form thicker cables (Figure 14.42). Larger and longer undersea cables that span thousands of kilometres are used as communication links across continents.

There are several advantages of using optical fibres over copper wires in telecommunications.

- The data transfer rate is ten to thousands of times faster as compared to using copper wires, radio waves or microwaves.
- There is less signal loss as compared to copper cables.
- Optical fibres are lighter and cheaper as compared to copper cables of similar length.

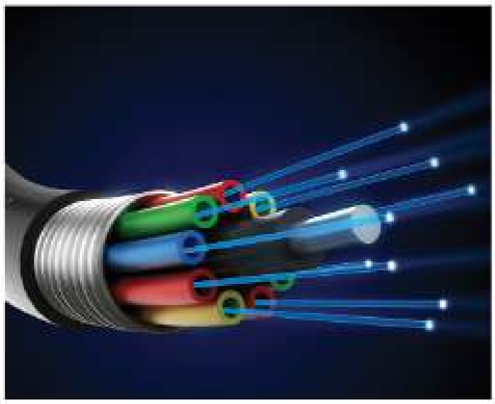


Figure 14.42 Optical fibre cables are commonly used in telecommunications these days.

Medical Use

An endoscope can be used to inspect the insides of hollow organs such as the digestive tract (Figure 14.43). The endoscope has a number of channels available for surgical instruments such as a laser and camera. Being flexible, optical fibres are ideal to be used in the endoscope to transmit light for illumination and to capture the images inside organs.

Similarly, optical fibres also play an important role in laparoscopy (a type of "keyhole" surgery). In laparoscopy, no large incisions are made in the skin as an instrument called laparoscope is used (Figure 14.44).

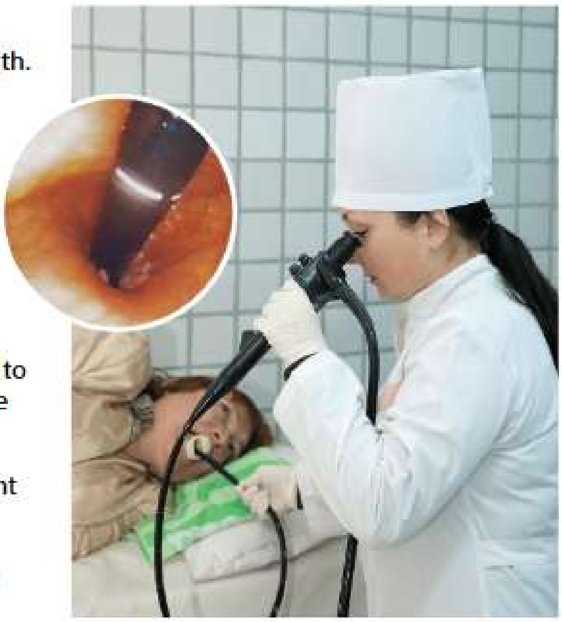


Figure 14.43 An endoscope is a long tube consisting of optical fibres. The inset shows the view inside the intestines captured using an endoscope.

Laparoscope is a small tube with a light source and a camera. The images captured are transmitted to a monitor. The small size and flexibility of optical fibres makes it ideal for use in laparoscope to transmit light. Laparoscopy greatly reduces the pain, bleeding and recovery time of patients.

The following lists the advantages of optical fibres in medicine.

- Optical fibres are thin and light. Thus, the endoscopes and laparoscopes are kept small for minimally invasive examination and surgery.
- Optical fibres are flexible. Thus, the endoscopes and laparoscopes can curve around obstacles when taking images inside the body.

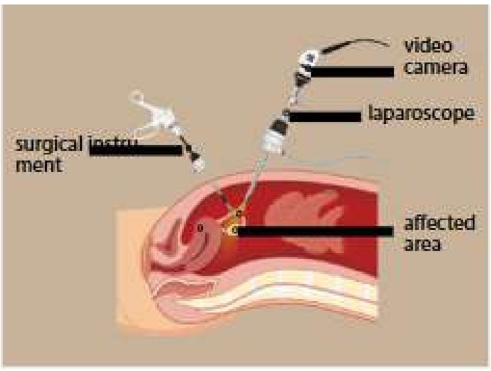


Figure 14.44 Laparoscopy is a type of surgery that uses a long fibre optic cable system, which allows viewing of the affected area.

Rain Sensor

A rain sensor is a small device attached to the inner side of the glass windshield (Figure 14.45).

When the windshield is dry, infrared light from the light emitting diode (LED) is able to reach the photodiode detector. When there are raindrops on the windshield, less infrared light is reflected to the photodiode detector. Thus, the sensor connected to the photodiode detector will turn on the windshield wiper.

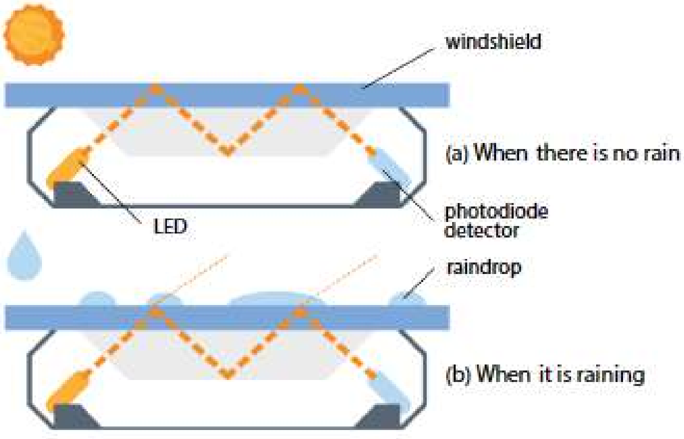


Figure 14.45 Rain sensor making use of total internal reflection

Worked Example 14C

When the first medium is not air or a vacuum, the more general formula for refractive index is:
$\frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1}$ where n_1 and n_2 are refractive indices of media 1 and 2 respectively (Figure 14.46).

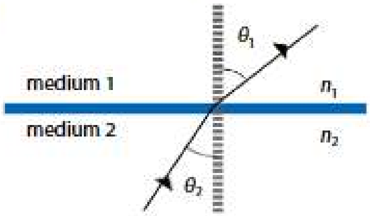


Figure 14.46

(a) If medium 1 is air and medium 2 is glass such that $n_{air} = 1.0$ and $n_{glass} = 1.5$, calculate the critical angle in this scenario.

(b) If medium 1 is replaced by water with $n_{water} = 1.3$, calculate the critical angle.

(c) The rain sensor distinguishes between a dry and wet day by the amount of infrared light received by the photodiode detector (Figure 14.47). If the infrared light is not to undergo total internal reflections on a wet day, what is the condition that must be applied to the angle of incidence?

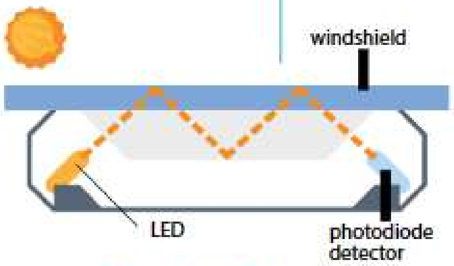


Figure 14.47 Rain sensor

Answer

(a) Let the critical angle be θ_c. The critical angle in the denser medium corresponds to 90 ° in the less dense medium.

$$\frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1}$$
$$\frac{1.0}{1.5} = \frac{\sin \theta_c}{\sin 90^\circ}$$
$$\sin \theta_c = 0.6667$$
$$\theta_c = 41.8^\circ$$

(b)
$$\frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1}$$
$$\frac{1.3}{1.5} = \frac{\sin \theta_c}{\sin 90^\circ}$$
$$\sin \theta_c = 0.8667$$
$$\theta_c = 60.1^\circ$$

(c) The beam's angle of incidence must not exceed 60.1 °. (Hence on a rainy day, the amount of light reaching the photodiode will be lower than on a dry day.)

Worked Example 14D

An optical fibre is used to transmit light by total internal reflection. The fibre core has a cladding layer as shown in Figure 14.48.

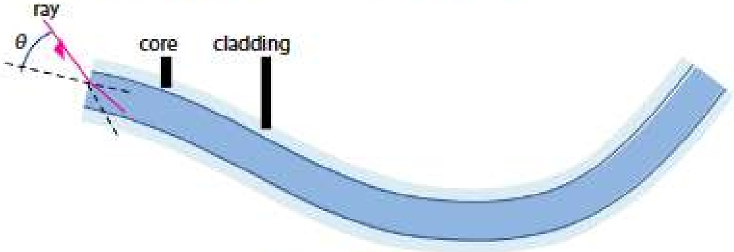


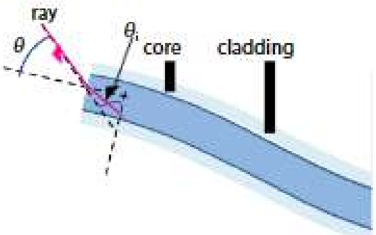
Figure 14.48

(a) Why must the cladding material have a refractive index that is lower than that of the core?
(b) Explain why the angle of incidence θ must not be too large.
(c) Suggest an example of how optical fibres are useful in medicine.
(d) Complete the path of the incident ray in Figure 14.48 until it emerges from the other end of the optical fibre.

Answer

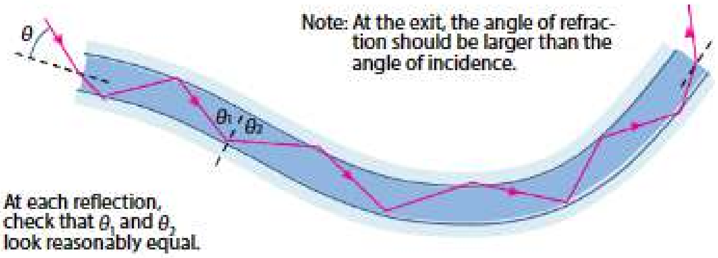
(a) A condition for total internal reflection (TIR) to occur is that the ray must travel towards an optically less dense medium, which has a lower refractive index.

(b) The second condition for TIR to occur is that the ray's angle of incidence θ_i (at the boundary between the core and cladding) must be greater than the critical angle.
If θ is too large, the angle θ_i will get smaller. If θ_i is smaller than the critical angle, there will be no TIR.



(c) Optical fibres are used in endoscopes or laparoscope to channel light to an area inside the body to generate an image.

(d)



Note: At the exit, the angle of refraction should be larger than the angle of incidence.

Note: At each reflection, check that θ_1 and θ_2 look reasonably equal.

Link
Theory Workbook
Worksheet 14C

Let's Practise 14.3

1 (a) Define *total internal reflection*.
(b) What are the conditions for total internal reflection?
2 Give **two** examples of how total internal reflection is useful.

14.4 How Does a Converging Lens Work?

Learning Outcomes

- Describe the action of a thin converging lens on a beam of light.
- Define the *focal length* for a converging lens.
- Draw ray diagrams to illustrate the formation of real and virtual images of an object by a thin converging lens.
- Describe the characteristics of images formed by a thin converging lens.

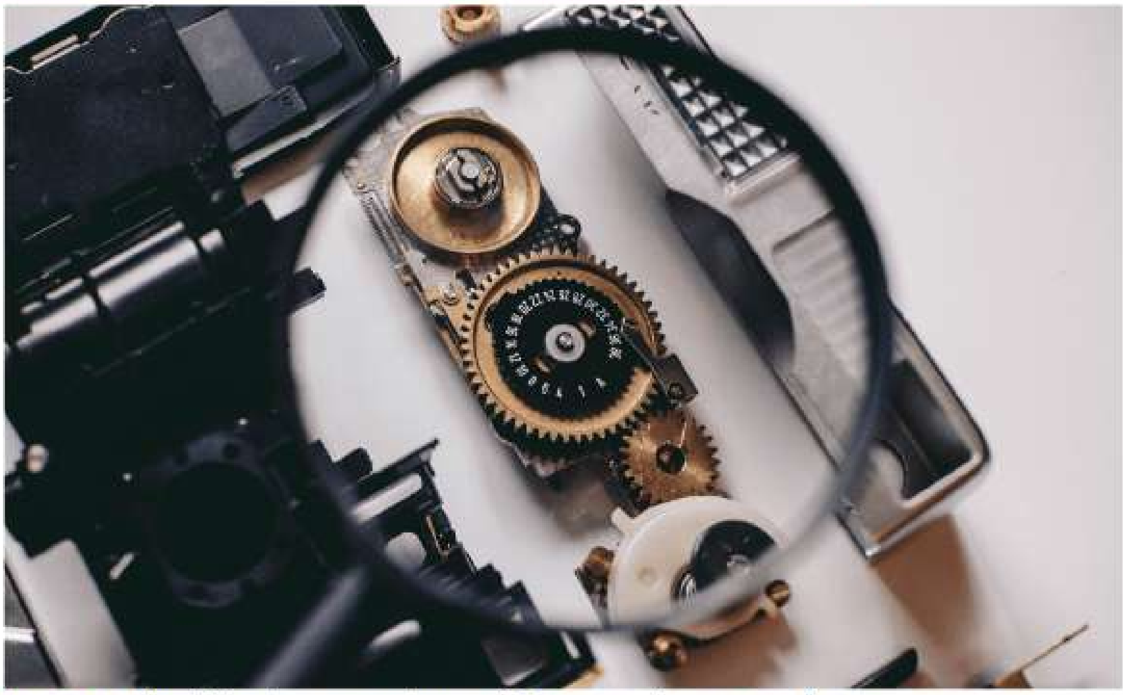


Figure 14.49 Magnifying glasses are used to magnify tiny parts such as screws and gears

A magnifying glass is an essential tool for people who have to work with tiny parts such as screws and gears (Figure 14.49). Have you noticed that the circular piece of glass is thicker in the centre than at the rim?

Figure 14.50 Side view of the lens of a magnifying glass

The side view of the magnifying glass is shown in Figure 14.50. Its shape is thicker in the centre such that a beam of parallel rays passing through it will be brought to a single focal point.

A device made of glass or other transparent material that is able to concentrate light rays is called a **converging lens** (Figure 14.51).

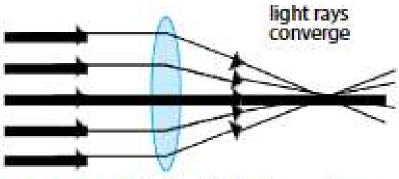


Figure 14.51 Path of light through a converging lens

Word Alert
Converge: Heading towards a single point

How does the converging lens **converge** the parallel rays to a point?

Consider the lens to be made up of different sections as shown in Figure 14.52. Notice that refraction happens upon entry and exit of each section. The lens is designed in such a way that all emerging rays converge at a point.

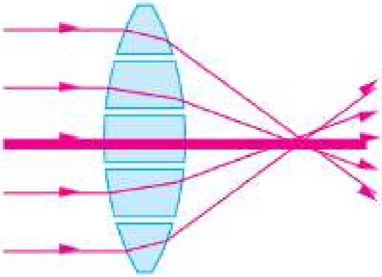


Figure 14.52 Illustration of refraction occurring at each section of a converging lens

Lenses come in various shapes and not all are converging. Figure 14.53 shows two types of lenses.

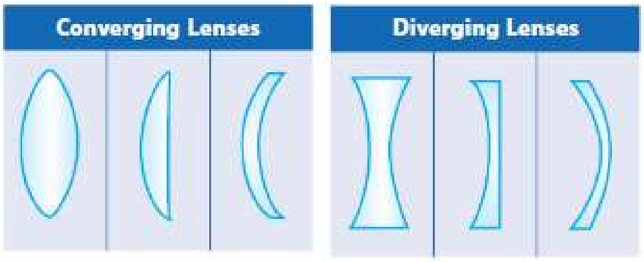


Figure 14.53 Different types of converging and diverging lenses

Word Alert
Diverge: Spread out

Notice that all converging lenses are thicker in the centre compared to their rims. In contrast, all diverging lenses are thinner at the centre. Diverging lenses cause the incoming rays to **diverge**.

In this section, we are going to focus on the thin symmetrical converging lens.

Terms Used to Describe Thin Converging Lenses

We will learn about the terms used to describe a thin converging lens (Figure 14.54).

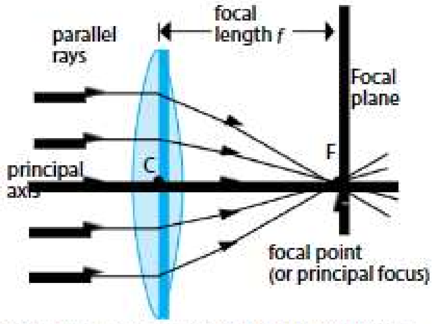
Principal axis
The line which passes through the centre of the lens and which is perpendicular to the plane of the lens

Optical centre C
The point on the principal axis that is the midpoint between the surfaces of the lens

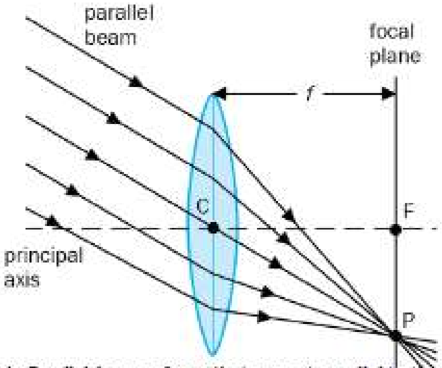
Principal focal point F
The point on the *principal* axis where all the rays parallel to the principal axis meet after passing through the lens

Focal plane
The plane perpendicular to the principal axis on which all parallel rays meet after passing through the lens (It is a plane of all the possible focal points.)

Focal length *f*
The distance between the optical centre C and the principal focus point F



(a) Parallel beam of rays that are parallel to the principal axis



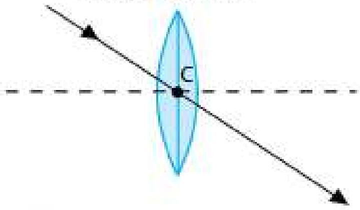
(b) Parallel beam of rays that are not parallel to the principal axis

Figure 14.54 Parallel beam of rays entering a converging lens

Ray Diagrams for Thin Converging Lenses

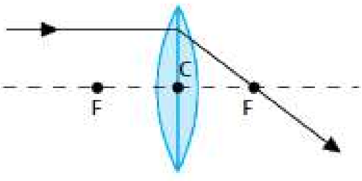
There are three rays passing through a converging lens that can be drawn accurately in ray diagrams. These rays are very useful in helping us locate where the image point will be for a given point on an object (Figure 14.55).

Ray 1: Passes Through Optical Centre C



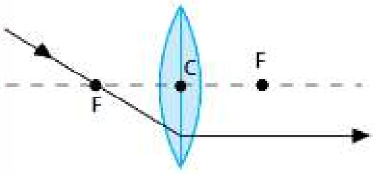
An incident ray will pass through the optical centre without bending. Recall that the emergent ray is parallel to the incident ray and that the shift is small if the lens is thin.

Ray 2: Parallel to Principal Axis



An incident ray parallel to the principal axis is refracted to pass through the principal focal point F.

Ray 3: Passing Through Focal Point F

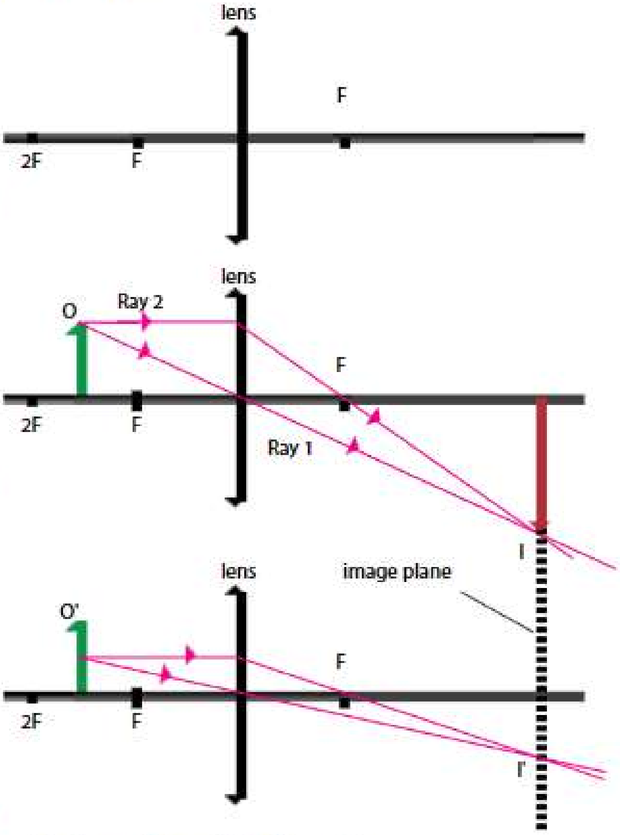


An incident ray passing through the principal focal point F before passing through the lens will emerge parallel to the principal axis (principal of reversibility).

Figure 14.55 Three key rays for drawing ray diagrams for thin converging lenses

Any two of the three rays in Figure 14.55 from a given object point will intersect at a point, which is where the image point is.

Figure 14.56 shows how we can draw the ray diagram for a thin converging lens where the object is an upward arrow located between F and 2F.



Step 1

- Set up the reference points and horizontal axis as shown.
- The double arrow represents the lens.

Step 2

- Draw the object arrow O (green).
- Rays 1 and 2 from Figure 14.56 are used to locate the image at point I. The point where the two rays intersect corresponds to the object point O at the arrow tip.

Step 3

Every point on the object will have a corresponding image point.

- Construction of rays for object point O' will give rise to its image point I'.
- If done accurately, all image points will fall on the image plane indicated by the dotted line.

Figure 14.56 Formation of a real image ($f < u < 2f$, where u is the object distance)

Figure 14.57 shows the ray diagram for a thin converging lens where the object is a downward arrow between F and the optical centre.

In Figure 14.57, we can see that the light rays do not intersect after passing through the lens. However, they intersect on the same side as the object when they are extended. When the light rays enter our eyes, they appear to come from the same side as the object.

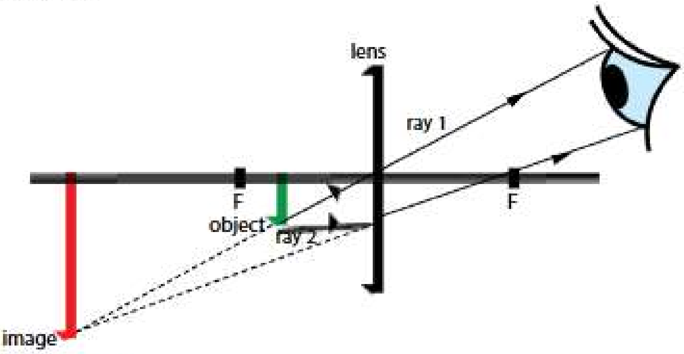


Figure 14.57 Formation of a virtual image ($u < f$, where u is the object distance)

If we were to repeat the construction of rays for other points of the object, we will find that the image plane is along the red arrow. Notice that the whole image as seen by the observer appears to be *magnified* compared to the actual object.

The image is *virtual* just like the image in a mirror.

Real and Virtual Images

When an image is formed by the intersection of light rays, it can be seen by placing a screen at the image plane. An example of this is the image formed on a screen by a video projector (Figure 14.58). Such an image is *real*.

Figure 14.58 Real image projected on a screen by a video projector

In contrast, for the virtual image in Figure 14.57, a screen placed at the image plane will not form a visible image.

▶ A **real image** can be formed on a screen placed at the image plane but a **virtual image** cannot be formed on a screen placed at its image plane.

Link

Recall from Section 14.1: Mirror images are virtual.

Let's Investigate 14B

Aim

To investigate and explain why an arrow may reverse its direction when seen through a beaker of water

Procedure

1 Print or draw two arrows on a piece of paper as shown in Figure 14.59. The arrows should be about 2 to 3 cm long.
2 Fill a beaker with water until it is three-quarter full.
3 Place the paper behind the beaker and in contact with the beaker.
4 Look through the water at the arrows while slowly moving the paper from left to right.
5 Pay attention to the sizes and directions of the arrows as they pass through the centre of the beaker.
6 Place the paper about 10 cm behind the beaker and repeat steps 4 and 5.

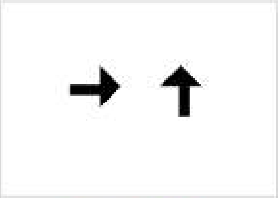


Figure 14.59

Observations

- The right pointing arrow reversed its direction when the paper was placed far away from the beaker. However, when the paper was close to the beaker, there was no inversion of the right pointing arrow.
- The upward pointing arrow was not inverted regardless of how far the paper was.

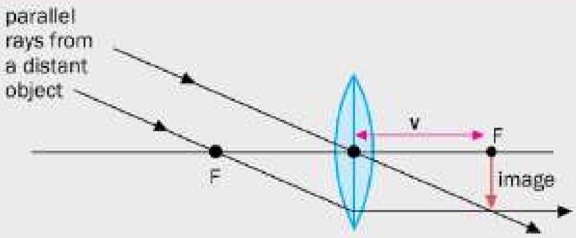
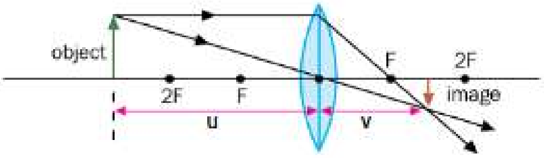
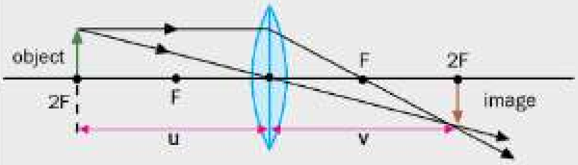
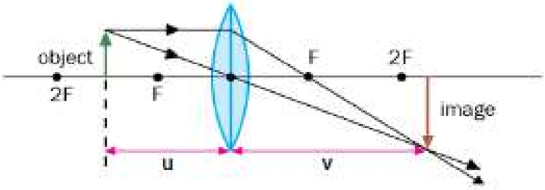
In Let's Investigate 14B, the beaker has a horizontally curved surface similar to that of a convex lens. However, the surface is not curved vertically. Thus, the beaker of water has a converging effect in the horizontal direction but not the vertical direction. In other words, horizontally, the beaker of water behaves like a convex lens but not vertically. This explains why the upward pointing arrow was not inverted regardless of how far the paper was from the beaker.

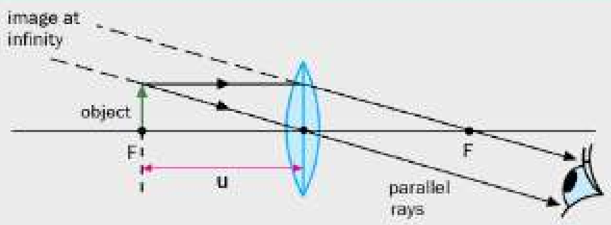
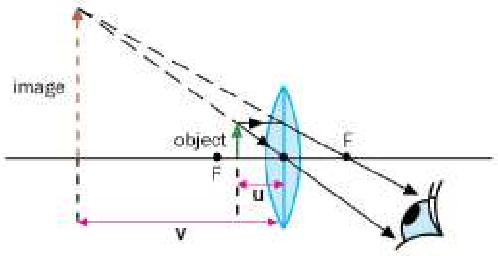
In a convex lens, there is a focal length. If the object distance is less than the focal length, the image is magnified and not inverted. However, when the object distance is greater than the focal length, the image is inverted. That is why inversion only happens when the paper is placed further away from the beaker.

Summary of Image Characteristics of Converging Lens

The distance of an object from a thin converging lens determines the type of image formed. Table 14.2 shows the ray diagrams and types of images formed when an object is placed at different distances from the lens.

Table 14.2 Types of images formed by a thin converging lens

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

Object Distance (u)	Ray Diagram	Type of Image	Image Distance (v)	Uses
$u = f$		• upright • virtual • magnified	• image at infinity • same side of the lens	• to produce a parallel beam of light, e.g. a spotlight
$u < f$		• upright • virtual • magnified	• image is behind the object • same side of the lens	• magnifying glass

Why are rays from a distant object considered to be parallel?

Consider a spherical object that is giving out light or reflecting light in all directions (Figure 14.60). If a lens is very far away, it will only receive a very tiny portion of rays and these rays will be almost parallel.

Link

Practical Workbook
Experiment 14E

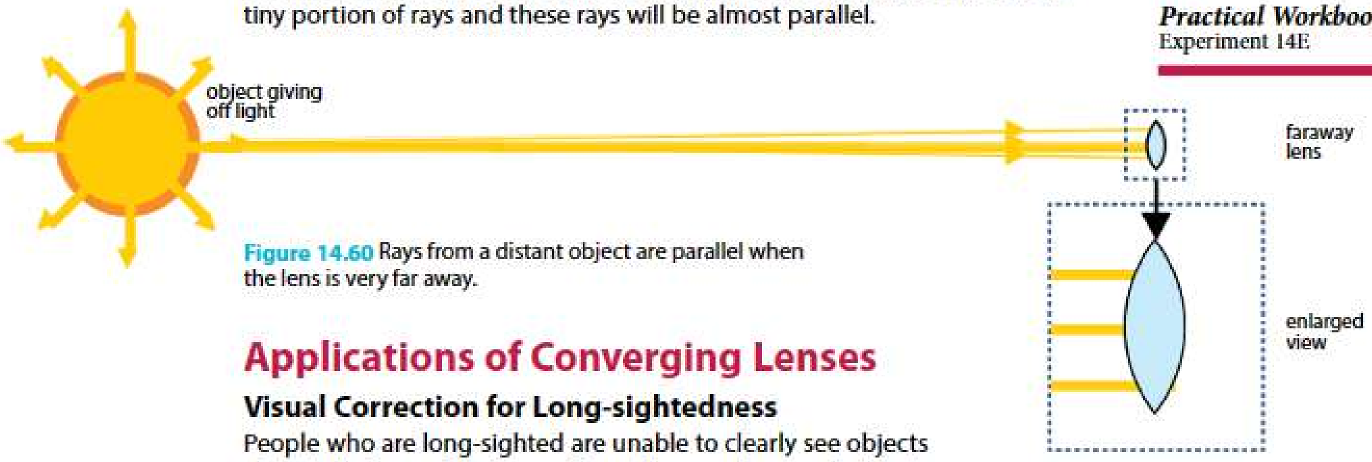


Figure 14.60 Rays from a distant object are parallel when the lens is very far away.

Applications of Converging Lenses

Visual Correction for Long-sightedness

People who are long-sighted are unable to clearly see objects close to their eyes. Their eyes focus the rays from each object point to a point beyond the retina (Figure 14.61). As the light rays are not focused on the retina, the rays from a single object point form an extended patch instead of a sharply focused point on the retina. When different object points form many overlapping patches on the retina, the overall image becomes unclear.

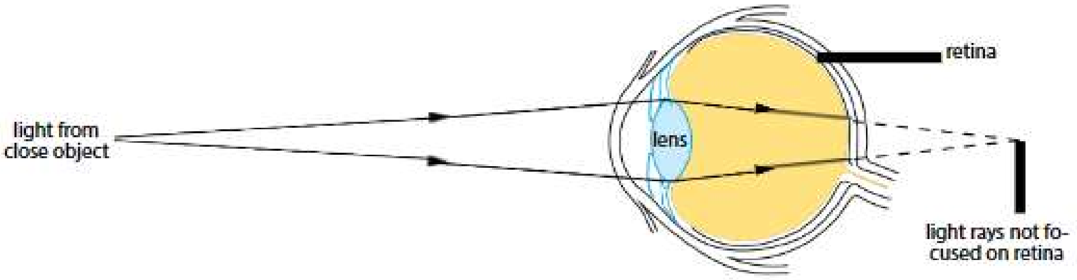


Figure 14.61 Long sightedness — the lens in the eye is unable to focus the rays onto the retina

Link

Biology
In Biology, we learn about the internal structure of the eye.

- The cornea is a clear protective outer layer of our eye. It refracts light into the eye.
- The lens is a clear, circular and biconvex structure that can change its shape to refract light on the retina.

By wearing a pair of spectacles with suitable converging lenses, the image focal points can be brought onto the retina to form a sharp image (Figure 14.62).

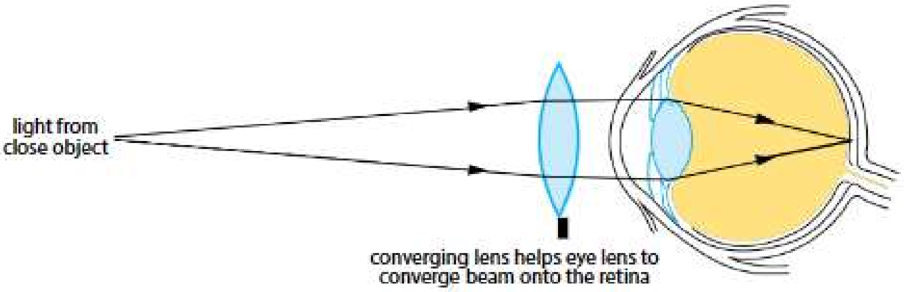


Figure 14.62 Long-sightedness can be corrected using a converging lens.

Forming Image in a Camera

A converging lens is used to form an inverted, real and diminished image on the sensor of a film camera. The focusing ring is used to adjust the lens to sensor distance (Figure 14.63).

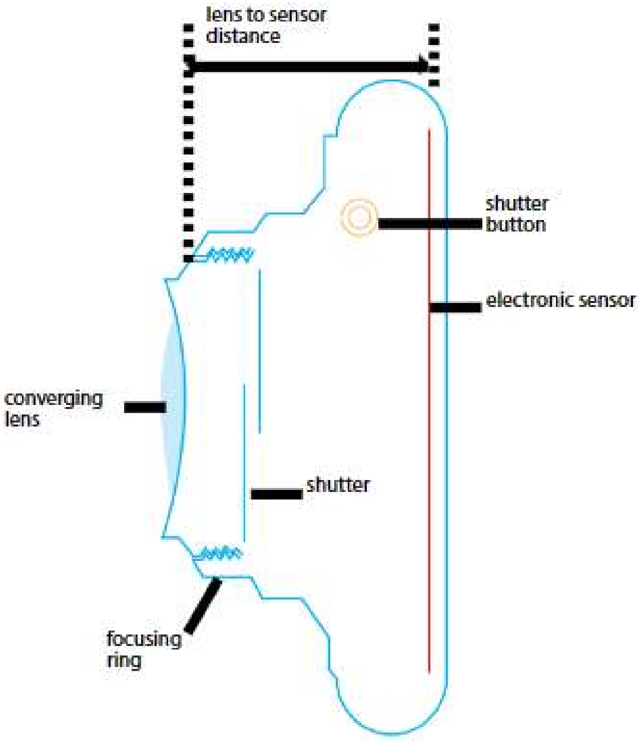


Figure 14.63 The focusing ring on the camera allows the user to vary the distance between the lens and the sensor.

At a minimum distance between the lens and sensor (i.e. focal length F), faraway objects will form sharp images on the sensor. As the lens is moved further out, nearer objects become more focused.

Let's Practise 14.4

1 A small object of height 1.5 cm is placed 6 cm away from a thin converging lens L of focal length 2 cm. By drawing a ray diagram:
  (a) find the height of the image and its distance from the lens;
  (b) determine whether the image is inverted;
  (c) determine whether the image is diminished; and
  (d) determine whether the image is virtual.

2 A small object of height 1.5 cm is placed 1.5 cm away from a thin converging lens L of focal length 2 cm. By drawing a ray diagram:
  (a) find the height of the image and its distance from the lens;
  (b) determine whether the image is inverted;
  (c) determine whether the image is diminished; and
  (d) determine whether the image is virtual.

Link

Theory Workbook
Worksheet 14D
Let's Assess
Let's Reflect

Cool Career

Photonics Engineer

Photonics deals with the use of optics and lasers for applications such as imaging, communications, sensing, manufacturing and surveying. An example of an innovative product brought about by photonics engineers is the thermal scanner for detecting people with fevers (Figure 14.64).

Photonics engineers are responsible for the building, maintenance and improvement of the fibre-optic networks that make our high-speed internet connection possible. Some engineers are also involved in research and development of new products. The future driverless cars will also depend on laser systems to sense people and the surroundings for navigation.

Optical systems are often linked to electronics, computing and software. Thus, engineers with different specialisations often have to work together to maintain and operate complex systems. The engineers need to have good mastery of technical skills and knowledge. It is also important to have good collaborative and communication skills.

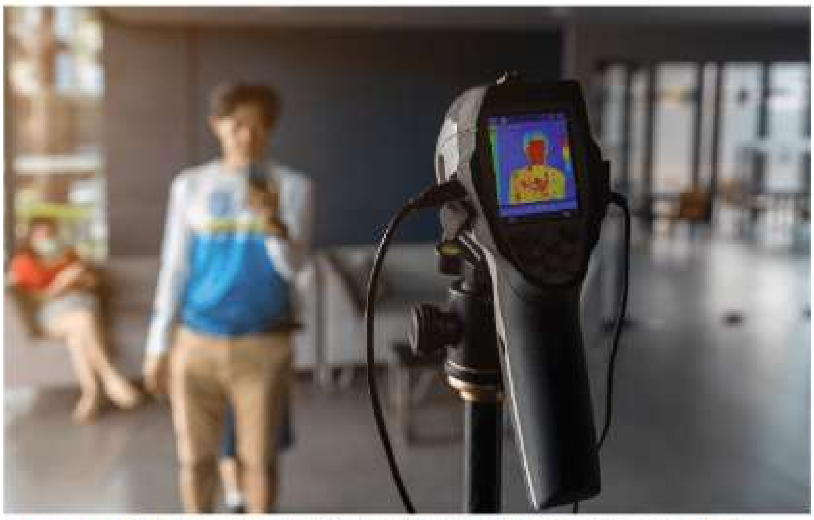
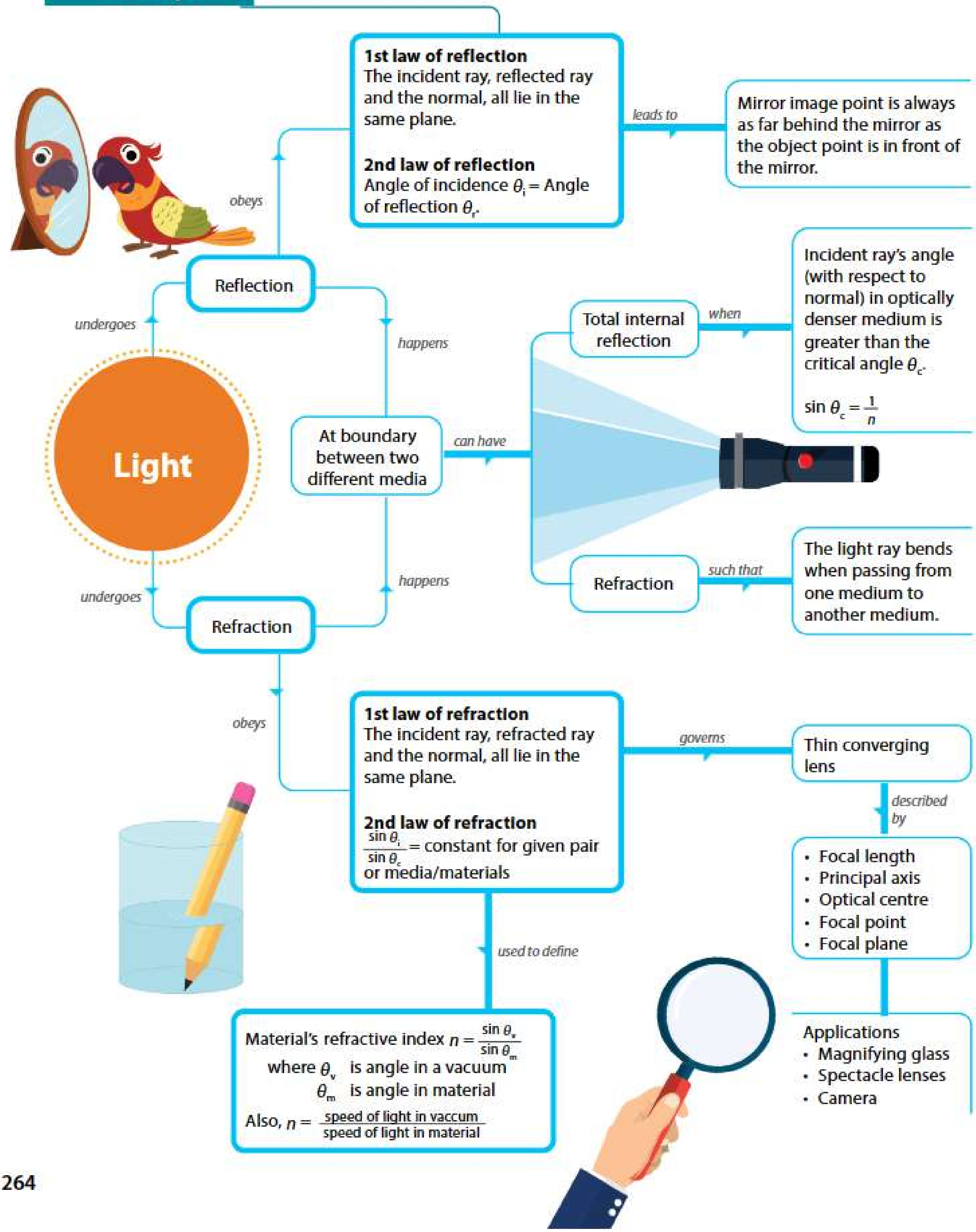


Figure 14.64 Thermal scanner detects infrared radiation and converts it into an image.

Let's Map It



Light

undergoes

Reflection

obeys

1st law of reflection
The incident ray, reflected ray and the normal, all lie in the same plane.

2nd law of reflection
Angle of incidence θ_i = Angle of reflection θ_r.

leads to

Mirror image point is always as far behind the mirror as the object point is in front of the mirror.

happens

At boundary between two different media

can have

Total internal reflection

when

Incident ray's angle (with respect to normal) in optically denser medium is greater than the critical angle θ_c.

$\sin \theta_c = \frac{1}{n}$

Refraction

such that

The light ray bends when passing from one medium to another medium.

undergoes

Refraction

happens

obeys

1st law of refraction
The incident ray, refracted ray and the normal, all lie in the same plane.

2nd law of refraction
$\frac{\sin \theta_i}{\sin \theta_c}$ = constant for given pair or media/materials

governs

Thin converging lens

described by

- Focal length
- Principal axis
- Optical centre
- Focal point
- Focal plane

Applications
- Magnifying glass
- Spectacle lenses
- Camera

used to define

Material's refractive index $n = \frac{\sin \theta_v}{\sin \theta_m}$
where θ_v is angle in a vacuum
θ_m is angle in material
Also, $n = \frac{\text{speed of light in vaccum}}{\text{speed of light in material}}$

Let's Review

Section A: Multiple-choice Questions

1 Which statement about a plane mirror's image is **false**?

○ **A** It can be bigger than the mirror.
○ **B** Its size depends on the object's distance from the mirror.
○ **C** It looks smaller when seen from a greater distance.
○ **D** It can look smaller than the object.

2 A, B, C and D are four objects separated from an observer O by a wall W (Figure 14.65). Which object **cannot** be seen by the observer?

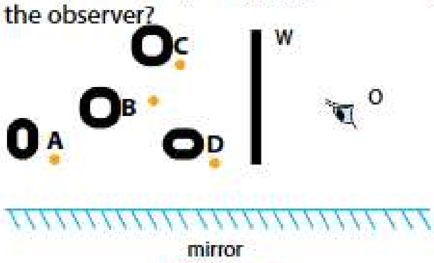


Figure 14.65

3 A light ray reflects off a mirror (Figure 14.66).

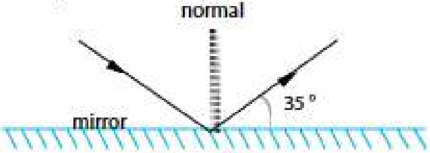


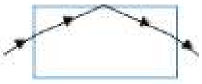
Figure 14.66

If the mirror is rotated anti-clockwise by 5 °, the new angle of reflection will be ▬▬.

○ **A** 30 °　○ **B** 40 °
○ **C** 45 °　○ **D** 50 °

4 Which of the following paths of a light ray through a glass block is impossible?

○ A



○ B

○ C

○ D

5 In which of the regions 1, 2 and 3 would an object produce a magnified image in Figure 14.67?

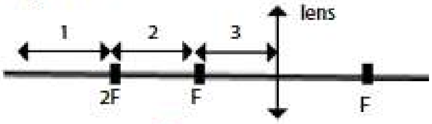


Figure 14.67

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

Section B: Structured Questions

1 Two mirrors are perpendicular to each other as shown in Figure 14.68.

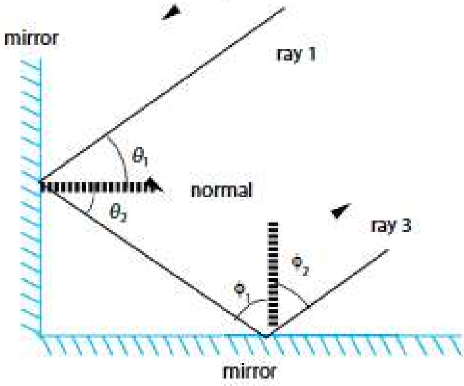


Figure 14.68

(a) Write down an equation relating θ_2 and ϕ_1.

(b) Hence, show that $\theta_1 + \theta_2 + \phi_1 + \phi_2$ is always equal to 180 °.

(c) For any value of θ_1, what can be said about the direction of ray 3 compared to ray 1?

2 An image is produced by a lens as shown in Figure 14.69.

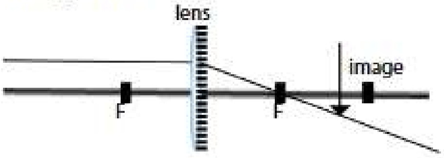


Figure 14.69

By drawing more rays, find the object's orientation and location.

3 Diamond has a refractive index of 2.4, which is higher than most other materials.

(a) Determine the critical angle for diamond.

(b) If glass and diamond are cut exactly the same way and same size for use as ornaments, diamond will be visibly more sparkly. By comparing the critical angles of diamond and glass, explain why diamond is more sparkly.

4 A swimming pool is illuminated at night with lights installed at the vertical sides of the pool. The light rays emerge in the directions shown in Figure 14.70.

Figure 14.70

(a) Given that the refractive index of water is 1.33, determine the critical angle in water.

(b) When the water surface is still, the man by the side of the pool cannot see the light from the opposite side. Suggest a reason for this.

(c) Explain why installing the lights at the bottom of the pool is not as effective in lighting up the pool.

5 The speed of light in a vacuum is the same for all coloured lights. However, in a given material such as glass, the speed of light varies slightly with the colour. Refractive index n

$$= \frac{\text{speed of light in vaccum}}{\text{speed of light in material}}$$

(a) For glass, the refractive index n_R for red light is slightly smaller than the refractive index n_V for violet light. Which light, red light or violet light, travels faster in glass?

(b) When rays of red and violet light enter a glass block at the same angle of incidence, which ray has a greater angle of refraction?

(c) If white light consisting of all colours enter a glass prism as shown in Figure 14.71, show the paths taken by the red and violet rays until they exit from the prism.

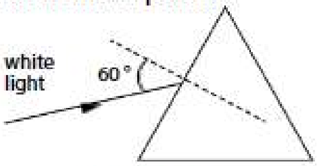


Figure 14.71

Section C: Free-response Questions

1 (a) A convex lens with focal length F is positioned in front of an observer O (Figure 14.72). Indicate the range of positions, along the principal axis, where an object needs to be placed so that the observer will see a virtual image.

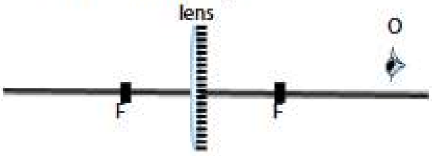


Figure 14.72

(b) Distinguish between a real and a virtual image.

2 Four media M1, M2, M3 and M4 are stacked together and a light ray's path through the top three layers is as shown in Figure 14.73.

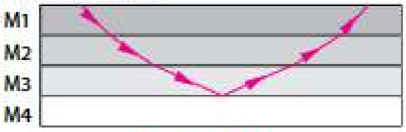


Figure 14.73

(a) Which medium has the highest and which has the lowest refractive index?

(b) Name the process that happens at the boundary between M3 and M4.

(c) If light rays from an object in M1 reach an observer O as shown in Figure 14.74, describe the orientation of the arrow as seen by O.

Figure 14.74

(d) The scenario in (c) where layers of air have increasing densities as their height above the ground increases happens in real life. On hot sunny days, why does the ground's temperature become higher than the air's temperature?

Link
Theory Workbook
Revision Worksheet 4

CHAPTER

15 Static Electricity

What You Will Learn

- What are electric charges and fields?
- How are objects electrostatically charged?
- What are some examples of electrostatic charging?

Did you know that Singapore is one of the places with the most lightning activity in the world? Lightning is an extremely large current within the clouds and between the clouds and Earth. Lightning occurs as charged particles accumulate in the clouds. The charged particles then flow to Earth as an electric current.

The large current is dangerous as the charges are discharged to a nearby object such as a tall building. This may cause excessive heating and explosive expansion of materials of the building. Are there instances whereby the build-up of charges on objects is helpful to us?

15.1 What Are Electric Charges and Fields?

Learning Outcomes

- State that there are positive and negative charges and that charge is measured in coulombs.
- State that unlike charges attract and like charges repel.
- Describe an electric field as a region in which an electric charge experiences a force.
- Draw the electric field of an isolated point charge and recall that the direction of the field lines gives the direction of the force acting on a positive test charge.
- Draw the electric field pattern between two isolated point charges.

Recall from Chapter 3 that a mass experiences gravitational force when it is in a gravitational field. Similarly, an electrically charged particle will experience a force when it is inside an electric field.

Disciplinary Idea

Conservation laws constrain the changes in systems.

The total charge of a system stays constant unless some charge enters or leaves the system. In other words, in an isolated system, the net charge must stay constant.

Electric Charge

An atom consists of electrons orbiting a nucleus made up of neutrons and protons (Figure 15.1).

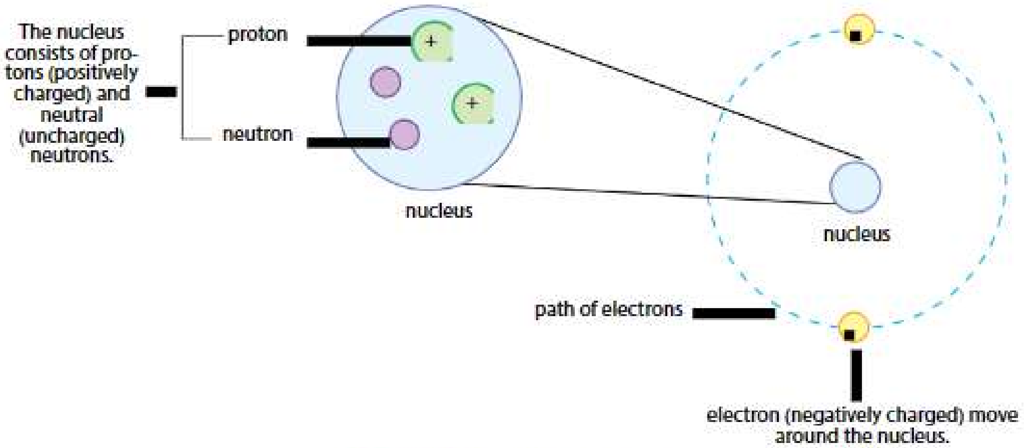


Figure 15.1 Model of an atom

Link

Chemistry
In Chemistry, we learnt about the charge and relative masses of protons, neutrons and electrons.

"Charge" is a property of an object, just like mass. An electron has a *negative* charge while a proton has a *positive* charge. The SI unit of electric charge is the **coulomb (C)**. Each electron or proton has the same amount of charge of 1.6×10^{-19} C.

An atom contains an equal number of protons and electrons. Thus, it is neutral. When an atom loses one or more electrons, we call it a *positively charged particle*. When an atom gains one or more electrons, we call it a *negatively charged particle*.

When two charged particles are brought together, they produce attractive or repulsive forces.

▶ Like charges repel each other while unlike charges attract each other.

Electric Field

An electric charge can exert a force on another nearby charge. This force is known as **electric force**. The electric force can be attractive or repulsive. The electric force gets weaker as the nearby charge moves further away. Generally, a region of influence is known as a field.

▶ **Electric field** is a region in which an electric charge experiences an electric force.

If we have two charged metal spheres X and Y (Figure 15.2), how do we know the nature of their electric fields? We can do that with the help of another *very small and light* positive charge sphere (called a "test charge") attached to a *very thin and light* thread.

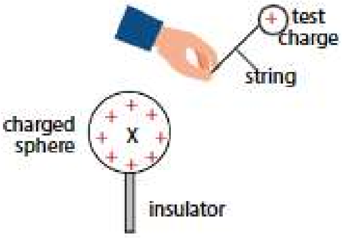


Figure 15.2(a) The small test charge is repelled.

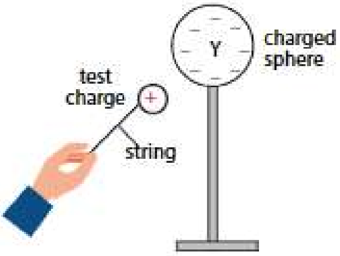


Figure 15.2(b) The small test charge is attracted.

In Figure 15.2(a), the string will always be pointing radially *outwards* from the centre of X as that is the direction of the electric force on the test charge. Similarly, in Figure 15.2(b), the string will always be pointing radially *towards* the centre of Y due to the direction of the electric force. In reality, the string would not be perfectly **radial** due to the weight of the string and test charge.

The repulsive and attractive effects of the two electric fields in Figure 15.2 can be illustrated using electric field lines (Figure 15.3). The arrowheads on the lines represent the direction of the electric field. In Figure 15.3(a), the electric field lines point radially outwards from the positive charge. This is because the positive test charge in the electric field will be repelled by the positive charge. In Figure 15.3(b), the electric field lines point radially inwards towards the negative charge. The positive test charge in the electric field will be attracted by the negative charge. Note that the field direction has been standardised to be the direction of the force on a *positive* test charge.

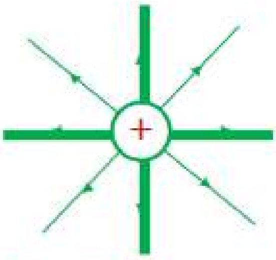


Figure 15.3(a) Electric field around a positive charge

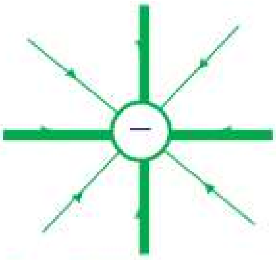


Figure 15.3(b) Electric field around a negative charge

Disciplinary Idea

Matter interacts through forces and fields.

An electric field is a region of space in which a charge experiences an electric force.

Word Alert

Radial: along the radius.

The electric field for any arrangement of charges can be represented using electric field lines according to these guidelines:

- The arrows always point towards a negative charge and away from a positive charge.
- The lines are closer together when the electric field and electric force are stronger.
- The field lines never cross one another.

Figure 15.4 shows the electric field patterns for different arrangements of charges.

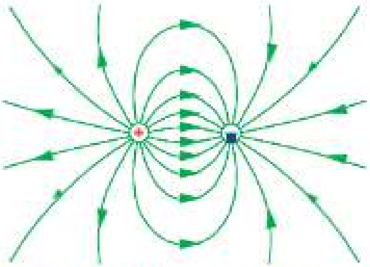


Figure 15.4(a) Electric field of a pair of opposite charges

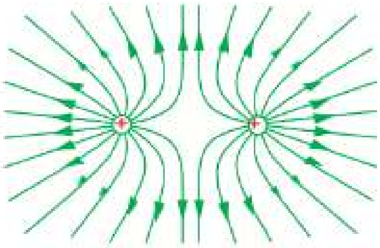


Figure 15.4(b) Electric field of a pair of positive charges

Worked Example 15A

(a) What is a "test charge" and what type of charge has been chosen as a test charge?

(b) What is the generic name given to "a region of influence" by a source such as a charge or mass?

(c) Does a proton and an electron attract or repel each other, and do they exert the same force on each other?

Answer

(a) A test charge is used to sense the strength and direction of an electric field at a point. Though a negative test charge could be used for this purpose, a test charge has been standardised and chosen to be positive.

(b) Field

(c) They have unlike charges, so they attract each other. They attract each other with the same force but in opposite directions according to Newton's third law.

Let's Practise 15.1

1 A small hidden metal sphere has an electric field around it and a portion of its field is shown in Figure 15.5.

(a) What is the type of the charge on the sphere?

(b) Draw a small circle to indicate the postion of the charge.

(c) In this portion of field shown, is the field strength stronger on the left or right?

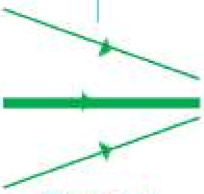


Figure 15.5

2 Given that an electron has a charge of 1.6×10^{-19} C, how many electrons are there in one Coulomb of charge?

Link
Theory Workbook
Worksheet 15A

15.2 How Are Objects Electrostatically Charged?

Learning Outcomes

- Show an understanding that electrostatic charging by rubbing involves a transfer of electrons.
- Describe experiments to show electrostatic charging by induction.

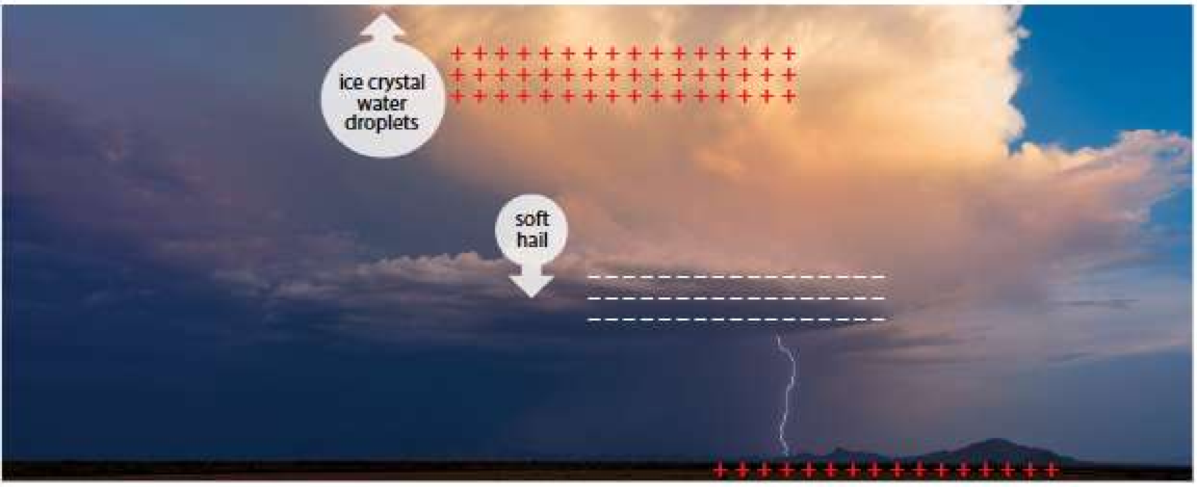


Figure 15.6 Cumulonimbus clouds

Inside a cumulonimbus cloud, lighter ice crystals and water droplets are carried upwards by rising air (Figure 15.6). On the way up, they collide with heavier falling or suspended soft hail. The contact or friction charges the water droplets and ice crystals positively while the soft hail is charged negatively. The process leads to the separation and accumulation of positive charges higher up in the cloud and negative charges at the base of the cloud. In addition, the negative base of the cloud repels electrons in the ground to form a positively charged layer at the ground surface.

Even though oppositely charged regions attract each other, they are separated by the insulating air. As the charged regions grow, the attractive forces eventually overcome the insulating air, and the charges start to flow. The large flow of electric charges result in lightning and thunder.

On a far smaller scale than what we saw in the cumulonimbus cloud, rubbing a balloon against hair can cause the balloon and hair to be oppositely charged (Figure 15.7). This explains why the balloons can stick to the girl's hair. Do you wonder why charges get transferred from one material to another simply by contact or friction?

Figure 15.7 A balloon and hair rubbed against each other acquire opposite charges.

Different Attraction of Electrons by Different Atoms

Atoms of different elements have different characteristics due to their different compositions. The electrons of some atoms are held more strongly by their nuclei than the electrons in other atoms. When two objects such as hair and a balloon come into contact, the less tightly held electrons from hair are attracted and transferred to the balloon (Figure 15.8). The oppositely charged hair and balloon attract each other and thus they stick together.

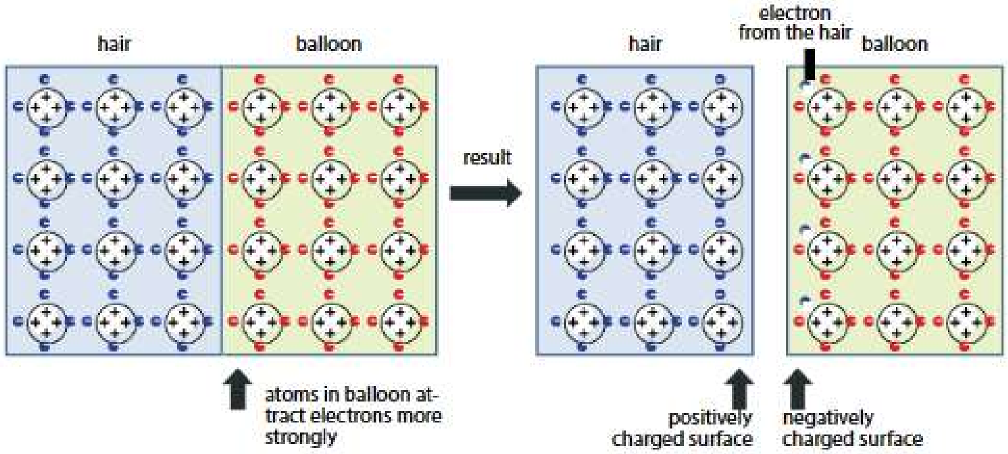


Figure 15.8 Illustration of electrostatic charging

Since hair and a balloon are both insulators, their electrons cannot move freely throughout the materials. Electrons transferred to the balloon's surface will not be able to move elsewhere. Similarly, the vacant electron sites in the hair cannot be refilled by other electrons in the hair. This is why they are called **static** electricity. Figure 15.9 shows a list of some materials that can be charged electrostatically.

Word Alert

Static: at rest or forces in equilibrium

Link

Chemistry

In Chemistry, we learn that ions are formed when atoms lose or gain electrons. An ionic bond is the electrostatic attraction between oppositely charged ions.

Some Materials for Electrostatic Charging
air
leather
rabbit's fur
glass
human hair
nylon
wool
lead
cat's fur
silk
amber
polyester
styrofoam
teflon
vinyl (PVC)
silicon rubber
ebonite

Greater *comparative* tendency to *lose* electron

- For example, rubbing leather with nylon will give them positive and negative charges respectively.
- For stronger electrostatic charging, choose a pair of materials that are spaced further apart.
- In a humid environment, the moisture on the surfaces and in the air can conduct and lead to the loss of the static charges.

Greater *comparative* tendency to *gain* electron

Figure 15.9 List of some materials that can be charged electrostatically

Let's Investigate 15A

Aim

To investigate how a gold leaf electroscope reveals the presence of charges

Procedure

1 Prepare an electroscope (Figure 15.10).
2 Rub a glass rod with a polyester cloth to positively charge the rod (Figure 15.11).
3 Touch the metal plate with the charged rod to transfer the charges to the electroscope (Figure 15.12).

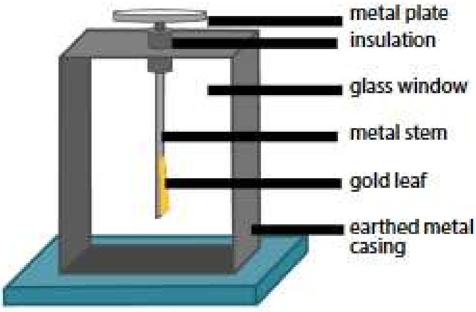


Figure 15.10 Uncharged electroscope

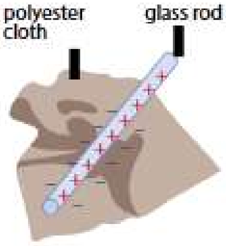


Figure 15.11 Glass rod and polyester cloth are oppositely charged.

Observations

1 The gold leaf is repelled by the stem (Figure 15.12). This is because the stem and the gold leaf are both positively charged.
2 After removing the glass rod, the gold leaf is still being repelled (Figure 15.13).

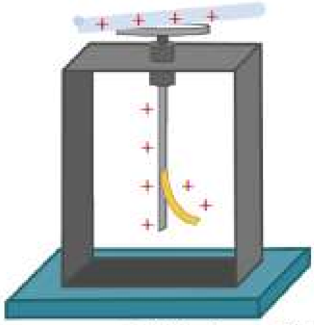


Figure 15.12 Gold leaf is repelled.

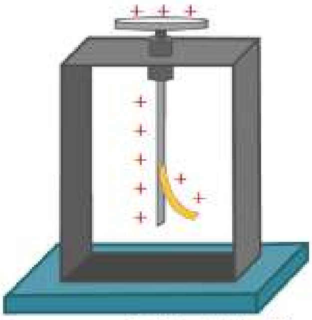


Figure 15.13 Gold leaf is is still repelled.

Questions

1 In metals, some of the electrons can move freely throughout the metal. The positively charged protons in the nuclei cannot move out of the atoms. How do the stem and gold leaf become positively charged?
2 What would happen to the charges in the electroscope if we were to touch the top plate after charging the electroscope?
3 Will you get an electric shock by touching the top plate?

Note: Due to our humid environment, this investigation is best done in an air-conditioned room.

In Let's Investigate 15A, the electroscope was charged by using the charged glass rod to touch the top plate. In fact, by placing the rod just above the top plate without touching, we can also get the gold leaf to be repelled as shown (Figure 15.14). Do you know why?

The positive charges in the glass rod attract the electrons from the plate, stem and gold leaf. This causes the electrons to accumulate in the top plate. Since the plate, stem and leaf were originally neutral, the movement of some electrons to the top results in an excess of positive charges at the bottom. Hence, the gold leaf is repelled. Do you know what will happen to the gold leaf when the rod is removed?

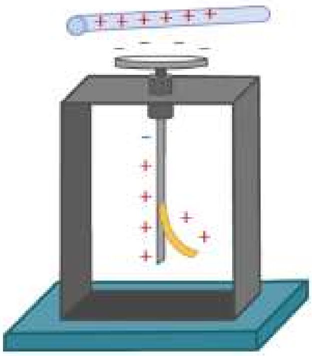


Figure 15.14 Gold leaf can be repelled by holding the rod just above the top plate without touching it.

Word Alert

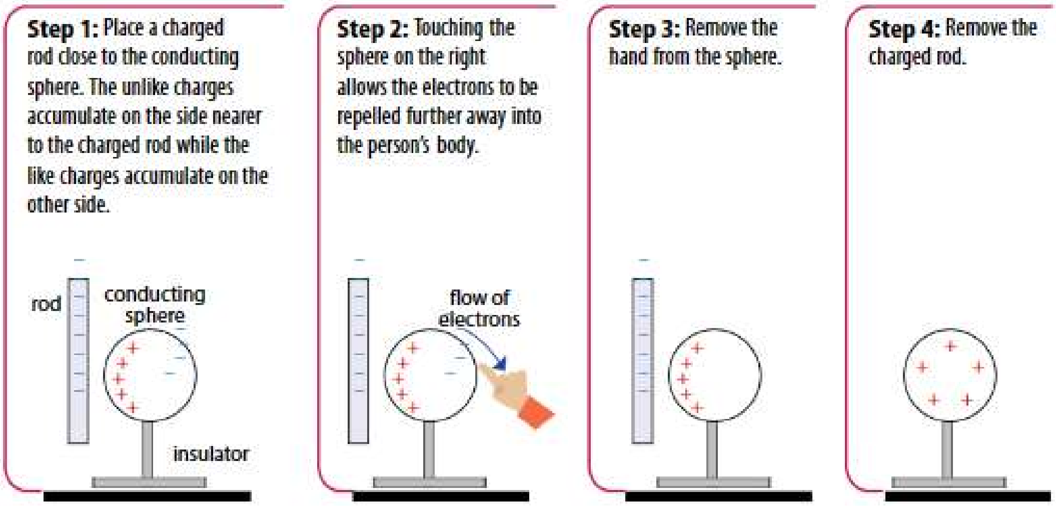
Induction: process or method to achieve a certain outcome

Induces: to cause or bring about

Electrostatic Charging by Induction

Objects can be charged by **induction**. **Induction** involves placing a charged rod close to the conductor(s) without contact. This **induces** the redistribution of charges in the conductors (Figures 15.15 and 15.16).

Charging One Conductor



Step 1: Place a charged rod close to the conducting sphere. The unlike charges accumulate on the side nearer to the charged rod while the like charges accumulate on the other side.

Step 2: Touching the sphere on the right allows the electrons to be repelled further away into the person's body.

Step 3: Remove the hand from the sphere.

Step 4: Remove the charged rod.

Figure 15.15 Steps to charge one metal sphere by induction

An alternative to touching the sphere in step 2 is to connect one end of a metal wire to a metal water tap and use the other end to touch the sphere. This will allow the electrons to flow to the Earth through the pipes. This connection is called **earthing**.

Charging Two Conductors

Step 1: Place a charged rod close to one of the conducting spheres that are in contact. Positive charges in the rod attract free electrons to the left, leaving the right side positively charged.

Step 2: Keeping the rod in position, separate the two spheres to isolate the two groups of opposite charges.

Step 3: Remove the charged rod. The two spheres now have equal but opposite charge.

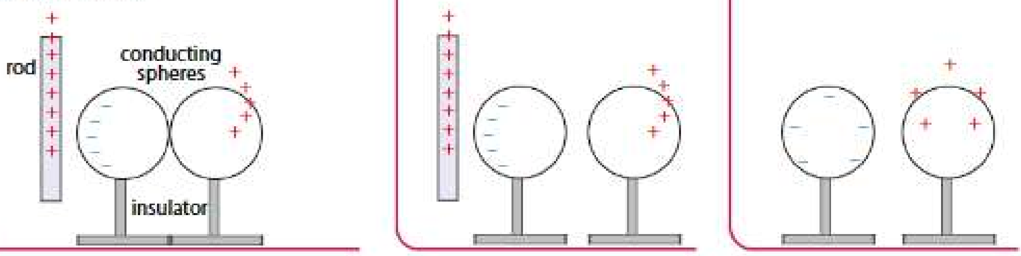


Figure 15.16 Steps to charge two metal spheres by induction

Worked Example 15B

A charged glass rod attracts paper bits when it is brought near them (Figure 15.17). Explain how an uncharged paper bit gets attracted to the glass rod.

Figure 15.17 Paper bits get attracted to a charged rod.

Answer

The positively charged rod induces both negative and positive charges in the paper bits (Figure 15.18). However, the negative charges in the paper bits are nearer to the rod. Hence, the attraction to the rod is stronger than the repulsion and the paper bits are attracted to the rod.

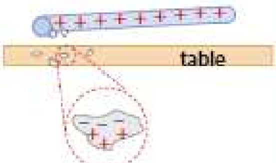


Figure 15.18 Paper bits get attracted to a charged rod.

Let's Practise 15.2

Two oppositely charged metal spheres on insulating stands are placed close to each other (Figure 15.19).

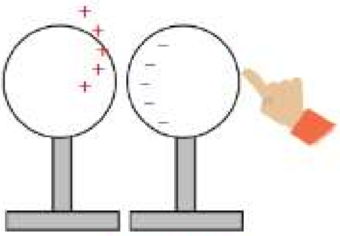


Figure 15.19

(a) If you were to touch the far-right side of the negatively charged sphere, what would happen to the negative charges and why?

(b) A charged plastic sphere needs to be discharged (Figure 15.20). Student A suggests touching any point on the sphere with a finger. Student B suggests pouring water over the sphere. Explain whether one method is more effective than the other.

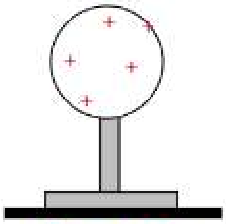


Figure 15.20

Link
Theory Workbook
Worksheet 15B

15.3 What Are Some Examples of Electrostatic Charging?

Learning Outcomes

- Describe examples where electrostatic charging may be a potential hazard.
- Describe the use of electrostatic charging in an electrostatic precipitator, and apply the use of electrostatic charging to new situations.

Figure 15.21 Can lightning be useful?

Scientists have indeed tried harnessing the significant amount of energy in lightning (Figure 15.21). An important advancement is the use of laser to create a path of ionised gas to facilitate and direct the lightning towards ground harvesting stations. However, there are a number of challenges such as coping with the very large and fluctuating current. With further research and experimentation, it might be possible one day.

Transfer of Fluids and Dry Bulk

As we have seen, lightning is an example of large electrostatic discharge that can cause harm and damage. However, a discharge does not need to be large to be dangerous.

Word Alert

Dry bulk: raw materials such as grains, coal and minerals

A common dangerous scenario occurs when **dry bulk** flows through a hose or pipe (Figure 15.22 on the next page). Friction against the inner walls can lead to electrostatic charging of the hose and the substance. At the outlet, the opposite charges between the hose and the substance can cause sparking. If the substance is combustible, such as fuel, the spark can start a fire or even an explosion. It may come as a surprise that many seemingly safe substances, such as flour mixed with plenty of air, can cause an explosion when ignited by a spark.

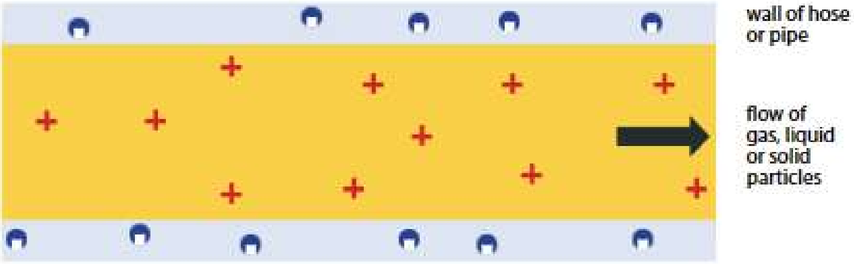


Figure 15.22 Friction between the flowing substance and the walls of the hose or pipe generates charges.

Due to the danger of electrostatic charging and discharge in the presence of combustible substances, preventive measures such as grounding or earthing are often carefully followed (Figure 15.23).

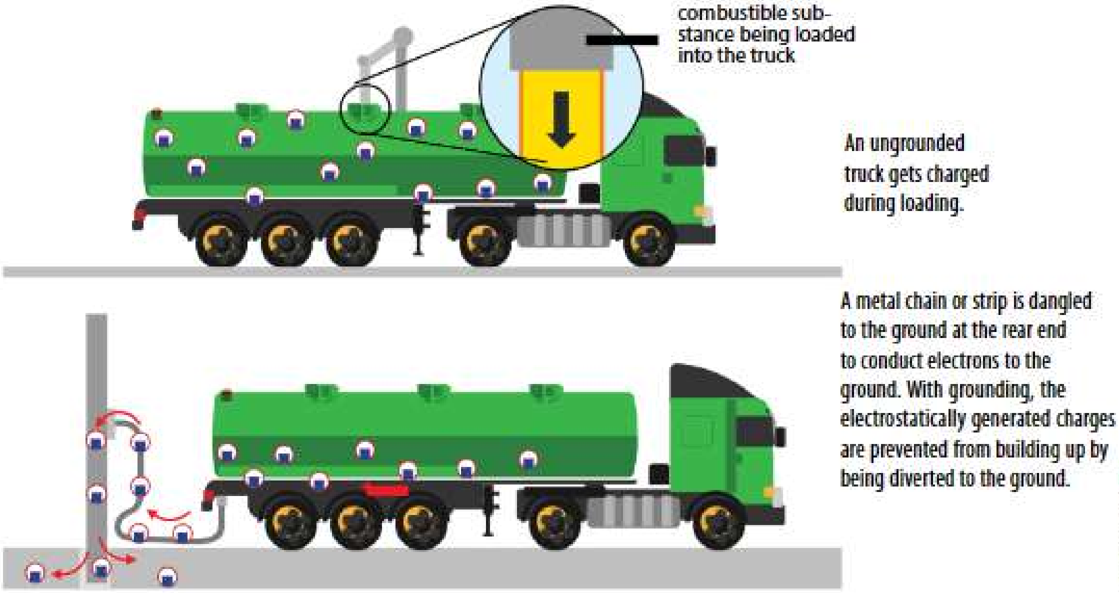


Figure 15.23 The dangerous build up of static charges and how grounding works to prevent that

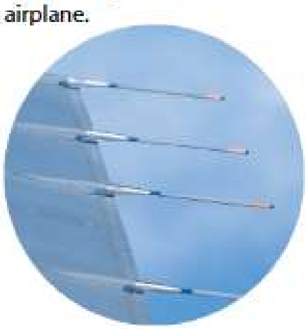
Air Flow Across Surface of Planes and Vehicles

In an environment with low humidity, a moving vehicle can acquire static charges due to friction between the vehicle body and the air. Sometimes, when alighting passengers touch the vehicle's outer metal body, they get a non-fatal but painful shock due to a small electric discharge. This small discharge is dangerous for trucks carrying volatile and flammable substances. The danger is reduced to some extent by using modern tyres containing carbon and embedded metal mesh which help to dissipate charges to the ground.

Similarly, an airplane acquires static charges due to friction with the air, ice crystals and other particles in the air. However, this build up of static charges on the plane will only stay on the outer metallic surface. This is because the charges repel each other and the furthest they can get away from each other is on the outermost surface.

Even if the airplane was struck by lightning, the charges from the lightning will also stay only on the outermost surface. Hence, the people and equipment inside the airplane will not be harmed by the lightning. The charges on the plane's surface will subsequently be discharged to the air via one of the many discharge rods (Figure 15.24). For mid-air refuelling between a tanker aircraft and the receiving aircraft, proper discharging of static charges becomes very important.

Figure 15.24 Static discharge rods on the wing of an airplane.



Spray Painting

When spray painting, if the paint is charged positively, the paint droplets will repel each other. This results in a more uniform mist (Figure 15.25). Usually, a car part being painted is metallic and grounded. When the positive droplets approach the part to be painted, free electrons in the metal are attracted to the surface. The attraction between the paint and the surface helps the droplets to land on the targeted part instead of drifting somewhere else. Compared to uncharged paint, there is less wasted paint and the resulting coat is more uniform. Though electrostatic charges are useful in this case, they may also cause sparking and turn the mist into a fire spray.

Figure 15.25 Spray painting a vehicle

Electrostatic Precipitator

Incineration plants, power stations, chemical plants and factories often produce waste gases containing particulate pollutants in the form of smoke, dust and chemical droplets. Some pharmaceutical facilities and hospitals also generate exhaust gases containing harmful bacteria and fungi that must be removed before the gases are released into the atmosphere. This removal can be accomplished effectively with an electrostatic precipitator. A key component of the precipitator and how it removes particulate matter is shown in Figure 15.26.

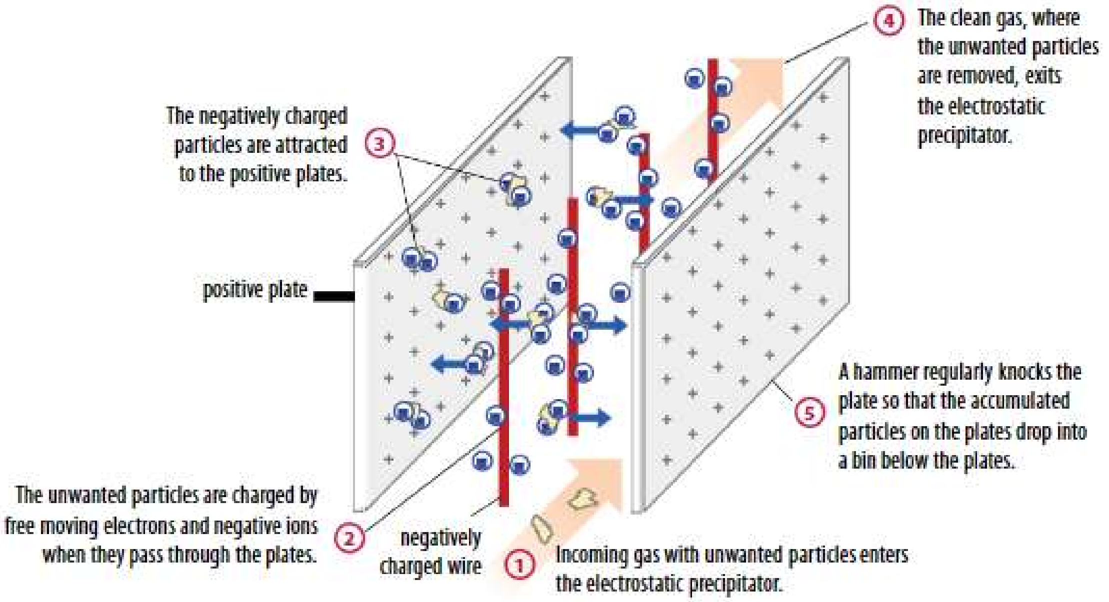


Figure 15.26 The key part of an electrostatic precipitator

Tech Connect

Have you wondered how orbiting space crafts and satellites do fine adjustments of their orientations?

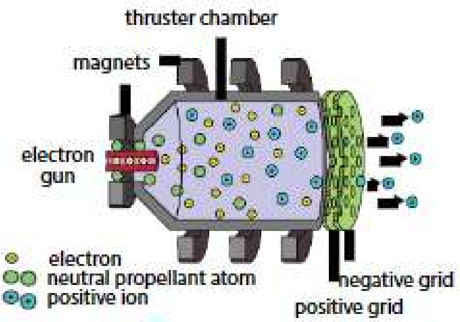


Figure 15.27

The space crafts and satellites use several "electrostatic ion thrusters" installed around the space craft for steering (Figure 15.27). When a propellant substance (green atoms) is injected into the thruster chamber, high speed electrons are shot into the chamber to ionise the propellant atoms by knocking out their electrons. The resulting positive propellent atoms then pass through the positive grid. They are then accelerated to high speed due to the strong electric field between the positive and negative grids. As the atoms exit the thruster at high speed, a small force is exerted on the thruster and the space craft. This results in fine adjustments of the orientations.

Due to the very high efficiency of such thrusters, scientists are currently working on improved versions and hoping to use them for long distance space travel.

Worked Example 15C

An anti-static bag has a thin metallic coating (Figure 15.28). Explain how the thin coating helps to protect the sensitive electronics inside the bag.

Answer

Any static charges transferred to the bag will repel each other to get as far away from each other as possible. The furthest separation between the charges is when the charges are all on the bag's outermost conducting surface. Thus, the charges will not be able to reach the electronics inside the bag. Furthermore, the conducting layer helps to pass on any accumulated charges to other outside objects that touch it.

Figure 15.28 Electronics protected by an anti-static bag

Let's Practise 15.3

(a) When taking off a woolen sweater in air with very low humidity, a crackling sound can sometimes be heard. What causes the sound?

(b) When transferring flammable fuel from a metal can to a larger drum, one of the safety precautions is to connect the drum to the can by a metal bonding wire (Figure 15.29). Explain how the bonding wire prevents dangerous sparks from forming.

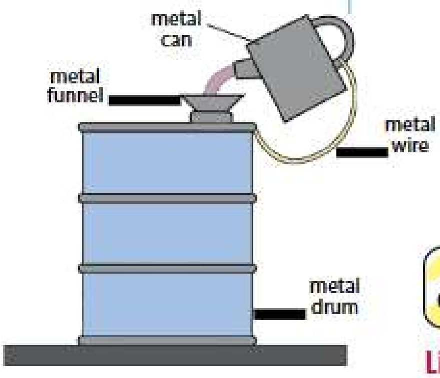


Figure 15.29 The use of metal bonding wire

Link

Theory Workbook
Worksheet 15C

Past to Present

Since ancient times, people have been finding ways to separate different materials. Some methods of separating mineral ores involve manual sorting, crushing with grindstones and the use of harmful chemicals.

Now a safer and more efficient way is to use an electrostatic separator. It exploits the different electrostatic behaviours to sort different materials.

Finely crushed materials are delivered to the rotating steel drum and given static charges. The particles that are conductors will lose their charges quickly to the earthed steel drum and fall into bin 3. The insulator particles stick to the drum because of their static charges. They are eventually brushed off the drum into bin 1. The particles that are in-between insulators and conductors will fall into bin 2.

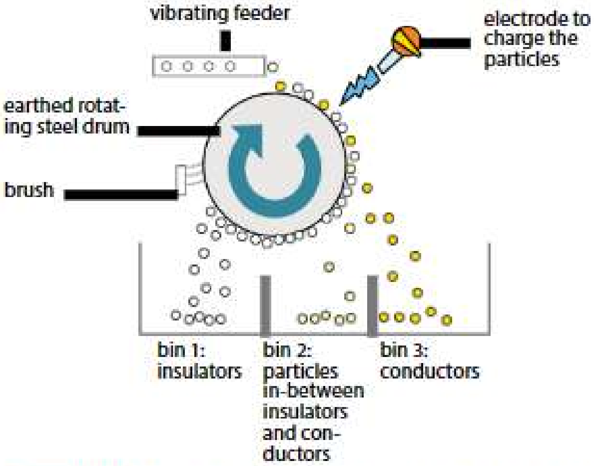


Figure 15.30 An electrostatic separator can efficiently separate insulators and conductors.

Problem-based Learning Activity

It was reported in the news that a supermarket in South East Asia has an unusually high amount of static electricity. Apparently, shoppers were getting zapped while pushing their trolleys, picking items off the shelves and when brushing past other shoppers in the store.

This supermarket was planning to sell electronic goods and appliances and the store managers were worried that these goods could be prematurely damaged by static electricity.

Your team is tasked to investigate:
- what causes static electricity;
- what kind of materials or environmental conditions give rise to more static electricity; and
- what could be the possible causes of this high amount of static electricity in this supermarket.

You should also provide some recommendations on how to keep these electronic goods safe.

Link

Theory Workbook
Problem-based Learning: Application

Practical Workbook
Problem-based Learning: STEM Project

Cool Career

Electronics Engineer

Electronics engineering is about designing and using miniaturised circuits to make gadgets and machines that are "intelligent" and able to interact with users (Figure 15.31). These tiny circuits are very vulnerable to damage from static discharge, so measures such as humidity control and appropriate clothing materials are important.

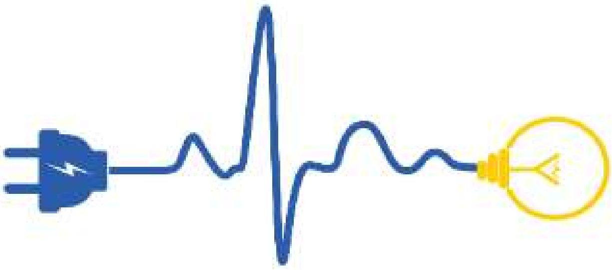
Electronic systems of different complexity and functions are used in commercial, industrial, scientific, medical and military applications. Therefore, electronics engineers need to understand the specific needs and constraints of different customers to work out the best solution.

Larger and more complex systems may involve many engineers. They must learn to adopt effective strategies to coordinate and keep track of their many concurrent activities in order to complete their project on time and within budget.

Figure 15.31 Electronics engineers design and develop electrical systems.

Let's Map It

Static Electricity



describes

Electric charges with limited mobility

which have

Two types of charges (+ and –)

such that

The net or unbalanced charge is a property of some matter and measured in coulomb (SI symbol: C).

and

Like charges repel, unlike charges attract.

and

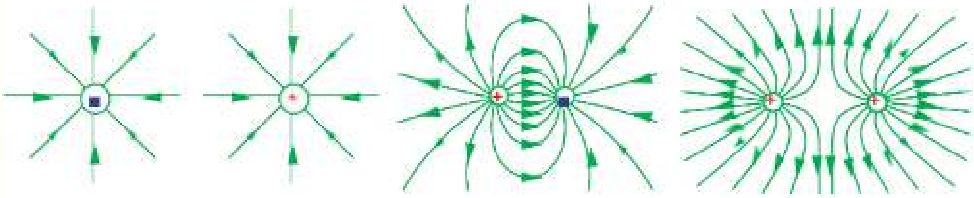
A charge has a region of influence called an electric field.

which is

A region in which an electric charge experiences an electric force.

and

Guidelines for drawing electric field lines:
1. field lines always point away from a + charge but towards a – charge;
2. regions with closer field lines indicate stronger field; and
3. direction of arrows indicate the direction of force on a + charge.



which are

Produced

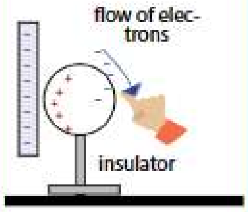
by

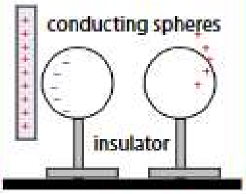
Contact or friction

Examples:
1. Collision between ice crystals, water droplets and soft hail in clouds
2. Flow of a gas/liquid/solid particles in a pipe/hose
3. Charging through contact with ions or free electrons

Induction

Set-ups





which have

Hazards

Examples:
1. Sparks from discharge can cause fires or explosions
2. Sparks can damage electronics
3. Extremely large discharge in the form of lightning can cause fires, damage to property or even death

Applications

Examples:
1. Charged paint droplets for spray painting
2. Electrostatic precipitator
3. Electrostatic separation of minerals

Let's Review

Section A: Multiple-choice Questions

1 Which of the following statements about charge is **false**?

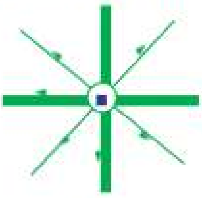
○ **A** Charge is measured in Coulomb.

○ **B** An object that has equal amount of positive and negative charges is overall neutral.

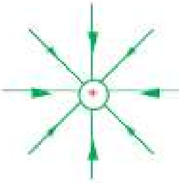
○ **C** Like charges attract.

○ **D** A charge produces an electric field around it.

2 Which of the following field diagrams is/are **incorrect**?



1



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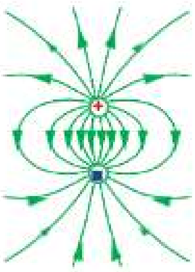

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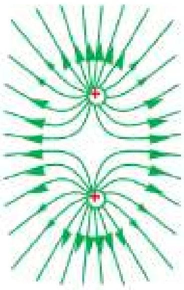


4

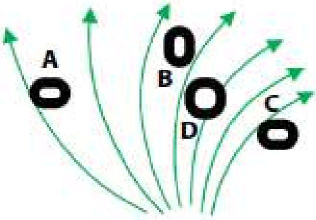
○ **A** 1 and 2 only

○ **B** 1, 2 and 4 only

○ **C** 3 and 4 only

○ **D** 2 and 3 only

3 A, B, C and D are four regions inside an electric field. Which region has the weakest field strength?



4 When a negatively charged rod is brought close to a metal sphere on an insulating stand, the left and right sides of the sphere become charged (Figure 15.32).

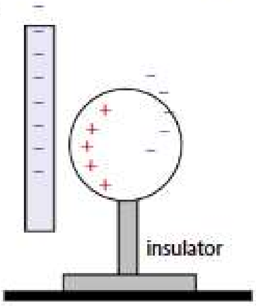


Figure 15.32

Which of the following description of charge movement is correct?

○ **A** Positive charges move from right to left in the sphere.

○ **B** Negative charges move from left to right in the sphere.

○ **C** The positive charges move to the left and the negative charges move to the right of the sphere.

○ **D** Positive charges in the sphere are attracted to the left by the rod, then some negative charges jump from the rod to the sphere and move to the right of the sphere.

5 A conducting sphere is mounted on a conducting stand. A negatively charged rod is brought near it (Figure 15.33). Which of the following diagrams shows the outcome correctly?

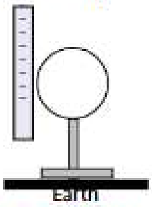
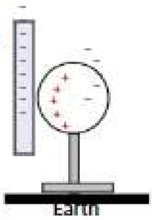
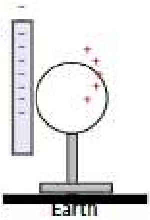
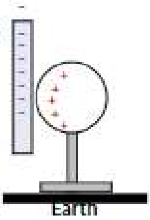


Figure 15.33

○ A


○ B


○ C


○ D


Section B: Structured Questions

1 In some work environment where sensitive electronic devices are handled, workers are required to wear a wrist strap (Figure 15.34).

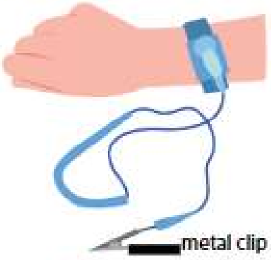


Figure 15.34

(a) The metal clip is to be connected to the metal casing of the electronic device being handled. Explain how the connection can prevent damage to the device from static discharge.

(b) In addition, the device is also connected to Earth. How does that further prevent damage due to discharge?

2 Explain why a car does not need a lightning rod to protect it from lightning strike.

3 In a low humidity environment, a girl rubbed an inflated rubber balloon against her hair.

(a) Why did the rubbing cause the girl's hair to stand up?

(b) The girl also found that the balloon could stick to the wall. Explain how the balloon is able to stick to the wall.

4 When nylon is rubbed against silicon rubber, nylon becomes positively charged.

(a) Which type of charge is transferred in the process?

(b) In which direction was the charge transferred?

5 When a plane is being refuelled, a metal bonding cable connects the fuel truck and the earthing point on the landing gear (Figure 15.35).

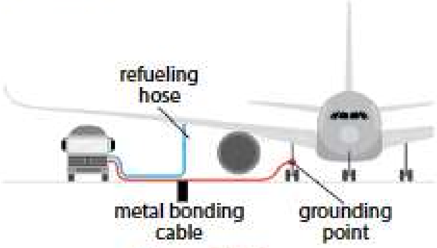


Figure 15.35

(a) How does the cable ensure safety during the refuelling operation?

(b) Why is it critical that the cable must be connected before the fuel hose is connected to the plane?

Section C: Free-response Questions

1 An electroscope has acquired an unknown type of charge (Figure 15.36).

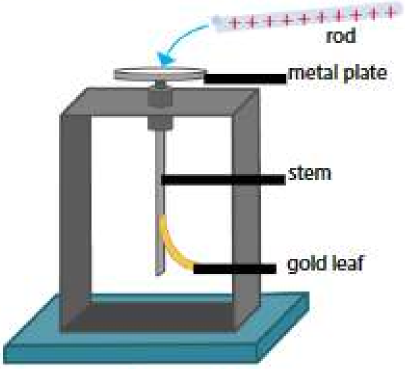


Figure 15.36

When a positively charged rod is brought near the metal plate, the gold leaf moves towards the stem.

(a) State the type of charge in the electroscope.

(b) Explain why the leaf moves towards the stem.

2 Two charged conducting spheres on insulating stands are placed close to each other (Figure 15.37).

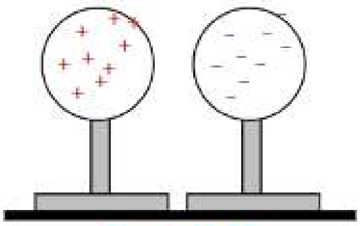


Figure 15.37

If the two spheres contain large enough amounts of charges, sparking between the spheres can be seen.

(a) Explain in terms of fields and forces, why sparking happens.

(b) The set-up serves as a way to store energy and it is known as a capacitor. Suggest how the amount of energy stored in the capacitor can be increased.

(c) Briefly describe a similar set-up that can be found in nature.

CHAPTER

16 Current of Electricity

What You Will Learn

- How do we describe the energy transfer by an electric current in an electric circuit?
- Why does the electrical resistance of metals increase with temperature?

Lighting displays in Singapore are a common sight. This dazzling display of lights will not be possible without electric currents. Ironically, we cannot see electric currents in most instances. We only recognise it when it flows through other objects. In our modern lives, as we learn how to harness and control it, electric currents has brought about many conveniences. It enables us to use our smartphones and the Internet. Electric currents also occurs in nature and is all around us. What are electric currents and how can we understand it?

16.1 How Do We Describe the Energy Transfer by an Electric Current in an Electric Circuit?

Learning Outcomes

- State that current is the rate of flow of charge and that it is measured in amperes.
- Distinguish between conventional current and electron flow.
- Recall and apply the relationship *charge* = *current* × *time* to new situations or to solve related problems.
- State that the electromotive force (e.m.f.) of a source is the work done per unit charge by the source in driving charges around a complete circuit and that it is measured in volts.
- Calculate the total e.m.f. where several sources are arranged in series.
- State that the potential difference (p.d.) across a component in a circuit is the work done per unit charge in driving charges through the component and that it is measured in volts.

Electric currents bring about convenience to modern living. Smartphones, room lighting and air conditioners can function through manipulation and control of electric currents. Increasingly, different modes of transport such as trains, trams and automobiles, are operated electrically. Electric currents also occur in nature, such as the lightning in a thunderstorm, the northern lights (Figure 16.1) and synapses in our body. There is just no escape from electric currents in our daily lives.

Figure 16.1 Charged particles are generated when a cloud of gas ejected from the sun collides with Earth's magnetic field. These charge particles collide with oxygen and nitrogen in the atmosphere and produce the majestic aurora borealis or northern lights.

»

Link

You will learn more about subatomic particles in Chapter 22.

To understand electric current, we need to know what an electric charge is. An electric charge is a property that many subatomic particles and ions possess. A subatomic particle such as an electron possesses a negative charge while an ion may possess a positive or negative charge. When these charges move, an electric current is produced.

▶ **Electric current** is the rate of flow of electric charge.

Mathematically, we write:

▶ $I = \frac{Q}{t}$ where I = current (A)
Q = charge (C)
t = time taken (s)

The SI unit for current is **ampere (A)** or coulomb (C) per second (s). One ampere is the electric current produced when one coulomb of charge passes a point in one second (Figure 16.2).

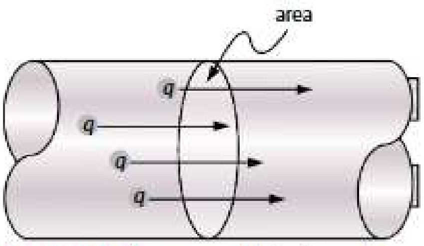


Figure 16.2 An ampere is the flow of one coulomb through an area in one second.

Note that coulomb is a derived unit. Ampere is an SI base unit. One coulomb is equal to the amount of charge when one ampere of current flows for one second. One coulomb is approximately equal to the charge of 6.25×10^{18} protons. The charge on each proton is about 1.60×10^{-19} C.

Disciplinary Idea

Microscopic models can explain macroscopic phenomena.

Electric current is the rate of flow of an electric charge, that is, the amount of charge transfer per unit time.

Conventional Current and Electron Flow

Electric current is the rate of flow of charge and not charged particles. Charged particles may have different amounts of charges. Calcium ions, for instance, have two positive charges per particle.

Before electrons were discovered, it was thought that electricity was a flow of positive charges only. This was proven wrong with the discovery of electrons. Nevertheless, the convention is to consider the flow of current as the flow of positive charges. The direction of flow of positive charges is described as the **conventional current**, which assumes that positive charges flow out of the positive terminal of a battery to the negative terminal (Figure 16.3).

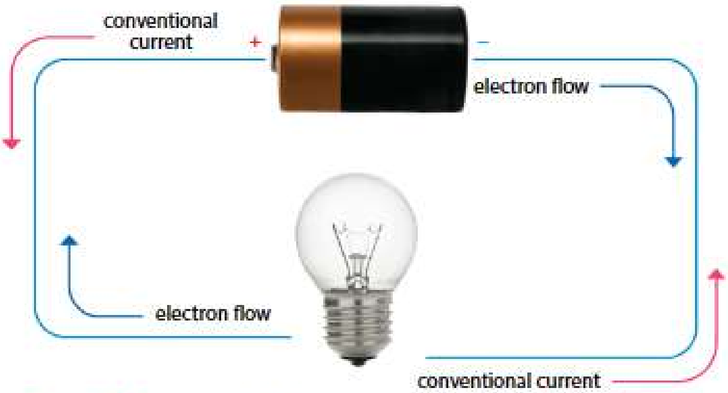


Figure 16.3 Conventional current versus electron flow

Link

Recall from Chapter 1: The following shows the SI base units.

- Length — meter (m)
- Time — second (s)
- Amount of substance — mole (mole)
- Electric current — ampere (A)
- Temperature — kelvin (K)
- Mass — kilogram (kg)

Helpful Note

A digital multimeter is a handheld measuring instrument that can measure multiple quantities such as voltage, current and resistance. The numerical measured values are shown on a digital display.

An **electric circuit** is a closed path connected with metal wires usually made from copper. It comprises a source, such as a battery, and a network of electrical components, such as a light bulb. In the electric circuit in Figure 16.3, electric current is caused by the flow of electrons. The flow of electrons from the negative terminal of the battery to the positive terminal is opposite to the conventional current. This movement of electrons in the electrical circuit is known as **electron flow**.

The direction of the current in a circuit is that of the conventional current and not the electron flow. The "direction" here is not a vector direction. In fact, electric current is a scalar quantity.

Electric current can be measured by an ammeter or a digital multi-meter (Figure 16.4).

(a) (b)

Figure 16.4 Both the (a) analogue ammeter and (b) a digital multimeter are used in measuring electric current.

Link

You will learn more about series and parallel circuits in Chapter 17.

The ammeter is connected in **series** in an electric circuit to measure the magnitude of electric current flowing in the circuit. An ideal ammeter is one that has zero resistance. Figure 16.5 shows how an ammeter is used to measure the current flowing in an electric circuit.

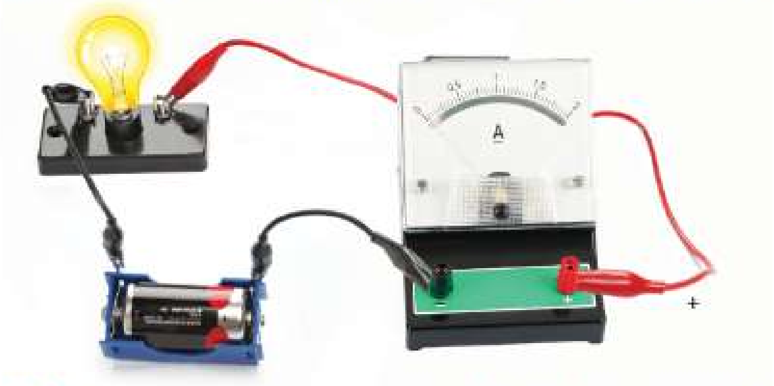


Figure 16.5 An ammeter is used to measure the current flowing through a light bulb.

Worked Example 16A

In Figure 16.5, if the switch has been closed for 0.5 hours and the current flowing in the circuit is 0.1 A, what is the total electric charge that has passed through the light bulb?

Thought Process

Since current is a flow of charges per unit time, and current has been flowing for 0.5 hours, then the amount of charge must be given by the product of current and time. We need to be mindful and convert all units to SI units.

Answer

Total electric charge is given by $Q = I \times t$

$$= 0.1\ \text{A} \times (0.5 \times 60 \times 60\ \text{s}) = 180\ \text{C}$$

Electromotive Force and Potential Difference

You may have seen danger signs in some parts of certain buildings (Figure 16.6). What is high voltage and why is it dangerous?

Volt is the SI unit for electromotive force (e.m.f.) and potential difference (p.d.). The volt is named in honour of the 18th–19th-century Italian physicist Alessandro Volta, who discovered the flow of an electric current between two different metals and a solvent, and developed the first battery. While both electromotive force (e.m.f.) and potential difference (p.d.) are measured in volts, these two terms are different and should not be confused.

Figure 16.6 A high voltage sign warning people to stay clear of certain areas

A common analogy for describing electric current flowing in a circuit is the flow of water. Consider the flow of water in Figure 16.7. For this analogy, it is also useful to think of water as the amount of charge. The battery is likened to the water pump and its e.m.f. is similar to the pumping action that creates the water flow. Energy in the chemical potential store is transferred to the kinetic store of the electric charge as it flows through the circuit.

Link

Chemistry

In Chemistry, we learn about electrolysis, which is the use of electricity to break down a compound.

Two English scientists used Volta's battery to decompose water into hydrogen and oxygen, giving rise to the field of electrochemistry.

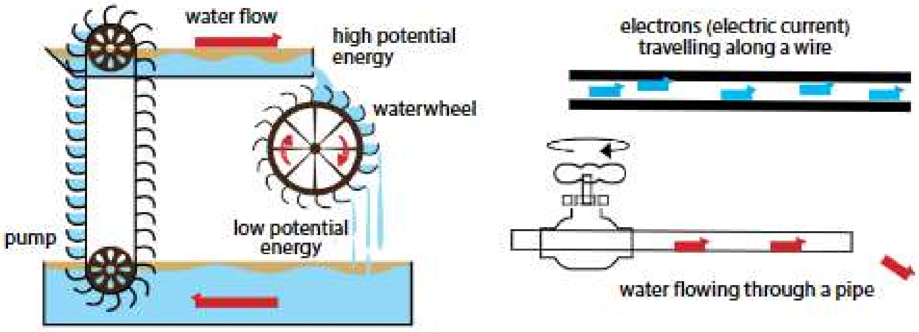


Figure 16.7 Using the flow of water as an analogy to describe electric current flowing in a circuit

The **electromotive force (e.m.f.)** of an electrical source is the work done by the source in driving a unit charge around a complete circuit.

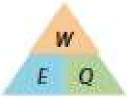
We use E to represent e.m.f.. Mathematically, we write:

$$E = \frac{W}{Q}$$

where E = e.m.f. of the electrical source (V)
W = work done (J)
Q = amount of charge (C)

Helpful Note

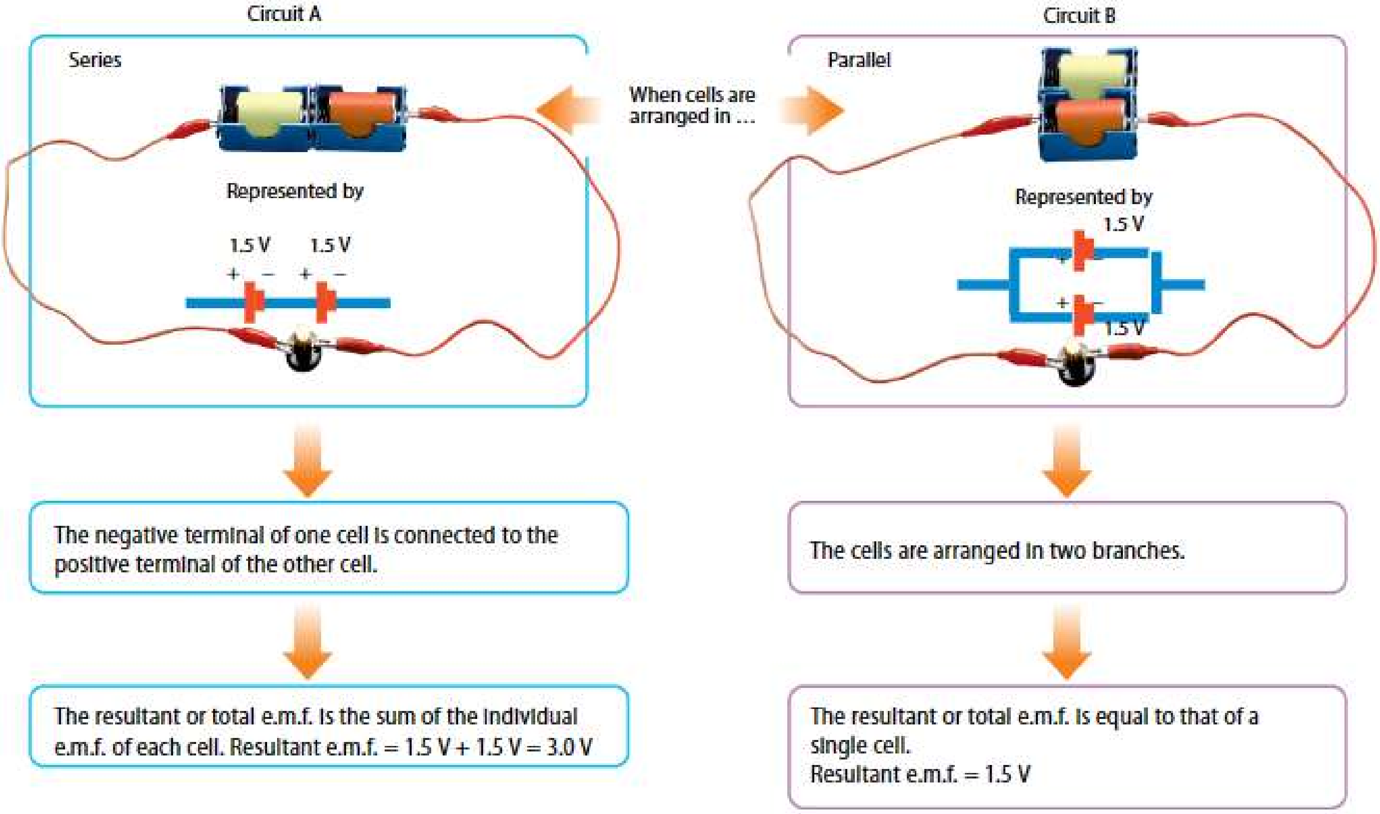
Use the "triangle" method to help you recall the relationship between e.m.f. of the electrical source E, work done W and amount of charge Q.



The SI unit of e.m.f. is **volt (V)**. Its SI unit may also be written as J/C, but it is uncommon to do so.

Cell Arrangement and E.m.f.

The e.m.f. of an electrical source is a scalar quantity. The arrangement of the electrical source (dry cell) determines the amount of e.m.f. supplied to the electrical components. Dry cells can be arranged in either **series** or **parallel** (Figure 16.8).



The negative terminal of one cell is connected to the positive terminal of the other cell.

The resultant or total e.m.f. is the sum of the individual e.m.f. of each cell. Resultant e.m.f. = 1.5 V + 1.5 V = 3.0 V

The cells are arranged in two branches.

The resultant or total e.m.f. is equal to that of a single cell.
Resultant e.m.f. = 1.5 V

Figure 16.8 How cell arrangement affects resultant e.m.f.

Let us look at Figure 16.7 again. Energy is transferred electrically from the chemical potential store of the battery to the kinetic (rotation) and internal (thermal) stores of the motor. The amount of electrical work done by each coulomb of charge passing through the motor is called the potential difference.

▶ The **potential difference (p.d.)** across a component in a circuit is the work done per unit charge in driving charges through the component.

We use V to represent p.d. The SI unit of potential difference is **volt (V)**. Mathematically, we write:

$$V = \frac{W}{Q}$$

where V = potential difference or voltage across a component (V)
W = work done (J)
Q = amount of charge (C)

The SI unit of p.d. or voltage is the same as that of e.m.f. of an electrical source even though potential difference is not electromotive force. We use the term e.m.f. for electrical source and the term p.d. for a component. For instance, the e.m.f. of a dry cell or p.d. of a light bulb.

Disciplinary Idea

Matter and energy make up the Universe.

In this section, we see that energy transfers in electrical circuits are brought about by a flow of electric charge (matter) or current and are related to potential differences. For instance, the motor is able to turn (increase in kinetic store of the motor). This is brought about by running an electric current through the motor.

Table 16.1 summarises the key differences between e.m.f. and p.d.

Table 16.1 Key differences between e.m.f. and p.d.

Electromotive Force (e.m.f.)	Potential Difference (p.d.)
E.m.f. is the work done to move each unit charge through the circuit.	P.d. is the work done by each unit charge passing through the components.
E.m.f. is present even when no current is drawn from the source.	P.d. across any electrical component is zero in the absence of current.

Both e.m.f. and p.d. can be measured by a voltmeter or a digital multi-meter. To measure the e.m.f. or p.d., the voltmeter or digital multi-meter must be connected across or in parallel with the electrical source or component. The positive terminal of an electrical source must be connected to the positive terminal of the voltmeter and vice versa (Figure 16.9).

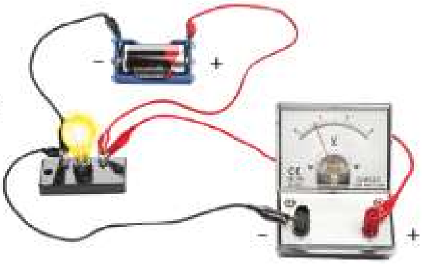


Figure 16.9 A voltmeter is used to measure e.m.f. or p.d. across an electrical source or component.

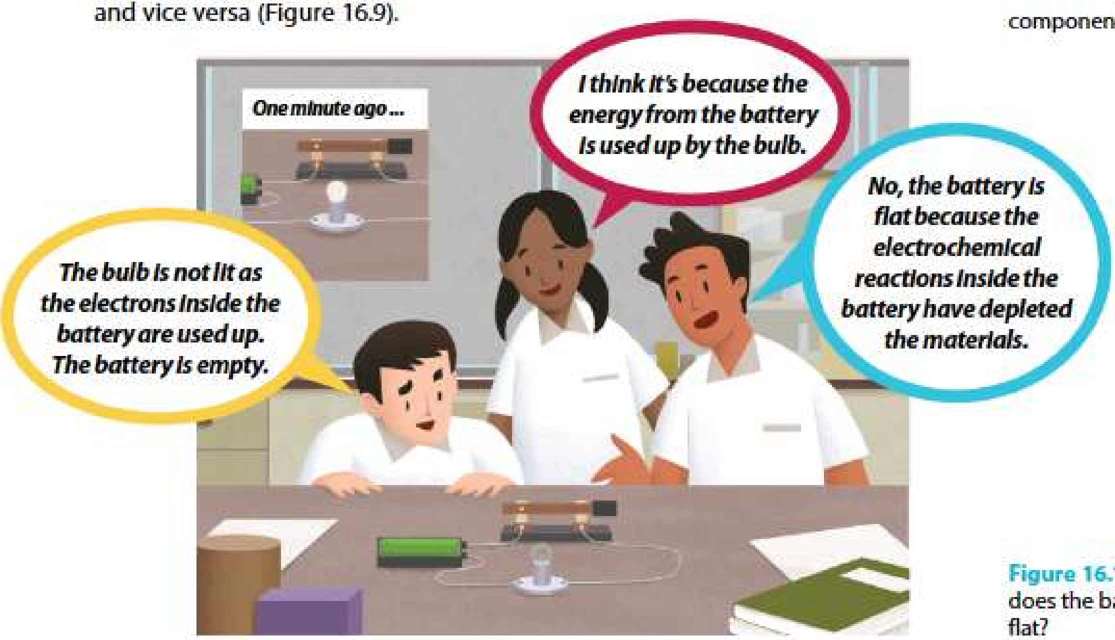


Figure 16.10 Why does the battery go flat?

After learning about how cell arrangement affects e.m.f. and how the p.d. across the source is measured, why do you think a battery goes flat (Figure 16.10)?

One common misconception about d.c. circuits is that electrons are stored in a battery and supplied to the circuit. This is not true. The electrons that flow through a circuit originate in the wire of the circuit. The battery supplies the energy that moves the electrons.

Another misconception is that energy is a quantity that can be "used up". Unlike in everyday conversation, energy does not get "used up". The principle of conservation of energy states that energy is neither created nor destroyed. Energy is transferred from one store to another. In this case, the energy from the chemical potential store of the battery is transferred electrically to the internal store of the filament.

A battery goes flat because the electrochemical reactions inside the battery have depleted the materials which produce these electrochemical reactions.

Worked Example 16B

In Figure 16.11, a Van der Graaff generator is allowed to discharge through a metal ball. Given that the discharge current is 0.01 A, the potential difference between the generator and ball is 100 kV, and the discharge takes 1 ms, what is the energy of the discharge?

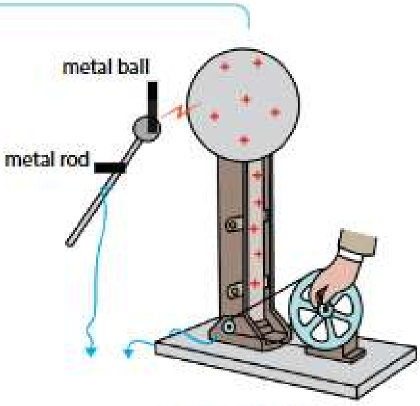


Figure 16.11

Thought Process
The potential difference is the energy applied to each coulomb of charge that is necessary for the charges to jump the gap. If we apply $V = \frac{W}{Q}$, then, the energy of the discharge is given by $W = QV$. In this second equation, the amount of charge can be obtained as the discharge current flowing for the duration of time given.

Answer
Total electric charge is given $Q = It$

$$= 1 \times 10^{-2}\text{ A} \times (1 \times 10^{-3}\text{ s}) = 1 \times 10^{-5}\text{ C}$$

Hence, the energy of the discharge $= QV$

$$= (1 \times 10^{-5})\,(1 \times 10^{5}) = 1\text{ J}$$

Let's Practise 16.1

1 Is electric current a flow of charged particles? Explain your answer.
2 Two dry cells with an e.m.f. of 1.5 V each are connected in series to a light bulb. The current flowing through the bulb is 1 A. Calculate the amount of electric charge flowing through the light bulb per minute. How much energy is dissipated per minute?

Link
Theory Workbook
Worksheet 16A

Past to Present

The first battery was designed by Alessandro Volta in 1799 (Figure 16.12(a)). It consisted of pairs of copper and zinc discs piled on top of each other and separated by cloth soaked in brine, which acted as an electrolyte (substance that conducts electricity). This construction has not changed much and the lead acid battery that we know of today still resembles Volta's design (Figure 16.12(b)). Perhaps the most widely known example of a present-day battery is the lithium-ion battery, which can be found in our smartphones. Even though it is called a dry cell, a lithium-ion battery is not actually "dry" (Figure 16.12(c)). Rather, the electrolyte is carefully sealed in a package.

(a) Alessandro Volta's battery design (b) Lead-acid battery (c) Lithium-ion dry cell

Figure 16.12 Different types of batteries through the years

16.2 Why Does the Electrical Resistance of Metals Increase with Temperature?

Learning Outcomes

- State that *resistance = p.d./current.*
- Apply the relationship $R = V/I$ to new situations or to solve related problems.
- Recall and apply the relationship of the proportionality between resistance and the length and cross-sectional area of a wire to new situations or to solve related problems.
- Describe the effect of temperature increase on the resistance of a metallic conductor.
- Sketch an interpret the I–V characteristic graphs for a metallic conductor at constant temperature (ohmic conductor), for a filament lamp and for a semiconductor diode.

Resistance

Let us revisit our water flow analogy. If there are sand or rocks in the path of the water flow, the flow would slow down. Electrical resistance acts in the same manner, slowing down the flow of electrons in a circuit. When the electrons flow through a component, they constantly collide with ions of the components and with other electrons (Figure 16.13). These collisions oppose the flow of the electrons. The degree of the opposing force which an electric current experiences when it flows through the component is the resistance of a component.

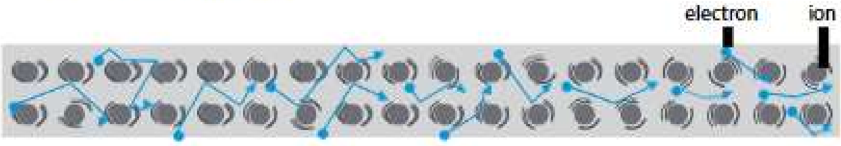


Figure 16.13 An electron flowing (blue line) through a component constantly collides with ions and electrons of the component, which in turn resist its flow across the component. There are many electrons taking different paths colliding into the ions at the same time.

▶ The **resistance** ***R*** of a component is the ratio of the potential difference V across it to the current I flowing through it.

Mathematically, we write:

$$R = \frac{V}{I}$$

where R = resistance of the component (Ω)
V = p.d. across the component (V)
I = current flowing through the component (A)

Resistance is a scalar quantity. The SI unit of resistance is **ohm (Ω)**, which is named after the German scientist Georg Simon Ohm.

From this equation, we can see that for a fixed voltage, the higher the resistance R, the smaller the electric current I. This is intuitive, given that resistance would impede the flow of electric charge.

Worked Example 16C

An electric iron is connected to a wall socket and has a potential difference of 240 V applied across its heating coil. What is its resistance if a current of 8 A flows through it?

Thought Process
The resistance of the heating coil is the ratio of its potential difference to the current flowing through it. Both values are given.

Answer
The resistance R of the heating coil is given by:

$$\begin{aligned} R &= \frac{V}{I} \\ &= \frac{240\ \text{V}}{8\ \text{A}} \\ &= 30\ \Omega \end{aligned}$$

Resistors

A resistor is a conductor or an insulator that has high resistance. It is used in a circuit to control the amount of current. Some resistors are shown in Figure 16.14. There are two types of resistors — fixed and variable.

A fixed resistor has a fixed value. It is made of a mixture of finely powdered carbon and ceramic, held together by a resin. The ratio of the mixture gives rise to different resistor values. These values are marked with colour bands on the resistor as shown in Figure 16.14. Resistors can have resistances that range from a few ohms to several million ohms.

Figure 16.14 These resistors called fixed resistors. The colour bands on the resistors indicate the value of the resistances. These resistors are also called colour band resistors.

Variable resistors, as the name suggests, can have different values of resistances. Examples of variable resistors are the rheostat and potentiometer (Figure 16.15).

(a) Rheostat

(b) Potentiometers

Figure 16.15 Different types of variable resistors

The basic construction of all variable resistors is the same. Different resistance values can be set by moving the slider along the metal rod to change the length of wire through which current flows through (Figure 16.16).

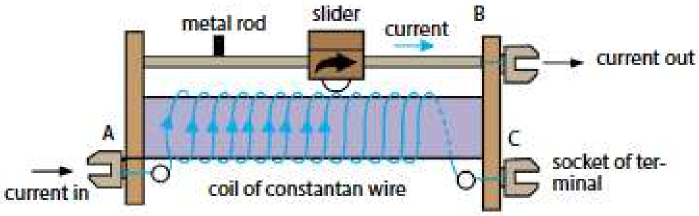
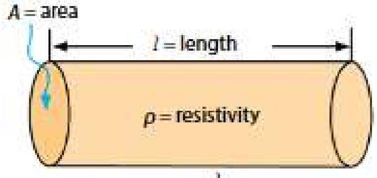


Figure 16.16 The resistance of a variable resistor can be varied by moving the slider along the metal rod.

Resistance of Objects

The resistance of an object depends on its shape and the material it is made of. To get an insight into how resistance is dependent on its shape, consider a cylindrical resistor (Figure 16.17).



$$R = \rho\frac{l}{A}$$

Figure 16.17 A cylindrical resistor of length l and cross-sectional area A

As you might expect, the longer the cylinder, the more collisions the electrons will make with its particles. Hence, the resistance R of the cylindrical resistor is directly proportional to the length of the cylinder l.

On the other hand, the larger the cross-sectional area A of the cylinder, the greater the number of electrons that can flow through it. Therefore, the resistance R of the cylindrical resistor is inversely proportional to the area of the cylinder A.

Mathematically, we write $R \propto l$ and $R \propto \frac{1}{A}$. Combining these two relationships, we have:

$$R = k\frac{l}{A}$$ where k is a constant.

We define a constant ρ as the **resistivity** of a substance that depends on what the material is composed of. The equation now becomes:

$$R = \rho\frac{l}{A}$$

Rearranging the equation:

$$\rho = R\frac{A}{l}$$

From $\rho = R\frac{A}{l}$, we can see that *resistivity* is the resistance of a material for a unit area per unit length. In other words, resistivity is independent of the shape or size of the material. In fact, resistivity is an intrinsic property of a material. The SI unit of resistivity is ohm metre (Ωm). The resistivity of some materials can be found in Table 16.2.

Table 16.2 Resistivity of some material measured at 20 °C

Material	Resistivity / Ωm	Material	Resistivity / Ωm
silver	1.6×10^{-8}	constantan	49×10^{-8}
copper	1.7×10^{-8}	nichrome	100×10^{-8}
tungsten	5.5×10^{-8}	graphite	3000×10^{-8}
iron	9.8×10^{-8}	polythene	about 10^{16}

Materials with low resistivities are good conductors of electricity. Copper is a common metal that has low resistivity and is often made into wires since electric current can flow easily through copper.

Materials with high resistivities are poor conductors of electricity. Such materials generate a lot of heat and can be used for heating purposes.

Worked Example 16D

Wire P and wire Q are both made from the same materials. They are 10 m long. The resistance of wire P is 75 Ω and its cross-sectional area is 0.1 mm². If wire P has a cross-sectional area of 1 mm², what is the resistance of wire Q?

Thought Process
Since wire P and Q are made from the same material, they have the same value of constant *k*.
As the length of both wires are the same, the difference in the resistances of the wires is only dependent on the cross-sectional areas.

Answer

$R = k\frac{l}{A}$

For wire P and wire Q, we can write the relationship as: $R_P = \frac{k_P}{A_P}$

$k_P = R_P A_P$ —— (1)

$R_Q = \frac{k_Q}{A_Q}$

$k_Q = R_Q A_Q$ ——(2)

Since the wire are of the same material, $k_P = k_Q$.

Equating equations 1 and 2: $\frac{R_Q}{R_P} = \frac{A_P}{A_Q}$

$R_Q = \frac{A_P}{A_Q} R_P = \frac{0.1}{1}(75) = 7.5\ \Omega$

Helpful Note

There is no need to convert the values of the cross-sectional areas to SI units since we are only interested in their ratio.

While we assume that the resistance of most metals is independent of temperature, it is not. The resistance of most metals increases linearly with temperature (Figure 16.18). For instance, the resistance of lead increases from R_1 to R_2 when temperature increases from t_1 to t_2. This is because at higher temperatures, the metallic ions vibrate more vigorously about their fixed positions. This increases the number of collisions between the free electrons and the metallic ions, which in turn opposes or slows down the flow of electrons.

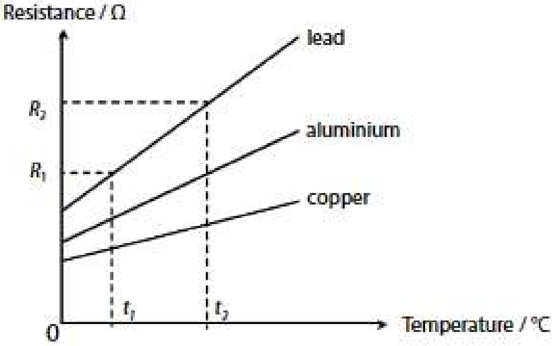


Figure 16.18 The resistance of most metals increases linearly with temperature.

Disciplinary Idea

Microscopic models can explain macroscopic phenomena.

In a metal conductor, increased electrical resistance of metals with increased temperature is due to increased collisions between mobile electrons and the fixed positive ions.

Recall that resistance $R = \frac{V}{I}$. We can rearrange this equation to form a relationship between voltage and current, that is, $V = IR$. The amount of current is directly proportional to the potential difference V applied across a material with resistance R. When a material exhibits this linear relationship between p.d. V and current I, it is said to be **ohmic**. Figure 16.19 shows the I–V characteristic graph of an ohmic conductor at constant temperature.

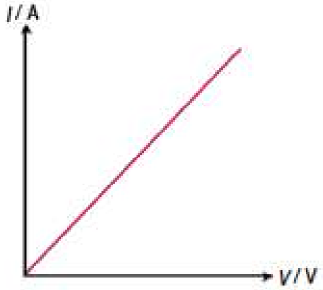


Figure 16.19 The I–V characteristic graph of an ohmic conductor is a straight line passing through the origin.

Helpful Note

This I–V graph is ohmic because it:

- is linear, or has a constant gradient; and
- passes through the origin.

Note that the resistance is given by the reciprocal of the gradient and is a constant.

This relationship between V and I is known as Ohm's law.

The voltage across a conductor is directly proportional to the current flowing through it. This is provided that all physical conditions and temperature remain constant.

Conductors that do not have a direct proportional relationship between V and I are known as non-ohmic conductors. This is because the resistances of these conductors change as their temperature changes. A tungsten filament lamp is an example of a non-ohmic conductor. The resistance of tungsten increases as temperature increases. Other examples of non-ohmic conductors are diodes and negative temperature coefficient (NTC) thermistors.

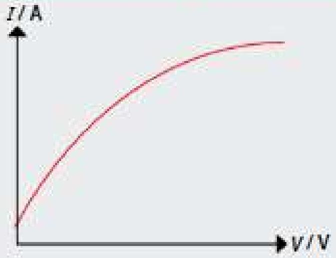
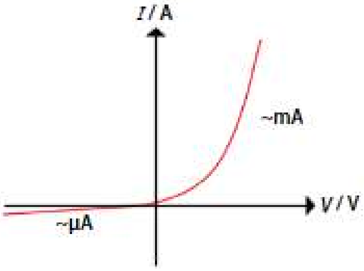
Word Alert

Diode: device that allows current to flow in one direction but not the other

Thermistor: thermal resistor; a resistor whose resistance depends on temperature

Table 16.3 shows the I–V characteristic graphs of a filament lamp and a *semiconductor* diode.

Table 16.3 I–V characteristics of a filament lamp and semiconductor diode

Non-Ohmic Conductor	I–V Graph	Description
filament lamp 		As electric current increases, more energy is transferred from the chemical potential store of the battery to the internal store of the filament. This in turn increases the resistance of the filament, which limits the rate of increase of current. The ratio of V to I shows the increase of filament resistance.
semiconductor diode 		When a positive voltage is applied to the anode of a diode, a large current flows. We say that the resistance in the forward direction is very low. In the reverse direction, when a positive voltage is applied to the cathode of a diode, the current is very low or almost zero. The resistance in the reverse direction is very high or almost infinite.

Let's Investigate 16A

Aim

To determine the resistance of an unknown ohmic resistor using a voltmeter and an ammeter

Procedure

1. Set up the apparatus according to the circuit diagram in Figure 16.20.
2. Adjust the rheostat to the maximum resistance so that the initial current is small. This also minimises heating of the rheostat.
3. Record the ammeter (I) and voltmeter (V) readings.
4. Adjust the rheostat to reduce the current by 1 A. Record the ammeter I and voltmeter V readings.
5. Repeat step 4 to obtain four more readings.
6. Plot V / V against I / A. Determine the gradient of the graph.

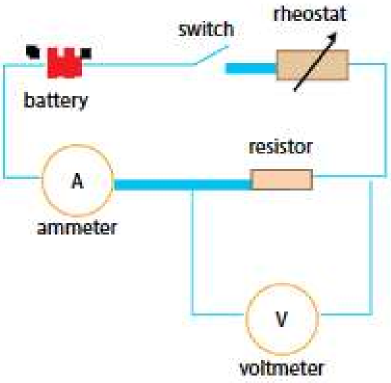


Figure 16.20 Experiment set-up to determine the resistance of an ohmic resistor

Observation

The plot of V / V against I / A is linear and the gradient gives the value of the resistance (Figure 16.21).

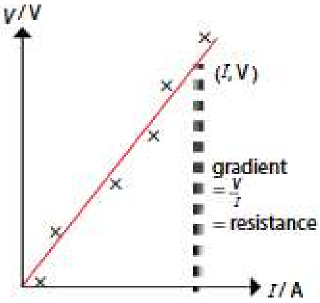


Figure 16.21 I–V graph

Questions

1. If I / A was plotted against V / V, how can the resistance be determined?
2. Does the graph begin at the origin? If the graph has a non-zero y-intercept value, is Ohm's law being observed?
3. What are the possible sources of error?

Link

Theory Workbook
Worksheet 16B
Let's Assess
Let's Reflect

Let's Practise 16.2

1. The maximum resistance of potentiometer shown in Figure 16.22 is 270 Ω. If the full range of the knob of the potentiometer is 270 °, what is the resistance when the knob is turned to 100 °?
2. A company makes two different models of electric kettles, model C and model D. Both models use different lengths of the same heating element. The resistance of the heating element of model C is 60 Ω and its length is 10 m. If the length of the heating element of model D is 12 m, what is the resistance?

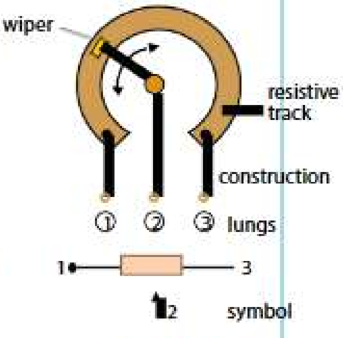


Figure 16.22

Tech Connect

When two sheets of graphene are stacked on top of each other at just the correct angle, their electrical property can change drastically, from non-conductive to superconductive. This behaviour was first postulated by physicist Antonio Castro Neto who stated that some new electrical properties may be obtained when two misaligned graphene sheets are stacked together. Since then, other scientists have been hunting for this "magic" angle and this has given rise to the emerging field of Twistronics. What are some possible uses of this new material?

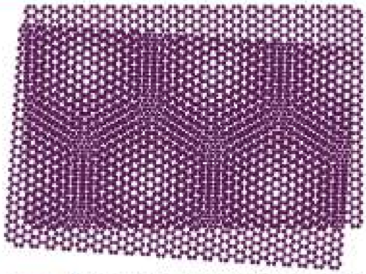


Figure 16.23 By stacking one graphene sheet on another at a "magic" angle, a superconductor can be obtained.

Cool Career

Applied Superconductor Researcher

The applied superconductor researcher is a research scientist that investigates how to apply or use superconductors. A superconductor is a conductor with very low or no resistance (Figure 16.24). Superconductors can be used in several applications. For instance, superconductors can potentially be used to build low voltage transmission lines, magnetic levitation trains, fast digital circuits and electric motors. Present day superconductivity can only be achieved when alloy metals are cooled below a critical sub-zero temperature, which makes them unsuitable for real-world applications. However, as new material properties are being discovered, the use of superconductivity in practical applications are within grasp. The applied researcher explores ways in which these applications can be turned into reality.

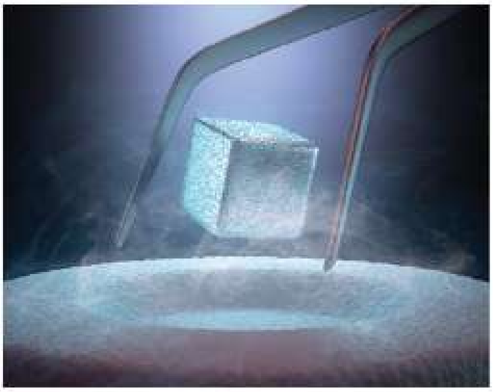
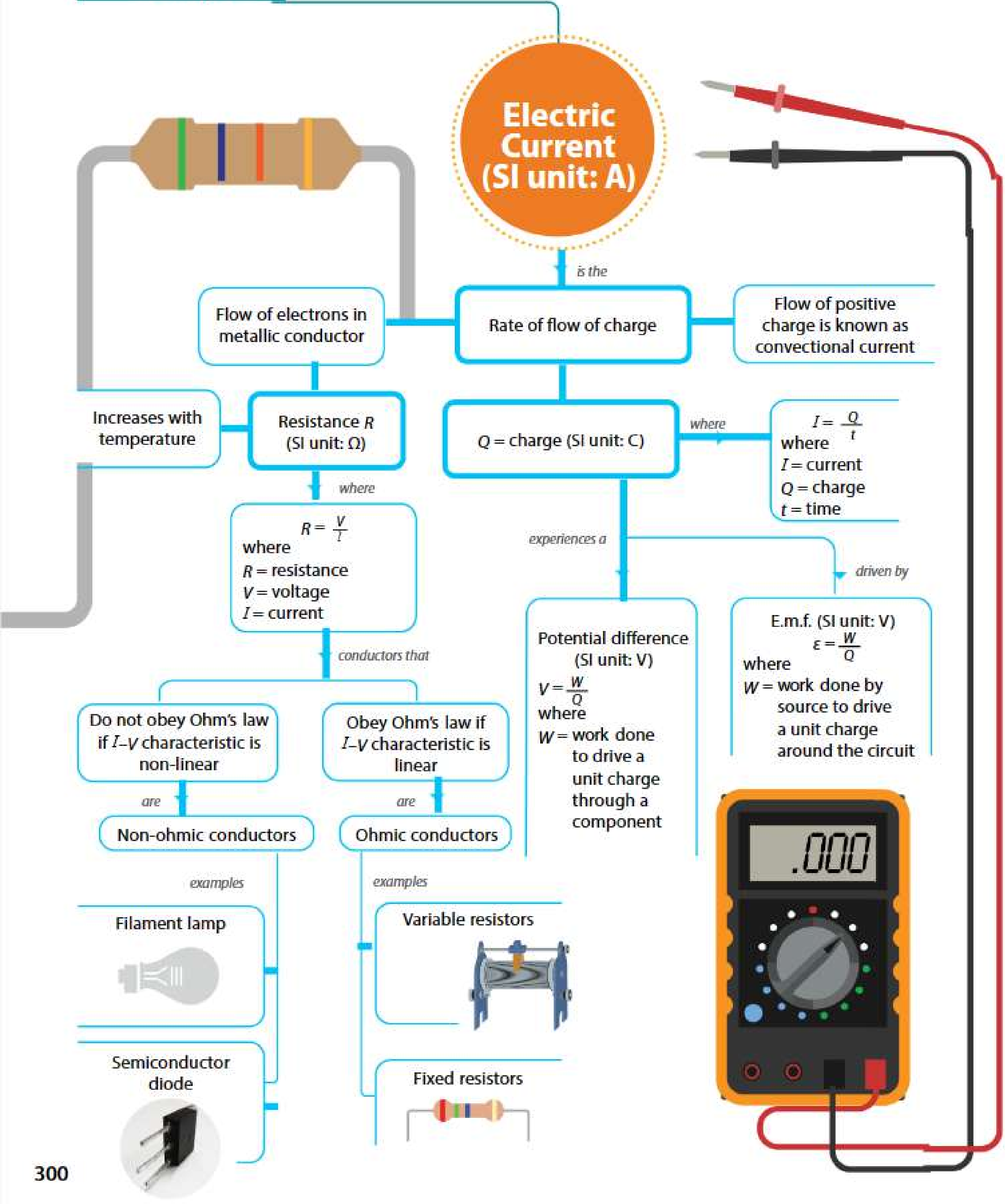


Figure 16.24 A superconductor hovering effortlessly over a strip of magnetic tracks

Let's Map It



Electric Current (SI unit: A)

is the

Rate of flow of charge

Flow of electrons in metallic conductor

Flow of positive charge is known as convectional current

Resistance R (SI unit: Ω)

Increases with temperature

where

$R = \frac{V}{I}$
where
R = resistance
V = voltage
I = current

conductors that

Do not obey Ohm's law if I–V characteristic is non-linear

are

Non-ohmic conductors

examples

Filament lamp

Semiconductor diode

Obey Ohm's law if I–V characteristic is linear

are

Ohmic conductors

examples

Variable resistors

Fixed resistors

Q = charge (SI unit: C)

where

$I = \frac{Q}{t}$
where
I = current
Q = charge
t = time

experiences a

Potential difference (SI unit: V)
$V = \frac{W}{Q}$
where
W = work done to drive a unit charge through a component

driven by

E.m.f. (SI unit: V)
$\varepsilon = \frac{W}{Q}$
where
W = work done by source to drive a unit charge around the circuit

Let's Review

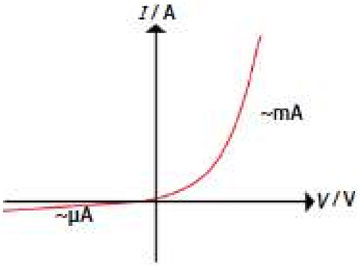
Section A: Multiple-choice Questions

1 When a car engine is cranked, 20 A of current is drawn by the starter motor in 20 ms. What is the charge flowing through the starter motor?

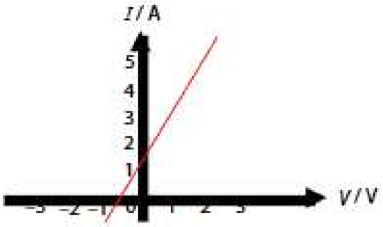
○ **A** 0.4 nC
○ **B** 40 μC
○ **C** 0.4 mC
○ **D** 0.4 C

2 Which of the following is the I–V characteristic of an ohmic conductor?

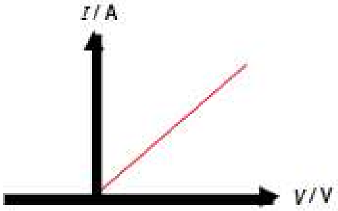
○ **A**



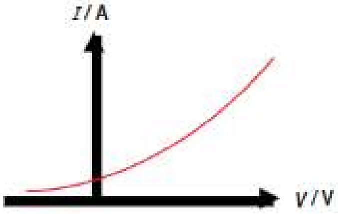
○ **B**



○ **C**



○ **D**



3 A charged cloud carrying a charge of 2000 C was discharged in 5 ms in a flash of lightning. What is the current flowing into the ground?

○ **A** 10 A
○ **B** 400 A
○ **C** 1×10^4 A
○ **D** 4×10^5 A

4 A resistor with resistance R is made from a material with length l. If a resistor with resistance of $2R$ is made from the same material and its cross-sectional area remains unchanged, what is the length required?

○ **A** $0.5l$
○ **B** l
○ **C** $2l$
○ **D** $4l$

5 A component is found to have I–V characteristics shown in Figure 16.25. What is this component likely to be?

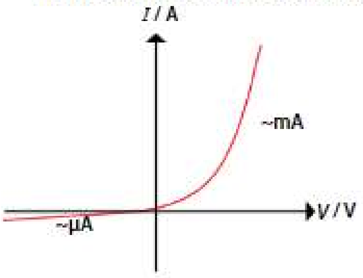


Figure 16.25

○ **A** fixed resistor
○ **B** rheostat
○ **C** filament lamp
○ **D** semiconductor diode

Section B: Structured Questions

1 Is electromotive force a kind of force? Distinguish between electromotive force and potential difference.

2 An electric eel can discharge about 500 mA of current for about 2 ms. Find the amount of charge that is generated.

3 Wire wound resistors of different values are made of different lengths of resistance wire enclosed by a ceramic casing. Figure 16.26 shows the internal construction of a wire wound resistor. To get a resistance of 100 Ω, 2 m of resistance wire is required. What is the length of resistance wire of a 470 Ω wire wound resistor?

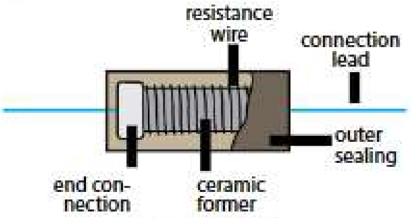


Figure 16.26

4 Transmission lines carry electricity from distant power stations to cities (Figure 16.27). Transmission lines are usually made of copper. The distance from a power station to city A is 100 km, and the resistance of the transmission line wires used is resistance 5 Ω.

(a) If the same transmission line wire is used to connect the power station to city B 150 km away, calculate the resistance of the transmission line wire used.

(b) Suggest **one** way to reduce the resistance. Explain your answer.

Figure 16.27

Section C: Free-response Questions

1 A driver forgot to turn off his car's headlights. When he returns to his car the next morning, he found the car battery to be completely flat.

(a) Define *electromotive force*.

(b) If the current drawn by the headlight is constant at 2 A, and the battery operated for 8 hours, find the charge passing through the headlights.

(c) What is the work done by the 12V battery, assuming that the wires connecting the battery to the headlights have zero resistance?

(d) When the driver touched his headlights, they felt hot. Would you expect the resistance of the filament to stay constant? Provide a microscopic explanation why or why not for your answer.

2 A technician found that there is a constant current of 0.1 A in a filament lamp when connected to a 12 V battery. He also found that the work done by the filament is 300 J over a five-minute period.

(a) Calculate the charge flowing through the lamp during the five-minute period.

(b) Calculate the p.d. across the lamp.

(c) Explain the difference between p.d. and e.m.f. in this case.

(d) The technician left the lamp operating for 10 hours and found that it has dimmed considerably. He measured the p.d. across the lamp and found it to be just 4 V. Using the I–V characteristic graph for the filament lamp shown in Figure 16.28, calculate the charge flowing in the lamp over a five-minute period.

(e) Determine the resistance of the lamp.

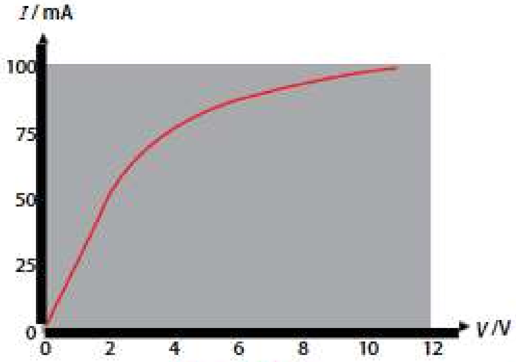
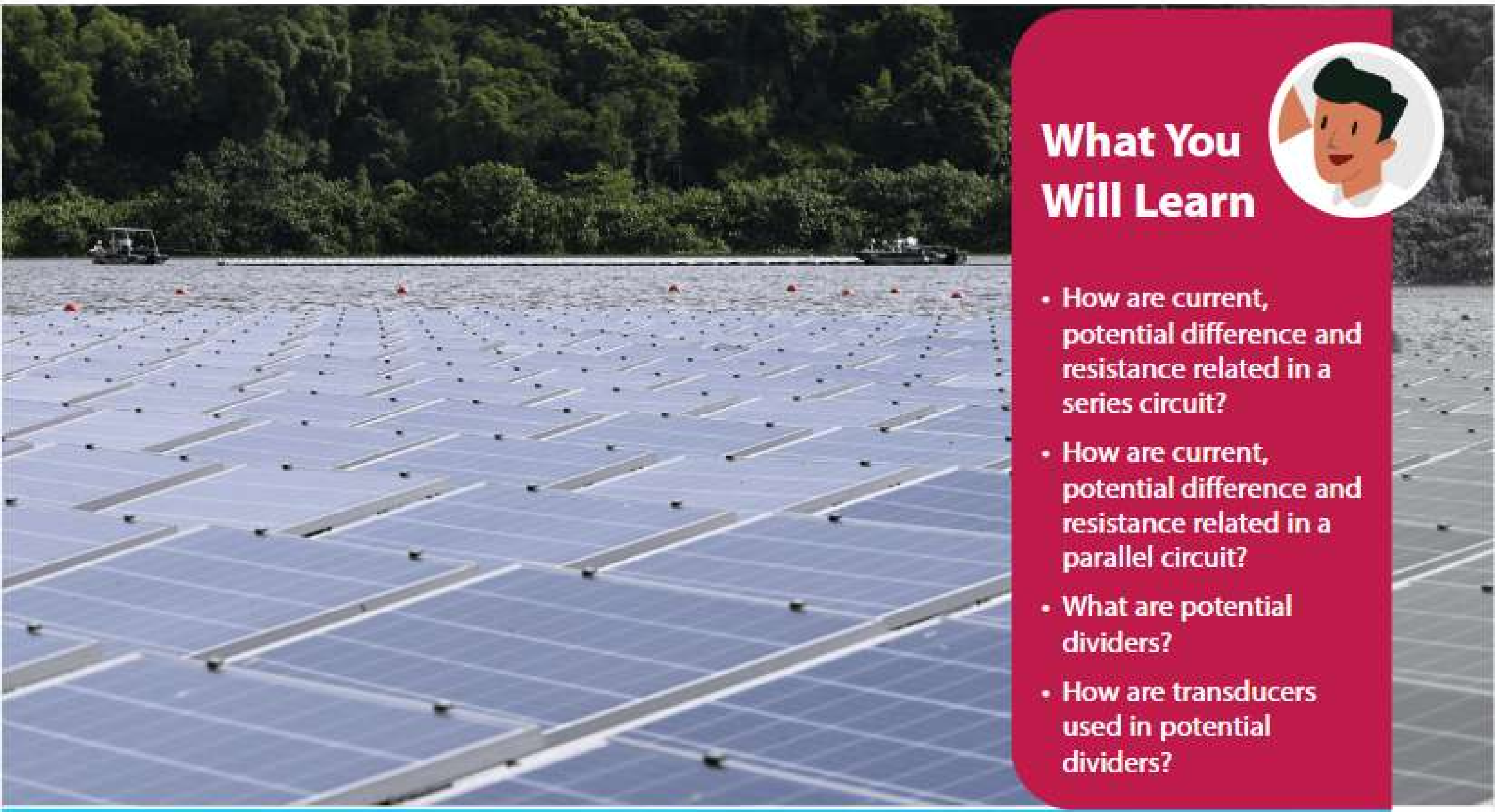


Figure 16.28

CHAPTER

17 D.C. Circuits



What You Will Learn

- How are current, potential difference and resistance related in a series circuit?
- How are current, potential difference and resistance related in a parallel circuit?
- What are potential dividers?
- How are transducers used in potential dividers?

If you walk along Tengeh Reservoir, you will come across several of these gigantic floating solar photovoltaic systems. These panels, when combined together, can generate power of 50 megawatt-peak (MWp, the maximum potential output of power). Little or no carbon dioxide is produced in the process. On the other hand, to produce an equivalent amount of power, gas turbine electric generators would give off about 28 000 tonnes of carbon dioxide.

Do you know that the electric currents generated by these panels are direct currents? This is different from electric currents which are produced by all other sources of electricity. What are direct currents?

17.1 How Are Current, Potential Difference and Resistance Related in a Series Circuit?

Learning Outcomes

- Draw circuit diagrams with power sources, switches, lamps, resistors, variable potential divider (potentiometer), fuses, ammeters and voltmeters, bells, light-dependent resistors, thermistors and light-emitting diodes.
- State that the current at every point in a series circuit is the same and apply the principle to new situations or to solve related problems.
- State that the sum of the potential differences in a series circuit is equal to the potential difference across the whole circuit and apply the principle to new situations or to solve related problems.

Direct current (d.c.) circuits are used in many electronic products such as mobile phones, laptops, smartwatches and other devices that are operated by batteries. What are d.c. circuits?

In d.c. circuits, current flows in only *one direction* and the applied voltage is usually quite low. This is different from an alternating current (a.c.) circuit. In a.c. circuits, current *changes direction* fifty or sixty times every second.

A simple d.c. circuit contains a d.c. power supply, a switch, and a component such as a resistor. Such circuits can be represented using a diagram called **circuit diagram**.

Circuit Diagrams

A circuit diagram, or an electrical diagram, is a simplified diagrammatic representation of an electric circuit. It shows the connections between **electrical components**, which are often represented by symbols.

Word Alert

Electrical components: devices that affect electrons or their associated fields

Figure 17.1 shows an example of a circuit diagram.

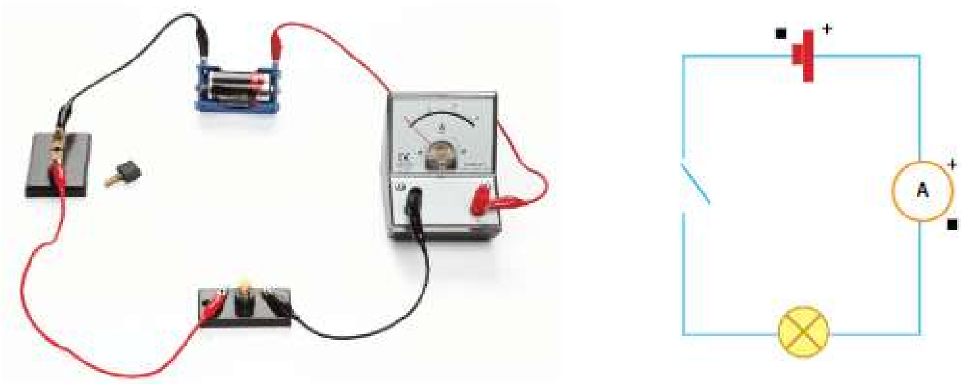
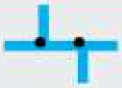
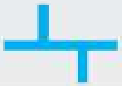
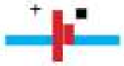
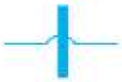
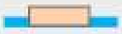
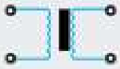


Figure 17.1 (a) An actual electric circuit and (b) its equivalent circuit diagram

Some common circuit symbols are given in Table 17.1.

Table 17.1 Common circuit symbols of electrical components

Symbol	Device	Symbol	Device	Symbol	Device
	switch	 or 	wires joined	 or 	galvanometer
	cell		wires crossed		ammeter
	battery		fixed resistor		voltmeter
	d.c. power supply		variable resistor (rheostat)		two-way switch
	a.c. power supply		fuse		earth connector
	light bulb		coil of wire		light-emitting diode
	potentiometer		transformer		thermistor
	light-dependent resistor (LDR)		semiconductor diode		bell

Series Circuits

There are two basic ways in which components of a circuit may be connected together — in series or in parallel.

A series connection is one in which the components are connected one after another in a single loop (Figure 17.2). Circuits that have components connected in series are called **series circuits**.

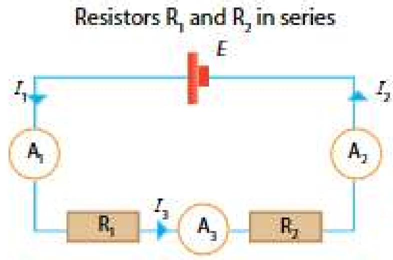


Figure 17.2 The currents $I_1 = I_2 = I_3$ must be equal.

In a series circuit, since there is only one single loop, the electric current has only one path to flow through.

► In a series circuit, the current at every point is the same.

In Figure 17.2, the currents $I_1 = I_2 = I_3$.

The potential difference (p.d.) across a resistor is the work done per unit charge in driving the charges through that resistor. Thus, there must be a fall in electrical potential as the charge flows across resistors R_1 and R_2 in Figure 17.2. These potential differences can be measured using a voltmeter as shown in Figure 17.3. The electromotive force of the cell E is equal to the sum of the potential differences across R_1 and R_2.

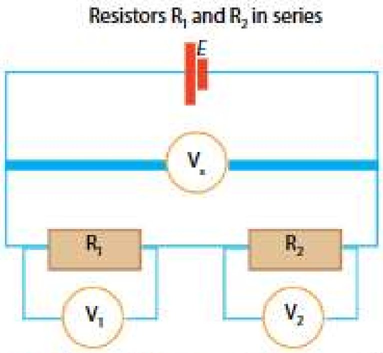

Resistors R_1 and R_2 in series

Figure 17.3 The voltage across the source E is the sum of V_1 and V_2.

▶ In a series circuit, the total potential difference supplied to the circuit E is equal to the sum of the individual potential differences across the resistors.

Mathematically, in reference to Figure 17.3, we write:

$$E = V_1 + V_2$$

Since $V = IR$:

$$V_\varepsilon = IR_1 + IR_2$$

$$R_1 + R_2 = \frac{V_\varepsilon}{I}$$

Link

Recall from Chapter 16:
$V = IR$

We can define an effective resistance R_e such that $R_e = R_1 + R_2 = \frac{E}{I}$.
Hence, the circuit diagram of Figure 17.3 can be replaced by an equivalent circuit diagram shown in Figure 17.4.

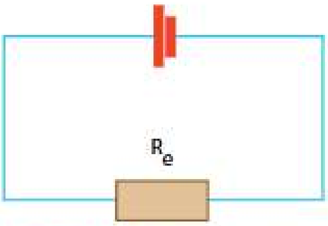


Figure 17.4 The two resistors in series can be replaced by a resistor with an effective resistance of R_e.

In general, if there are n resistors connected in series, then:

$$E = V_1 + V_2 + \ldots + V_n$$

Since p.d. $= IR$:

$$V_\varepsilon = IR_1 + IR_2 + \ldots + IR_n$$

▶ $$\therefore R_e = \frac{V_\varepsilon}{I} = R_1 + R_2 + \ldots + R_n$$

This means that when resistors are connected in series, they can be represented by an effective resistance of R_e.

▶ In a series circuit, the effective resistance R_e is equal to the sum of the individual resistances.

Worked Example 17A

Two resistors with values 2.0 Ω and 4.0 Ω are connected in series to a 12 V cell.

(a) Calculate the current flowing in the circuit.

(b) Calculate the potential difference across each resistor.

(c) Draw a graph on the axes in Figure 17.5, showing the changes in electrical potential along the circuit.

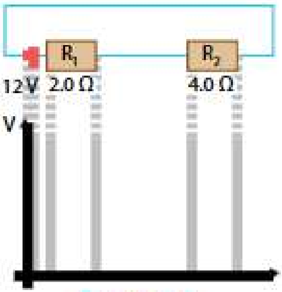


Figure 17.5

Thought Process

(a) The keywords for this example are "connected in series".

The current at every point in a series circuit is the same. The sum of the p.d. in a series circuit is equal to the p.d. across the whole circuit. Since $V = IR$, if I is the current flowing in the circuit, then $2I$ and $4I$ are the p.d. of the resistors. The sum of these p.d. is equal to 12 V, which is the p.d. across the whole circuit.

An alternative method is to consider replacing the two resistors by its effective resistance R_e. Then the current flowing in the circuit is $I = \frac{\text{e.m.f.}}{R_e}$.

(b) Once the current flowing in the series circuit is found, the p.d. across each resistor can be obtained from the equation, $V = IR$.

(c) The cell has energy in the chemical potential store. The electric current transfers energy from the chemical potential store of the cell to the internal stores of the resistors. Thus, the temperature of the resistors increases when the current flows through them. The net change in potential energy for a charge making a round trip around a complete circuit must be zero.

Answer

(a) The effective resistance of the circuit Re = 2.0 Ω + 4.0 Ω = 6.0 Ω

Therefore, the current I flowing in the circuit = $\frac{12\text{ V}}{6.0\ \Omega}$ = 2.0 A

or

Sum of p.d. in the series circuit = $2I + 4I$

The p.d. across the whole circuit = e.m.f. of battery = 12 V

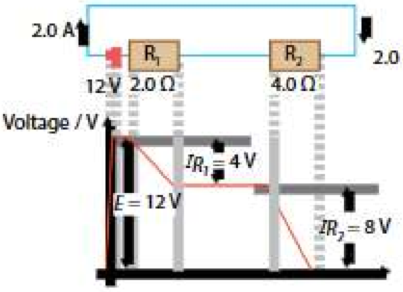
Hence, $6I$ = 12 V

I = 2.0 A

(b) P.d. across 2 Ω resistor = 2.0 A × 2.0 Ω = 4.0 V

P.d. across 4 Ω resistor = 2.0 A × 4.0 Ω = 8.0 V

(c) The changes in electrical potential along the circuit are as follows:



Disciplinary Idea

Conservation laws constrain the changes in systems.

The conservation of energy has to be observed. The energy supplied by the cells is equal to the total energy dissipated in the circuit. Hence, the drop in potential across a circuit is equal to the electromotive force generated by the sources in the circuit.

Let's Investigate 17A

Aim

To verify that the sum of the potential differences in a series circuit is equal to the potential difference across the whole circuit

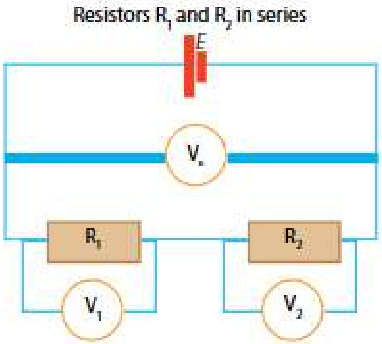


Figure 17.6

Procedure

1. Set up the circuit shown in Figure 17.6.
2. Record the readings on the voltmeters V_1, V_2 and $V_ε$.
3. Add another dry cell of the same type in series to the power supply.
4. Repeat step 2.
5. Repeat steps 3 and 4 until at least three sets of readings have been obtained.

Observation

The sum of the readings on V_1 and V_2 is almost equal to $V_ε$.

Questions

1. What are the possible reasons that the sum of the readings in V_1 and V_2 is not exactly $V_ε$?
2. Would your results be more accurate if larger readings in R_1 and R_2 are used?

Let's Practise 17.1

1. In Figure 17.7, two resistors with values 2 Ω and 1 Ω are connected in series to a 1.5 V cell.

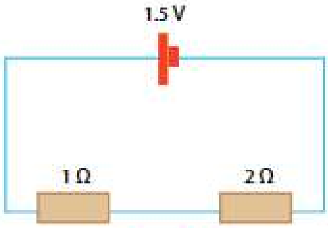


Figure 17.7

Calculate:

(a) the effective resistance of the circuit; and

(b) the potential difference across each resistor.

2. The 2 Ω resistor in Figure 17.7 is replaced by an unknown resistor with value of R Ω and the current in the circuit is found to be 0.1 A. What is the value of R?

Link

Theory Workbook
Worksheet 17A

17.2 How Are Current, Potential Difference and Resistance Related in a Parallel Circuit?

Learning Outcomes

- State that the sum of the currents in the separate branches of a parallel circuit is equal to the current from the source and apply the principle to new situations or to solve related problems.
- State that the potential difference across the separate branches of a parallel circuit is the same and apply the principle to new situations or to solve related problems.
- Recall and apply the formulae for the effective resistance of a number of resistors in series and in parallel to new situations or to solve related problems.
- Recall and apply the relevant relationships, including $R = V/I$ and those for current, potential differences and resistors in series and in parallel circuits, in calculations involving a whole circuit.

Parallel Circuits

A parallel connection is one in which the components are placed next to each other in parallel and the ends are connected like the rungs of a ladder (Figure 17.8). Circuits that have components connected in parallel are called **parallel circuits**.

In the parallel circuit in Figure 17.8, the electric current I is split into two paths at junction X. Thus, the sum of these two electric currents I_1 and I_2 in the two parallel branches must be equal to I. These two electric currents then recombine at junction Y into I.

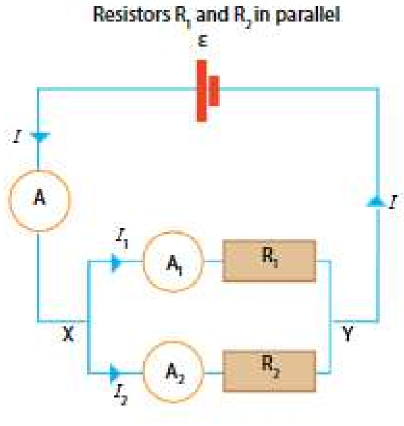


Figure 17.8 The current I is split at junction X into two currents I_1 and I_2, which are recombined at junction Y.

Mathematically, in reference to Figure 17.8, we write:

$$I = I_1 + I_2$$

► In a parallel circuit, the total current flowing into or out of the parallel branches is equal to the sum of the individual currents in each parallel branch.

Disciplinary Idea

Conservation laws constrain the changes in systems.

The total charge of a system is constant unless some charge enters or leaves the system. Hence, the total current entering a junction is the same as the total current leaving a junction. This is also known as the conservation of charge.

The potential difference across each branch must be the same as the electromotive force of the cell. This is because the cells are directly connected to the components. This is shown in Figure 17.9

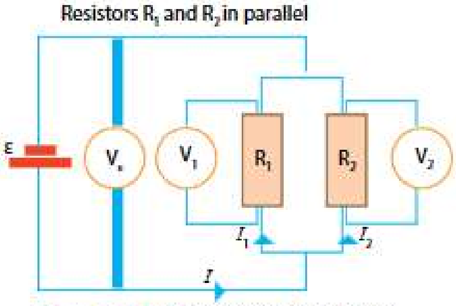


Figure 17.9 The voltages V_1, V_2 and V_ε must be equal since they are connected in parallel to each other using only wires.

Thus, $V_\varepsilon = V_1 = V_2$.

In a parallel circuit, the p.d. across the parallel branches is the same.

In Figure 17.9, since $I = I_1 + I_2$:

$$I = \frac{V_1}{R_1} + \frac{V_2}{R_2}$$

$$I = V_\varepsilon\,(\frac{1}{R_1} + \frac{1}{R_2})$$

$$\frac{I}{V_\varepsilon} = \frac{1}{R_1} + \frac{1}{R_2}$$

We can define an effective resistance R_e such that: $\frac{I}{V_\varepsilon} = \frac{1}{R_e} = \frac{1}{R_1} + \frac{1}{R_2}$

The reciprocal of the effective resistance is the sum of the reciprocal of the individual resistances. If we simplify the equation further:

$$\frac{1}{R_e} = \frac{R_1 + R_2}{R_1 R_2}$$

$$R_e = \frac{R_1 R_2}{R_1 + R_2}$$

Helpful Note

A simple way to remember the formula for effective resistance of two parallel resistors is "product of resistance over sum of resistances".

In the special case where $R_1 = R_2 = R$, applying the formula above will give $R_e = \frac{R}{2}$. In addition, the current in each branch of the parallel circuit is $\frac{I}{2}$. This is intuitive, since we can expect that half the current will flow in one branch and the other half in another branch.

The circuit diagram of Figure 17.9 can be replaced by an equivalent circuit diagram shown in Figure 17.10.

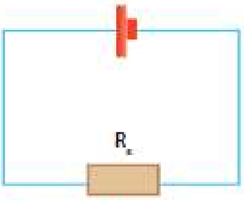


Figure 17.10 The two resistors in parallel can be replaced by a resistor with an effective resistance of R_e.

In general, if there are n number of parallel connections, then the main current I is the sum of the individual currents flowing in the different branches. That is:

$$\boldsymbol{I = I_1 + I_2 + \ldots + I_n}$$

The voltages across these n number of branches are the same, that is:

$$\boldsymbol{V_\varepsilon = V_1 = V_2 = \ldots = V_n}$$

If we combine these information, then:

$$I = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \ldots + \frac{V_n}{R_n}$$

$$I = V_\varepsilon(\frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n})$$

$$\frac{I}{V_\varepsilon} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$$

The effective resistance R_e such that $R_e = \frac{V_\varepsilon}{I}$ becomes:

$$\frac{1}{R_e} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$$

Word Alert

Reciprocal: A reciprocal for x is denoted by $\frac{1}{x}$, and gives "1" when multiplied by x

In other words, the effective resistance of all the resistors connected in parallel can be represented by a single resistor R_e such that R_e can be found using the equation above.

In a parallel circuit, the **reciprocal** of the effective resistance of resistors $\frac{1}{R_e}$ is equal to the sum of the reciprocal of the individual resistances.

Worked Example 17B

Two resistors with values 2 Ω and 4 Ω are connected in parallel to a 12 V battery. Calculate:

(a) the current flowing through the 2 Ω resistor;
(b) the current flowing through the 4 Ω resistor;
(c) the current flowing from the battery; and
(d) the equivalent resistance of the two resistors.

Thought Process

(a)/(b)
Since the resistors are connected in parallel, the p.d. across the separate branches is the same. Therefore, the p.d. across the 2 Ω resistor is equal to the e.m.f. of the battery. This information can be used to find the current flowing through the 2 Ω resistor.
The same method is used to find the current flowing through the 4 Ω resistor.

(c) The sum of the currents in the separate branches of a parallel circuit is equal to the current from the source. Therefore, the sum of these currents found gives the current flowing from the battery, which is also the total current in the circuit.

(d) The effective resistance R_e of the two resistors can be found by, $\frac{\text{e.m.f.}}{I}$. This should be the same as using: $\frac{1}{R_e} = \frac{1}{R_1} + \frac{1}{R_2}$

Answer

(a) Current flowing through the 2 Ω resistor $= \frac{12\text{ V}}{2\ \Omega} = 6\text{ A}$

(b) Current flowing through the 4 Ω resistor $= \frac{12\text{ V}}{4\ \Omega} = 3\text{ A}$

(c) Current flowing from the battery = 6 A + 3 A = 9 A

(d) Effective resistance of the two resistors $= \frac{12\text{ V}}{9\text{ A}} = \frac{4}{3}\ \Omega = 1.33\ \Omega$

or

$$\frac{1}{R_e} = \frac{1}{2\ \Omega} + \frac{1}{4\ \Omega}$$
$$\frac{1}{R_e} = \frac{2+1}{4}$$
$$R_e = \frac{4}{3}\ \Omega = 1.33\ \Omega$$

Helpful Note

It can be seen that when resistors are connected in parallel, the effective resistance is lower than the individual resistances of the resistors.

Series and Parallel Circuits

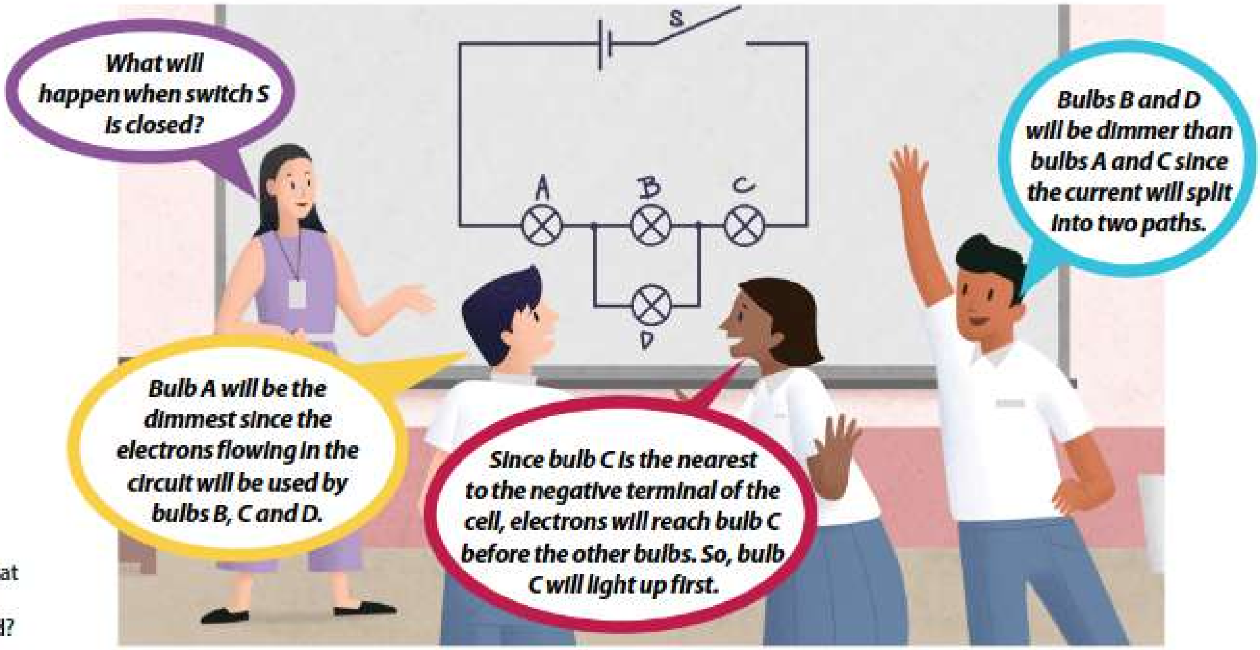


Figure 17.11 What happens when switch S is closed?

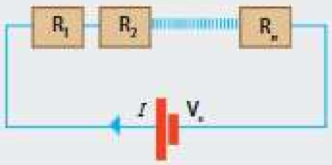
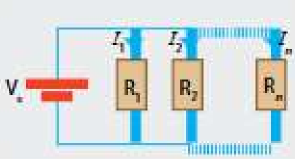
The circuit diagram in Figure 17.11 contains resistors arranged both in series and in parallel. What happens when switch S is closed? Recall what we have learnt about both series and parallel circuits:

- The current at each point in a series circuit is the same.
- The total current flowing into or out of the parallel branches is equal to the sum of the individual currents in each parallel branch.

Assuming that each of the bulbs (A, B, C and D) has the same resistance, we can expect that bulbs A and C have the same brightness since the current flowing through them is the same. Bulbs B and D are half as bright as bulbs A and C since half the current flows to bulb B and the other half flows to bulb D.

A comparison of the effect of electrical components arranged in series and parallel on the resistance, current and potential difference of a circuit is summarised in Table 17.2.

Table 17.2 Effect of the different arrangements of electrical components on the resistance, current and potential difference of the circuit

	Series Circuit	Parallel Circuit
Circuit Diagram		
Effective Resistance R_e	$R_e = R_1 + R_2 + \ldots + R_n$	$\frac{1}{R_e} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$
Current in the Circuit	$I = \frac{V_e}{R_e}$	$I = \frac{V_e}{R_e} = I_1 + I_2 + \ldots + I_n$
P.d. Across Any One Resistor R_1	$V_1 = IR_1$	V_e

When you replace the dry cells in your flashlight or a remote control, you usually use more than one dry cell (Figure 17.12). Are the dry cells connected in series or in parallel? Why do we sometimes connect circuits in series and sometimes in parallel?

Figure 17.12 Why are the batteries in a remote control arranged this way?

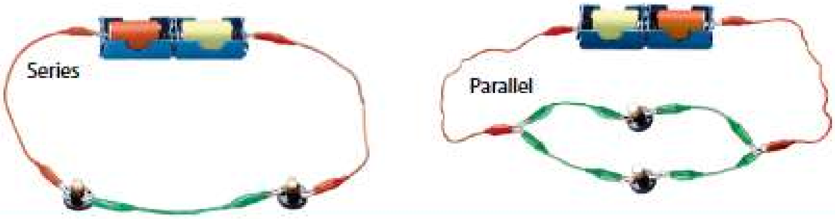
Circuits are connected in series or parallel to meet voltage and current requirements. These days, most flashlights use light emitting diode (LED) bulbs. However, the older flashlight bulbs use filament bulbs that work on 3 V. When 3 V are applied to these bulbs, they light up at their designed brightness. If less than 3 V are applied to these bulbs, then, they are less bright. Since most dry cells are rated at 1.5 V, we need to connect two dry cells in series to supply the required 3 V.

The effective resistance of a circuit changes if the electrical components are arranged differently. For instance, we connect resistors in series if we want to achieve a higher resistance. This is because when the resistors are connected in series, the effective resistance is the sum of the resistances of the individual resistors.

Link

Practical Workbook
Experiment 17A

There are advantages and disadvantages when arranging electrical components in series or parallel. Consider the series and parallel circuits that are made up of identical bulbs in Figure 17.13.



Series Circuits	Parallel Circuits	Summary
① The voltage across the bulbs in the series connection is half the voltage of the electromotive force of the dry cells. Voltage across each bulb = $\frac{V_E}{2}$	The voltage across each bulb in the parallel branch is identical to each other. Voltage across each bulb = V_E	The bulbs in parallel will be brighter than the bulbs in series.
② The current is the same at every point of the circuit. Current through each bulb $= \frac{V_E}{2R}$	The current splits across different parallel branches. Current through each bulb $= \frac{V_E}{R}$	If more parallel branches are added to the parallel circuit, it could result in overdrawing of current from the power source. The power source is depleted more quickly. If a circuit requires a constant current, parallel connections should be avoided.
③ If one of the bulbs blows, the electrical path would be open and the other bulb will not lit up.	If one of the bulbs blows, the other bulb will remain lit.	Parallel connections ensure that if one bulb blows, the rest of the bulbs are not affected.

Figure 17.13 Comparison of series and parallel circuits

Worked Example 17C

In Figure 17.14, calculate the p.d. V.

Thought Process

- To find the p.d. V, we need to know the value of the current I_1 flowing through the 1 Ω resistor since $V = (I_1)(1\ \Omega)$.
- I_1 is half of I since $I = I_1 + I_2$ and $I_1 = I_2$ because the resistance in each branch is the same.
- To find I_2, we need to know the effective resistance of the circuit. This can be done by first replacing R_1 and R_2 with an equivalent resistor. The effective resistance is the sum of the resistances of the equivalent resistor and the 1 Ω resistor.

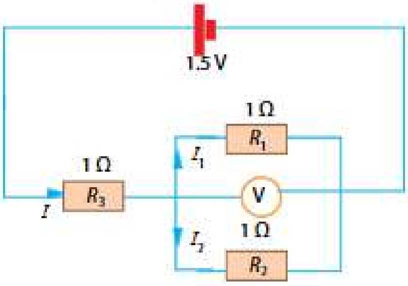


Figure 17.14

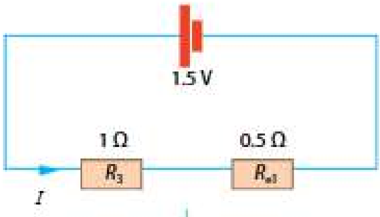
Answer

The equivalent resistance of R_1 and R_2 is:

$$R_{e1} = \frac{R_1 R_2}{R_1 + R_2} = \frac{1\ \Omega \times 1\ \Omega}{1\ \Omega + 1\ \Omega}$$

$$R_{e1} = \frac{1}{2}\ \Omega = 0.5\ \Omega$$

This simplifies the circuit to an equivalent circuit shown on the right.



The effective resistance of this circuit is

$$R_{e2} = R_3 + R_{e1} = 1\ \Omega + 0.5\ \Omega$$
$$R_{e2} = 1.5\ \Omega$$

Hence, the current I is:

$$I = \frac{V_s}{R_{e2}} = \frac{1.5\ \text{V}}{1.5\ \Omega}$$
$$I = 1.0\ \text{A}$$

Current I_1 can be found from $I = I_1 + I_2$, and since $I_1 = I_2$:

$$I_1 = 0.5\ \text{A}$$

Therefore, p.d. V is given by:

$$V = I_1 R = (0.5\ \text{A})(1\ \Omega) = 0.5\ \text{V}$$

Let's Practise 17.2

1 Figure 17.15 shows two resistors connected in parallel to a 1.5 V cell. Calculate the current flowing through and the potential difference across each resistor.

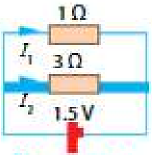


Figure 17.15

2 Determine the e.m.f. of the cell in Figure 17.16.

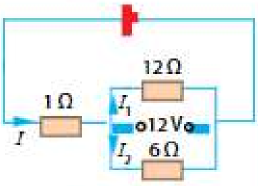


Figure 17.16

Link

Theory Workbook
Worksheet 17B

17.3 What Are Potential Dividers?

Learning Outcome

- Describe the action of a variable potential divider (potentiometer).

Potential Dividers

If the power supply is a 1.5 V dry cell, but only 0.5 V is needed for the electrical component to work, how can this variable potential difference be supplied? In such circumstances, we make use of potential dividers.

A **potential divider** is a voltage divider, which makes use of the voltage drop across resistors in series to divide voltage.

Consider the series circuit shown in Figure 17.17.

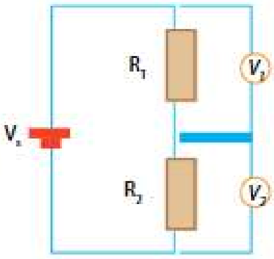


Figure 17.17 The supply voltage V_s is divided between V_1 and V_2. V_s can be determined by the ratio of the resistor values used.

We know that the current at every point in a series circuit is the same. Let this current be I. Then, the potential difference across resistors R_1 and R_2 would be given by IR_1 and IR_2 respectively.

Since the sum of the potential differences in a series circuit is equal to the potential difference across the whole circuit:

$$V_s = IR_1 + IR_2 \quad (1)$$

$$I = \frac{1}{R_1 + R_2} V_s \quad (2)$$

$$V_1 = IR_1$$

Substitute (1) into (2):

$$V_1 = \frac{R_1}{R_1 + R_2} V_s$$

The term $\frac{R_1}{R_1 + R_2}$ is a proper fraction and has a value less than 1. Hence, we can see that the voltage V_1 is a fraction of the supply voltage V_s.

Likewise, since:

$$V_2 = IR_2$$

$$V_2 = \frac{R_2}{R_1 + R_2} V_s$$

Hence, both V_1 and V_2 are fractions of the supply voltage, and the fractions are determined by the choice of resistors R_1 and R_2.

Worked Example 17D

Consider the circuit in Figure 17.18. Calculate the voltage V_1 and V_2. What value of resistance should R_2 have to make $V_1 = V_2 = 1$ V?

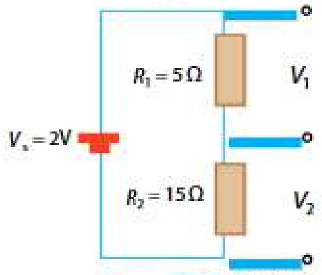


Figure 17.18 A voltage divider circuit

Thought Process
This is a potential divider circuit with two resistors R_1 (5 Ω) and R_2 (15 Ω) connected in series. Hence, V_1 and V_2 can be found using the voltage divider method.
For voltages V_1 to be equal to V_2, R_1 and R_2 should have the same value.

Answer
Given $V_s = 2$ V, $R_1 = 5\,\Omega$ and $R_2 = 15\,\Omega$
The voltages V_1 and V_2 are given by:

$$V_1 = \frac{R_1}{R_1 + R_2}V_s$$
$$V_1 = \frac{5}{5+15}(2) = 0.5 \text{ V}$$
$$V_2 = \frac{15}{5+15}(2) = 1.5 \text{ V}$$

For $V_1 = V_2 = 1$ V, the 15 Ω resistor needs to be replaced by a 5 Ω resistor.

$$V_1 = \frac{5}{5+5}\ (2) = V_2$$
$$V_1 = V_2 = 1.0 \text{ V}$$

Note that by selecting different combinations of R_1 and R_2, different values of V_1 and V_2 can be obtained.

Helpful Note

A potentiometer is a three-terminal variable resistor. The third terminal is connected to an adjustable knob and it can be adjusted to give any fraction of the potential difference across the ends of the resistor.

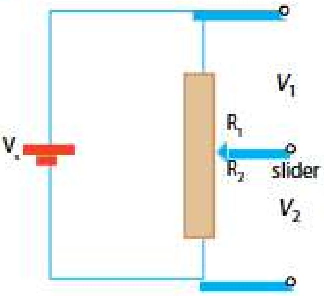


Figure 17.19 The slider can be adjusted to obtain different values of R_1 and R_2 so that different values of V_1 and V_2 may be obtained.

In the potential divider circuit in Figure 17.17, if we replace resistors R_1 and R_2 with a **potentiometer**, a continuous range of voltages for V_1 and V_2 can be obtained. This is shown in Figure 17.19. Larger values of V_2 can be obtained by increasing the value of R_2 and vice versa.

An example of a circuit with a potentiometer is found in the volume control knob of a radio or an electric guitar as shown in Figure 17.20. This circuit is also called a variable potential divider.

Figure 17.20 Potentiometers are used in electric guitars to control the volume.

With a potentiometer, the potential differences V_1 and V_2 follow the same formula, that is:

$$V_1 = \frac{R_1}{R_1 + R_2} V_s \text{ and } V_2 = \frac{R_2}{R_1 + R_2} V_s$$

This ratio of the resistances can also be expressed in terms of the length of the resistor or rheostat or the angle of turns of a potentiometer slider. Since R is proportional to I, V_1 and V_2 may be expressed as:

$$V_1 = \frac{I_1}{I_1 + I_2} V_s$$

$$V_2 = \frac{I_2}{I_1 + I_2} V_s$$

where I_1 and I_2 are the equivalent lengths of R_1 and R_2

Worked Example 17E

The circuit diagram of a volume control knob of an electric guitar is shown in Figure 17.21. The full range of the potentiometer is 270 °. If the slider is at 90 °, find the output voltage V_{out} if the supply voltage V_s is 15 V. You may assume that the resistance of the potentiometer increases or decreases linearly.

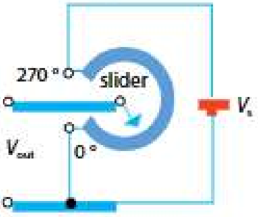


Figure 17.21 A volume control knob

Thought Process

- Recall that a potentiometer is a voltage divider and the voltage is a fraction of the supply voltage.
- This fraction may be found from the ratio of the angles, since the resistance of the potentiometer increases or decreases linearly.

Answer

The voltage V_{out} is given by:

$$V_{out} = \frac{90\,°}{270\,°} V_s$$

$$V_{out} = \frac{90\,°}{270\,°} (15)$$

$$V_{out} = 5 \text{ V}$$

Let's Practise 17.3

1 Figure 17.22 shows two resistors connected in series. Calculate the current flowing in the circuit and the potential difference across each resistor. Is this a potential divider circuit?

2 An additional resistor of 20 Ω is added in parallel to the resistors in Figure 17.22.

- (a) Calculate the effective resistance.
- (b) What is the current drawn from the 2 V cell? Is the effective resistance in Question 1 larger or smaller than that in Question 2?

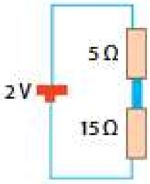


Figure 17.22

17.4 How Are Transducers Used in Potential Dividers?

Learning Outcomes

- Describe the action of negative temperature coefficient (NTC) thermistors and light-dependent resistors and explain their use as input transducers in potential dividers.
- Solve simple circuit problems involving NTC thermistors and light-dependent resistors.

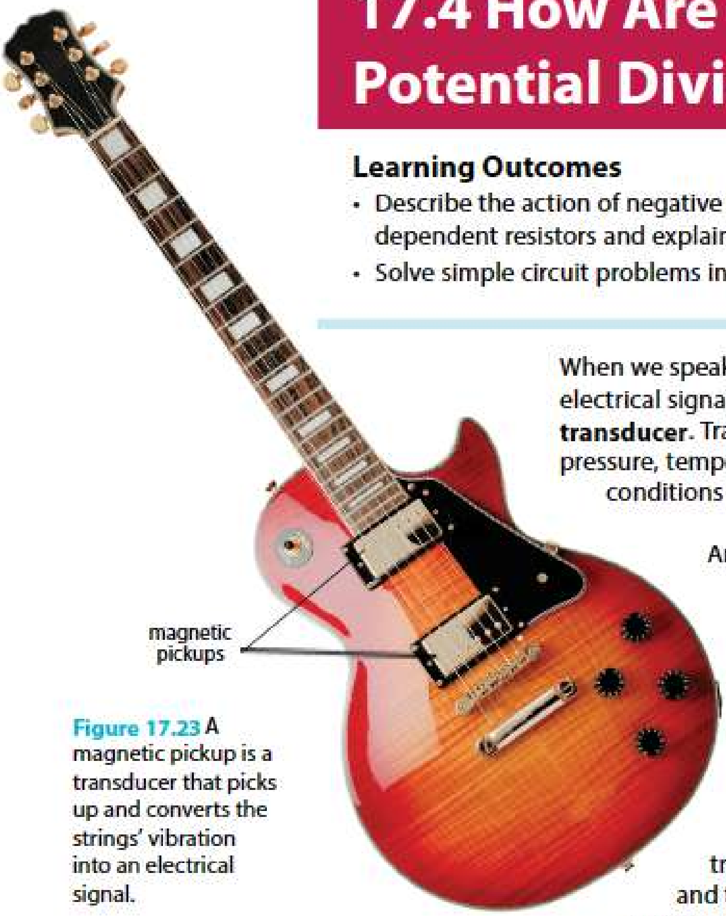
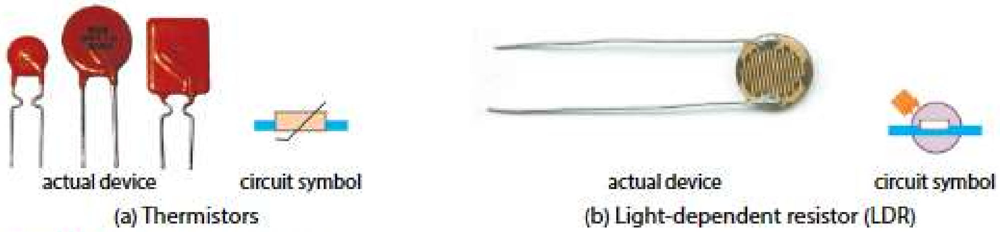


Figure 17.23 A magnetic pickup is a transducer that picks up and converts the strings' vibration into an electrical signal.

When we speak into a microphone, sound waves are converted into electrical signals through the use of an electronic device known as a **transducer**. Transducers convert changes in physical conditions, such as pressure, temperature or light, into electrical signals so that these physical conditions can be measured.

Another example of a transducer is a magnetic pickup that is commonly used in electric guitars (Figure 17.23). Magnetic pickups in the electric guitar allow the sound of the instrument to be heard. This is done by converting the sound into an electrical signal that is then transferred into a sound amplifier.

There are a wide range of transducers. **Thermistors**, **light-dependent resistors** (LDRs), **photovoltaic cells**, and **piezoelectric sensors** are just some examples of transducers. We will be focusing only on how the thermistor and the light-dependent resistor work. These devices are shown in Figure 17.24.



(a) Thermistors

(b) Light-dependent resistor (LDR)

Figure 17.24 Examples of transducers

Helpful Note

There are positive temperature coefficient (PTC) thermistors as well. The resistance of PTC thermistors increases with temperature.

The thermistor is a type of semiconductor. The resistance of a thermistor varies with temperature, and thus thermistors are also known as thermally sensitive resistors. A negative temperature coefficient (NTC) thermistor is one where its resistance decreases with temperature.

Thermistors are very accurate and cost-effective sensors for measuring temperature. Consider the potential divider circuit in Figure 17.25 where one of the resistors is replaced by a NTC thermistor.

If the temperature increases, the resistance of the NTC thermistor R_{TH} would decrease by a disproportionally higher amount. This causes the output voltage V_{out} to increase. The increase in V_{out} can be measured to determine the increase in temperature.

Link
Practical Workbook
Experiment 17B

① The output voltage is given by:

$$V_{out} = \frac{R}{R + R_{TH}} \times V_{\varepsilon}$$

where R = resistance of the fixed resistor (Ω)
R_{TH} = resistance of the thermistor (Ω)
V_{ε} = voltage supplied by electrical source (V)

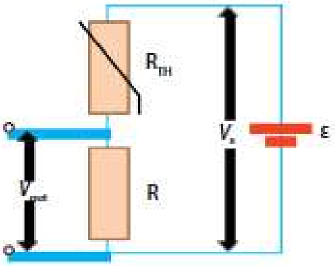


Figure 17.25 Thermistor in a potential divider

② Since the resistance R_{TH} of the common thermistor decreases as its temperature increases, the output voltage V_{out} also increases with temperature.

Worked Example 17F

Figure 17.26 shows the circuit diagram of a kitchen stove heat sensor. If the stove temperature is kept at 300 °C for more than 30 minutes, the thermistor will be heated to 300 °C. When this happens, the resistance of the thermistor will fall from 2 kΩ to 100 Ω. The supply voltage V_s is 15 V and the resistance R_1 is 1.9 kΩ.

What will happen to the output voltage V_{out}? Suggest how this circuit can be used to detect if a stove has been left unattended for an extended time.

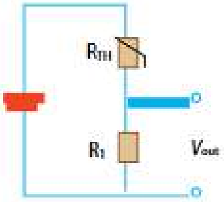


Figure 17.26 A thermistor is used as a kitchen stove heat sensor

Thought Process
The circuit is the connected as a potential divider. Thus, we can make use of the result $V_{out} = \frac{R_1}{R_1 + R_{TH}} V_s$ to find V_{out} before the temperature of the thermistor rises, and when the temperature of the thermistor reaches 300 °C.

Answer
The voltage V_{out} when R_{TH} is initially at 2 kΩ is given by:

$$V_{out} = \frac{1900}{1900 + 2000} 15 \text{ V}$$
$$V_{out} = 7.31 \text{ V}$$

When the temperature of the thermistor reaches 300 °C, R_{TH} falls to 100 Ω. Hence, the voltage V_{out} is given by:

$$V_{out} = \frac{1900}{1900 + 100} 15 \text{ V}$$
$$V_{out} = 14.3 \text{ V}$$

If the output is connected to an alarm or warning light which operates at 14 V, the alarm or warning light would be triggered if this threshold is reached.

The light-dependent resistor (LDR) responds to light the same way a NTC thermistor responds to temperature. As the amount of light shining on an LDR increases, the resistance of the LDR decreases. Like thermistors, LDR are also made from semiconductors.

Worked Example 17G

Figure 17.27 shows the simplified circuit diagram of an automatic street light controller. The voltage V_{out} needs to be at least 12 V in order to turn on the street light. During the day, the resistance of the LDR is 100 Ω. The supply voltage V_s is 15 V and resistance R_1 is 27 kΩ.

(a) Explain why the street light does not turn on during the day.

(b) During sunset, the resistance of the LDR increases to 1 MΩ. Will the street light turn on?

(c) It was found that when the street light turns on, its light reduces the resistance of the LDR back to 100 Ω, and causes the street light to turn off. In the absence of light, the street light turns on again. This cycle repeats and the street light turns on and off repeatedly. Suggest a way to prevent this from happening.

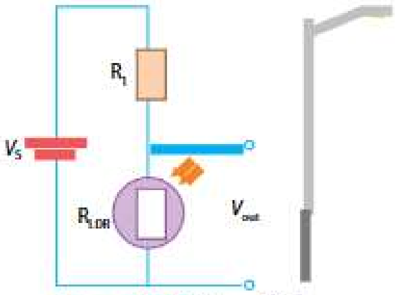


Figure 17.27 A simplified automatic street light controller circuit

Thought Process

- In (a), since the circuit is connected as a potential divider, we can make use of the result $V_{out} = \frac{R_{LDR}}{R_2 + R_{LDR}} V_s$ to find V_{out}. If V_{out} is less than 12 V, the street light will not turn on.
- In (b), a similar approach may be used to determine if V_{out} is at least 12 V.

Answer

(a) The voltage V_{out} during the daytime is:

$$V_{out} = \frac{R_{LDR}}{R_1 + R_{LDR}} V_s$$

$$V_{out} = \frac{100}{27\,000 + 100} 15$$

$$V_{out} = 0.06 \text{ V}$$

Since $V_{out} < 12$ V, the street light will not turn on.

(b) The voltage V_{out} during sunset is:

$$V_{out} = \frac{R_{LDR}}{R_1 + R_{LDR}} V_s$$

$$V_{out} = \frac{1 \times 10^6}{27\,000 + 1 \times 10^6} 15$$

$$V_{out} = 14.6 \text{ V}$$

Since $V_{out} > 12$ V, the street light will turn on.

(c) Place the LDR on top of the street light so that light from the street light cannot reach it.

Let's Practise 17.4

1 Figure 17.28 shows a resistor of resistance 10 kΩ and a light-dependent resistor (LDR) connected in series. The LDR has a resistance of 500 Ω in bright light. Calculate the output voltage and the current flowing in the circuit.

2 In dim light, the LDR in Figure 17.28 has an output voltage V_{out} of 8 V. Calculate the resistance of the LDR.

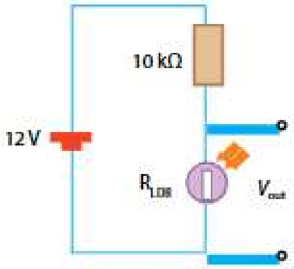


Figure 17.28

Link

Theory Workbook
Worksheet 17C
Let's Assess
Let's Reflect

Tech Connect

Wearable electronics are d.c. circuit devices that can be worn by people. They may be interwoven into clothing or worn in the form of jewellery, eyeglasses or wristwatches. Wearable electronics function as sensors or as computers that can collect, transfer and compute data. Wearable electronics is a relatively new concept which began only in the last decade. Due to rapid technological advances, wearable electronics are finding their way into medical, academic, sports and consumer markets.

Past to Present

D.c. circuits have come a long way since the 1960s. Before the iPod was introduced, music was recorded in cassette tapes, which could store about a dozen songs. These cassette tapes were played back using a cassette player, commonly known as a boombox (Figure 17.29(a)). While portable, they are large and cumbersome to lug around.

Fast forward to the 21st century where the portable digital music player was invented (Figure 17.29(b)). It is much smaller than the portable cassette player, contains thousands of songs and can operate up to twelve hours.

(a) Cassette player (1960s)

(b) Portable digital music player (2012)

Figure 17.29 Portable music players past and present

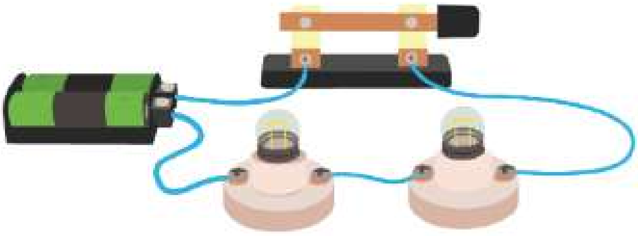
Cool Career

Semiconductor Process Engineer

Semiconductor process engineers ensure that the processes required to manufacture a semiconductor are within controlled requirements, so that the semiconductor produced has the desired functionality and quality. Computer processors and graphics processors are examples of semiconductors.

The manufacturing processes can be divided into two main groups, namely, "front-end" and "back-end". The front-end processes are extremely sophisticated processes to fabricate the semiconductor wafers, and the back-end processes comprise of assembly and testing. To ensure that the quality of the semiconductors is consistent, the engineers fine tune equipments and make use of control techniques such as statistical process control.

Let's Map It



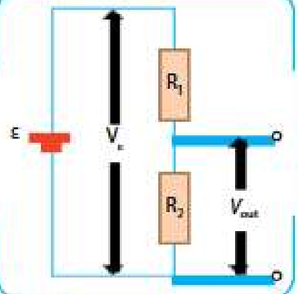
D.C. Circuits

are

Direct current circuits used in battery-operated electronic devices

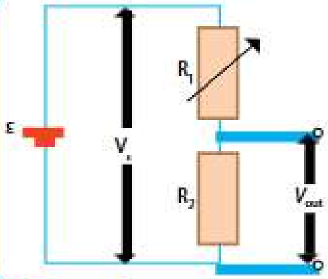
Potential divider circuit

connected with fixed resistors



$$V_{out} = \frac{R_2}{R_1 + R_2} V_ε$$

connected with potentiometer

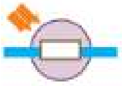


R_1 can be replaced with a transducer

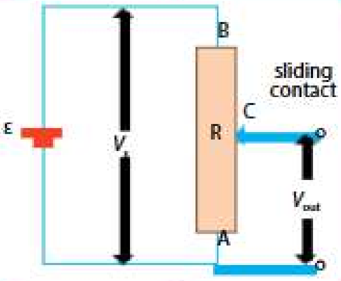
Thermistor

where resistance varies with temperature

Light-dependent resistor (LDR)



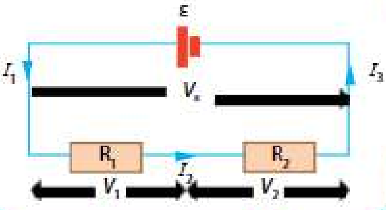
where resistance decreases when the amount of light shining on it increases



$$V_{out} = \frac{R_{AC}}{R_{AB}} V_ε$$
$$= \frac{AC}{AB} V_ε$$

connected in

Series



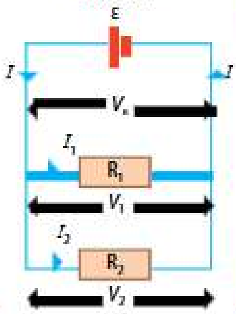
has these characteristics

Current:
$I_1 = I_2 = I_3$
Potential difference:
$V_ε = V_1 + V_2$
Effective resistance:
$R_e = R_1 + R_2$

Advantages:
- Achieves a higher resistance

Disadvantage:
- Becomes an open circuit when a component is damaged

Parallel



has these characteristics

Current:
$I = I_1 + I_2$
Potential difference:
$V_ε = V_1 = V_2$
Effective resistance:
$$\frac{1}{R_e} = \frac{1}{R_1} + \frac{1}{R_2}$$

Advantage:
- An open circuit in one branch does not affect the components in other branches

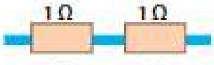
Disadvantage:
- Current varies when more branches are added

Let's Review

Section A: Multiple-choice Questions

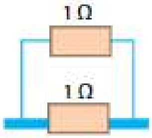
1 Which circuit has the largest effective resistance?

○ A

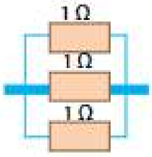


○ B

○ C



○ D



2 In Figure 17.30, which path carries the lowest current?

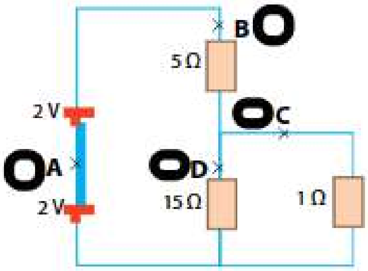


Figure 17.30

3 The light falling on the light-dependent resistor in Figure 17.31 increases in brightness. What will happen to the resistance of the LDR and the reading on the voltmeter?

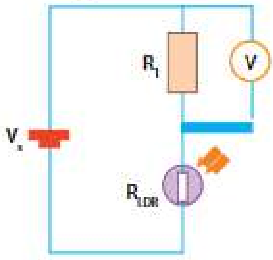


Figure 17.31

	Resistance of LDR	Reading on Voltmeter
○ A	increases	increases
○ B	increases	decreases
○ C	decreases	increases
○ D	decreases	decreases

4 In the circuit of Figure 17.32, which statement is correct?

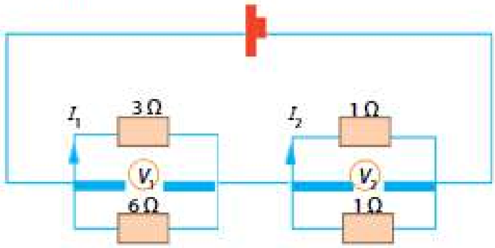


Figure 17.32

○ A $I_1 > I_2$ and $V_1 > V_2$
○ B $I_1 > I_2$ and $V_1 < V_2$
○ C $I_1 < I_2$ and $V_1 > V_2$
○ D $I_1 < I_2$ and $V_1 < V_2$

Section B: Structured Questions

1 What is the voltmeter reading in the circuit shown in Figure 17.33?

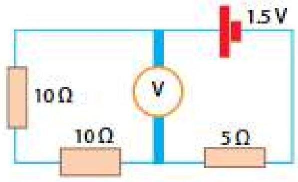


Figure 17.33

2 In Figure 17.34, if the reading on the voltmeter is 4 V, what is the e.m.f. of the cell?

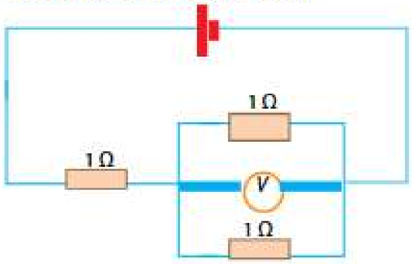


Figure 17.34

3 Figure 17.35 shows the resistance–temperature characteristics of a thermistor.

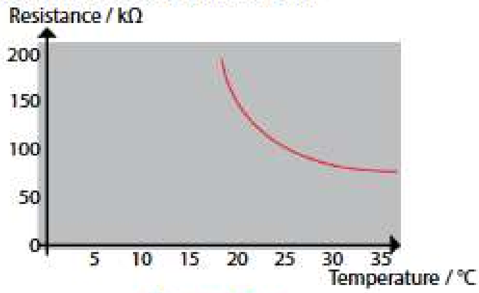


Figure 17.35

(a) If this thermistor is used in the circuit shown in Figure 17.36, what is the reading on the voltmeter if the temperature is 25 °C?

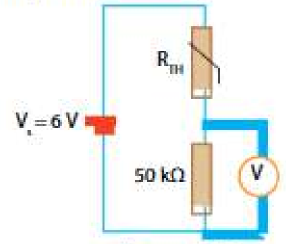


Figure 17.36

(b) If the temperature drops to 20 °C, what would be the reading on the voltmeter?

(c) Suggest a way in which the circuit may be used to control the temperature of a room.

4 Figure 17.37 shows two parallel resistive networks.

(a) Calculate the effective resistance of each network.

(b) Which resistive network has a larger effective resistance?

(c) Deduce the effective resistance if four 1 Ω resistors are connected in parallel.

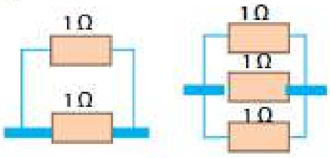


Figure 17.37

5 (a) In the circuit in Figure 17.38, what is the value of current I?

(b) What is the value of current I if switch S is closed?

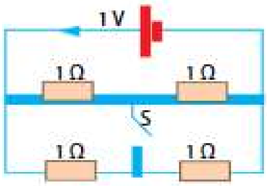


Figure 17.38

Section C: Free-response Questions

1 For the circuit in Figure 17.39, if the e.m.f. of the cell is 5 V, calculate:

(a) the effective resistance of the circuit;

(b) the total current flowing from the cell; and

(c) I_1, I_2, V_1 and V_2.

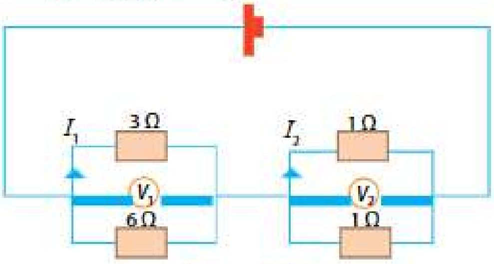


Figure 17.39

2 Two 12 V batteries are connected in parallel as shown in Figure 17.40.

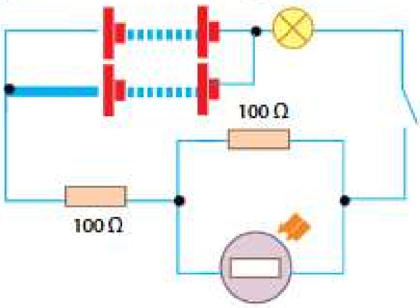


Figure 17.40

(a) State an advantage of connecting the two batteries in parallel as shown.

(b) If the circuit in Figure 17.40 is placed in a dark room and the switch is closed, describe what happens to the light bulb. Assume that the light bulb has a fixed resistance of 100 Ω.

(c) Calculate the p.d. of the light bulb if the initial resistance of the LDR is 10 kΩ.

(d) When the light bulb is fully lit, the resistance of the LDR falls further to 100 Ω. What is the p.d. of the light bulb?

CHAPTER

18 Practical Electricity

ENERGY EFFICIENCY RATING

Good

Annual Energy Cost	Annual Energy Consumtion
$72	267 kWh

Brand ABC
ABC123

Refrigerator-Freezer
Capacity: 350 L

Tested in accordance with IEC 62552.
Based on 27¢/kWh electrcity cost and 24 hours daily usage.
Actual annual energy consumption and cost may vary.
For more information and to compare models, visit www.nea.gov.sg
MELS-ABC-12345

What You Will Learn

- What is electric heating and how is electricity consumption measured?
- How do we use electrical components safely?

This energy label on the refrigerator is commonly found on home appliances. Do you know that different countries have different energy labels? In Singapore, the National Environment Agency (NEA) is responsible for issuing this label.

The purpose of this label is to encourage consumers in Singapore to switch to more energy efficient products. Consumers are encouraged to purchase appliances with more ticks. Energy efficient products reduce carbon emission and are more environmentally-friendly. Using energy efficient products also reduces our electricity bills. How is the cost of electricity calculated?

18.1 What Is Electric Heating and How Is Electricity Consumption Measured?

Learning Outcomes

- Describe the heating effect of electricity in appliances such as electric kettles, ovens and heaters.
- Recall and apply the relationships $P = VI$ and $E = VIt$ to new situations or to solve related problems.
- Calculate the cost of using electrical appliances where the energy unit is the kW h.

In Chapter 7, we learnt that energy can be transferred between different stores. Do you know the energy transfer when we used an electric kettle, an oven or a water heater at home?

When using these appliances, some energy is transferred electrically to the internal (thermal) stores of the heating elements of these appliances. Heating elements are usually made from long and thin wires of nichrome or iron-chromium-aluminium **alloy**. When electric current passes through these alloys, their temperature increases rapidly. Figure 18.1 shows what heating elements look like. Why are these wires long and thin?

Word Alert
Alloy: a mixture of metal with one or few other elements

Link
Recall from Chapter 16:
$R = \frac{\rho l}{A}$

Figure 18.1 Heating elements are usually made from long and thin nichrome or iron-chromium-aluminium wires that are wound into long cylindrical shapes to increase the length of the wires used.

All heating elements have high electrical resistances. These resistances oppose the flow of charge. In the case of alloys, the free electrons bump into ions, which are obstructions to the flow. As a result of the collision, the fixed-position ions vibrate more vigorously, which in turn raise the temperatures of the alloys.

This rise in temperature means that energy in the internal store of the elements increased. The energy in the internal stores is useful and hence, we want to know how to measure this amount of energy. Recall from Chapter 16 that the potential difference V across a component, for instance a heating element, is given by the following relationship:

$V = \frac{W}{Q}$ where W is the work done needed to move a unit charge through a potential difference of 1 V

Since $Q = It$, we can obtain work done in terms of its voltage, current and time, which are easily measured.

▶ $W = VIt$ where V = p.d. of electrical component or heating element (V)
I = current following through the component (A)
t = time (s)

The SI unit of work done or energy is **Joule (J)**.

Helpful Note

We can use the following to remember the formula for work done.

Energy has vitality.
$W = VIt$

Very often, electrical appliances do not state the electricity consumption. The electricity consumption of an electrical appliance depends on its usage and this is different for each household. Instead of stating an electricity consumption, a power rating is given. For example, in Figure 18.2, a laptop power adaptor shows the marking "65 W". This is the power rating of the laptop. What is power rating?

In Chapter 7, we learnt that power is the rate of change of energy. It is given by:

$$P = \frac{W}{t}$$

By replacing W with $= VIt$ and simplifying, we have

▶ $P = VI$

The power rating of an appliance indicates the maximum allowable voltage and current for the appliance. In Figure 18.2, "2.0 V" refers to the operating voltage. The operating voltage is the voltage level which an electrical system is designed to operate at. The internal circuitry operates with a voltage of 2.0 V.

Figure 18.2 The power rating of a laptop is indicated to provide information of the energy consumed.

Worked Example 18A

An LED bulb rated 10 W, 240 V will light up a room just as much as a fluorescent lamp rated 32 W, 240 V.

(a) Calculate the current flowing through the LED bulb.

(b) Calculate the current flowing through the fluorescent lamp.

(c) Calculate the energy transferred to the LED bulb and fluorescent lamp when both are turned on for 30 minutes.

(d) If you wish to lower your electricity consumption, which lighting, the LED bulb or the fluorescent lamp, would be more suitable?

Answer

(a) The current flowing through the LED bulb is:

$$I = \frac{P}{V} = \frac{10}{240} = 0.04 \text{ A}$$

(b) The current flowing through the fluorescent lamp is:

$$I = \frac{32}{240} = 0.13 \text{ A}$$

(c) The energy transferred to the LED bulb is:

$W = VIt = 240 \times 0.04 \times (30 \times 60) = 18$ kJ

The energy transferred to the fluorescent lamp is:

$W = 240 \times 0.13 \times (30 \times 60) = 57.6$ kJ

(d) In the same amount of time, the fluorescent lamp consumes more energy. This is also why its power rating is higher. To lower electricity consumption, I would choose the LED bulb.

In the case of heating appliances, energy is transferred electrically to the internal store of the resistor. To measure the rate at which energy is transferred to the internal store of the resistor, we can make use of this relationship, $V = IR$, in our energy and power equations.

Since $W = VIt$, its relationship to the resistance of the heating element is:

$$\mathbf{W = I^2Rt} \text{ (since } V = IR\text{)}$$

$$\mathbf{W = \frac{V^2t}{R}} \text{ (since } I = \frac{V}{R}\text{)}$$

where I = current flowing in the resistor or heating element (A)
R = resistance of the resistor or heating element (Ω)
t = time (s)
V = p.d. across the resistor or heating element (V)

Helpful Note

Note that we cannot use these equations to say that power is directly proportional to resistance or power is inversely proportional to resistance since resistance, voltage and current are interlinked.

Energy is measured in **Joules (J)** and is a scalar quantity.

The relationship between power and the resistance of the heating element is:

$$\mathbf{P = I^2R} \text{ (since } V = IR\text{)}$$

$$\mathbf{P = \frac{V^2}{R}} \text{ (since } I = \frac{V}{R}\text{)}$$

where I = current flowing in the resistor or heating element (A)
R = resistance of the resistor or heating element (Ω)
V = p.d. across the resistor or heating element (V)

Power is measured in **watt (W)** and is also a scalar quantity.

Worked Example 18B

A three-litre water tank is heated by a heating element of resistance 80 Ω connected to a 240 V mains.

(a) Calculate the electrical power produced in the heating element.
(b) Calculate the amount of energy transferred to the internal store of the heating element if the switch was turned on for 10 minutes.
(c) If the energy in the internal store of the heating element is transferred to the internal store of the water, determine the increase in water temperature. Take density of water as 1000 kg/m^3 and specific heat capacity of water as 4200 J/(kg K).

Thought Process

As current flows through the heating element, energy is transferred electrically to the internal store of the heating element. The rate of energy transfer is the power, which is related to the resistance of the heating element.

Answer

(a) The electrical power produced in the heating element is:

$$P = \frac{V^2}{R}$$
$$= \frac{(240\ \mathrm{V})^2}{(80\ \Omega)}$$
$$= 720\ \mathrm{W}$$

(b) The amount of energy transferred to the internal store of heating element is:

$$E = \frac{V^2 t}{R}$$
$$= \frac{(240\ \mathrm{V})^2 \times (10 \times 60)\ \mathrm{s}}{80\ \Omega}$$
$$= 432\ \mathrm{kJ}$$

Alternatively, we can use the relationship between power and energy. Since power is the rate of energy transfer,

$E = Pt$

$E = 720\ \mathrm{W} \times (10 \times 60)\ \mathrm{s}$

$E = 432\ \mathrm{kJ}$

(c) The mass of water m can be found using, $m = \rho V$, where ρ is the density of water and V is the volume of water in m^3. Hence,

$m = 1000\ \mathrm{kg/m^3} \times \frac{3}{1000}\ \mathrm{m^3}$

$m = 3\ \mathrm{kg}$

The increase in water temperature is $\Delta\theta$ and is given by $Q = \mathrm{mc}(\Delta\theta)$, where Q is the energy supplied to the water. Since, energy is transferred to the internal store of the water, Q is 432 kJ.

$$432 \times 10^3\ \mathrm{J} = 3\ \mathrm{kg} \times 4200\ \mathrm{J/(kg\ K)} \times \Delta\theta$$
$$\Delta\theta = 34.3\ \mathrm{K}$$

Note that a huge amount of energy (432 kJ) is required to raise the temperature of water. Can you also identify the home appliances that consume high amount of energy?

Link

Recall from Chapter 9: $Q = mc(\Delta\theta)$

From Worked Examples 18A and 18B, we can see that different appliances use different amounts of energy. Some appliances have low electricity consumption, such as the LED bulb (Figure 18.3). Other appliances have high electricity consumption, such as a water heater or an electric kettle.

Figure 18.3 LED bulbs are commonly found in new buildings and homes as they are more energy efficient than florescent bulbs.

To conserve energy and reduce our carbon footprint, it is important to:

- reduce usage of the appliances with higher electricity consumption; and
- choose those with lower electricity consumption if possible.

Every household has an electricity meter (Figure 18.4) that measures its electricity consumption. The meter is usually located at the entrance to the household unit, and is easily recognisable.

The amount of electricity consumed is measured in **kilowatt-hours (kW h)**. Each kilowatt-hour is equivalent to 3.6 MJ. That is 3 600 000 J of energy. We can see that measuring household electricity consumption in SI units is impractical because the number will be very large and cumbersome to record.

Figure 18.4 An electricity meter commonly found in front of household units in Singapore

One kW h of electricity is the energy used by a 1 kW device in an hour.

$$\begin{aligned} 1\text{ kW h} &= 1\text{ kW} \times 1\text{ h} \\ &= 1000\text{ W} \times 3600\text{ s} \\ &= 3.6 \times 10^6\text{ J} \end{aligned}$$

Disciplinary Idea

Matter and energy make up the Universe.

Many appliances are powered electrically and even involve electric circuitry in their key functionality.

A common practical unit of energy consumption is in kW h.

Worked Example 18C

Consider the case of a typical household in Singapore. Each evening, the household:
- switches on all the lights for 5 hours;
- watches television for 2 hours;
- switches on the fan for 5 hours;
- use the water heater for 1 hour; and
- uses the desktop computer for 3 hours.

The power rating of:
- all the lights are 240 W;
- the television is 120 W;
- the fan is 80 W;
- the water heater is 4000 W; and
- the desktop computer 200W.

Calculate the total energy consumption in kW h. If each kW h of energy costs 19.5 cents, what is the cost of electricity consumption of a typical household unit in an evening?

Thought Process

Energy is a scalar quantity and so the units may be added.

Energy consumption for the individual appliance can be calculated using $E = Pt$ and may be added to determine the total energy consumption.

Answer

The information given may be tabulated as follows:

Electrical Appliance	Power Rating / W	Time Used / h	Energy Consumed / kW h
lights	240	5	1.20
television	120	2	0.24
fan	80	5	0.4
water heater	4000	1	4.00
desktop computer	200	3	0.60

The total energy consumption is 6.44 kW h.

Cost of electricity consumption = 6.44 × 0.195 = $1.26

National statistics shows that the average household unit consumes 15 kW h of energy a day. What are other common household electrical appliances that are not mentioned in Worked Example 18C?

Let's Investigate 18A

Aim

To investigate the electricity consumption in your household

Procedure

1. Identify and record a list of all the electrical appliances in your household.
2. Check and record the power rating of each appliance. This information is usually indicated on the product or can be found online.
3. Measure or estimate to the nearest hour the amount of time each appliance is being used each day. Record this reading.
4. Do a search on the Internet to find out the electrical cost per unit kW h in Singapore. Take note that the electrical cost differs in different countries.
5. Calculate the total cost of electricity consumption in your household.

Discussion

1. Does this investigation tally with your household monthly electricity bill?

Questions

1. Which appliance in your household consumes the most electricity?
2. Compare the power rating of some appliances (Figure 18.5). How can you and your family cut down on the electricity consumption?

Figure 18.5 An air conditioner has a higher power rating than a fan.

Let's Practise 18.1

1. An air conditioner draws 10 A of current from 240 V mains. What is its power rating?
2. The air conditioner is turned on for 8 hours a day. What is the daily cost of electricity consumption if the electricity tariff is \$0.20 per kW h?

Link

Theory Workbook
Worksheet 18A

18.2 How Do We Use Electrical Components Safely?

Learning Outcomes

- State the hazards of using electricity in the following situations:
  - (i) Damaged insulation
  - (ii) Overheating of cables
  - (iii) Damp conditions
- Explain the use of fuses and circuit breakers in electrical circuits and of fuse ratings.
- Explain the need for earthing metal casings and for double insulation.
- State the meaning of the terms *live, neutral* and *earth*.
- Describe the wiring in a mains plug.
- Explain why switches, fuses, and circuit breakers are fitted to the live wire.

Electrical Hazards

Electrical faults in circuits and appliances are hazardous and can cause burns, electric shocks or fires. Extra care needs to be taken when handling an electrical fault. What are electrical faults and how do we take precautions to protect ourselves?

How does electricity kill us? The human body can only withstand a small current of about 50 mA. Larger amount of current can cause burns or damage to tissues or organs. Electric current flowing through our bodies can cause involuntary contractions of muscles, such as heart or lung muscles, and can result in death. Therefore, we should pay heed to hazardous situations when using electricity. The three most common situations are **damaged insulation, overheating of cables** and **damp conditions**.

Damaged Insulation

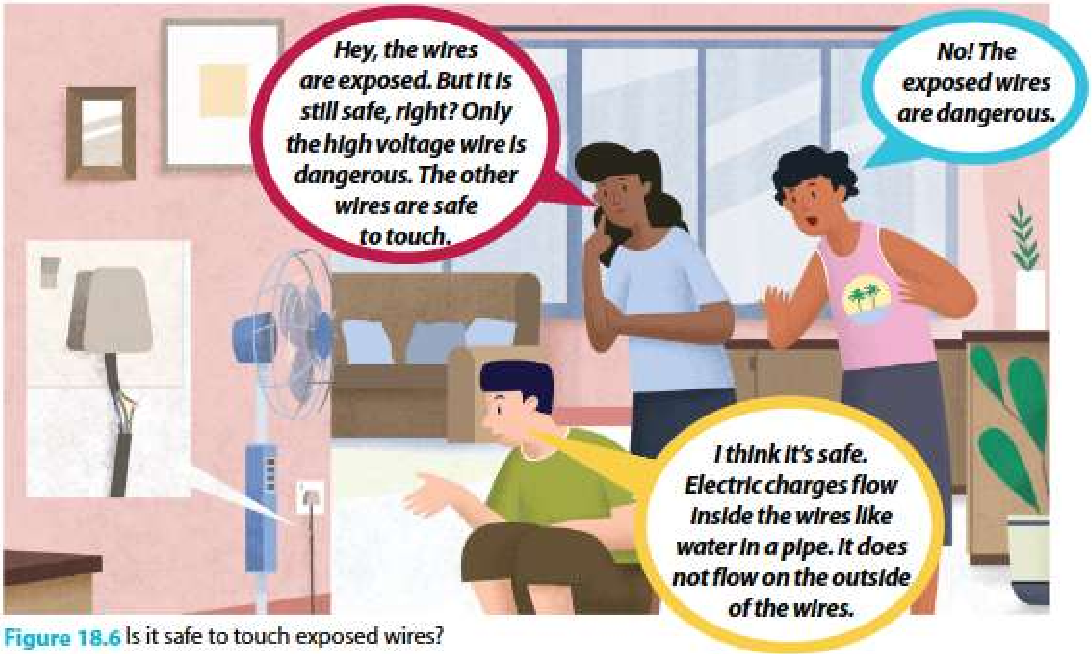


Figure 18.6 Is it safe to touch exposed wires?

The most common electrical fault is damaged insulation (Figure 18.6). Wires are usually covered with insulating materials to prevent electric shocks. Insulation can be damaged with age and prolonged use (Figure 18.7).

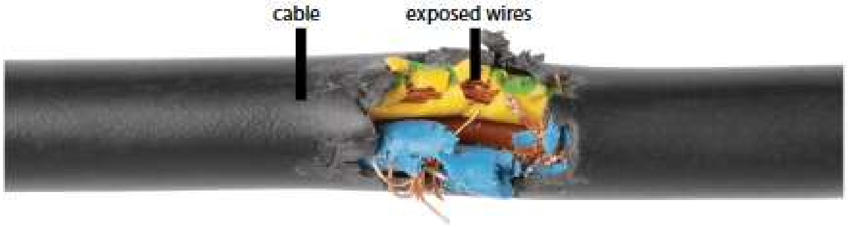


Figure 18.7 Exposed wires are hazardous because they can cause electric shock when touched accidentally.

Aging of insulation can occur due to stresses such as high electric field (due to high voltage supply) and temperature. When insulators age, they become brittle and break apart, exposing the live conducting wires underneath. In some buildings, insulation may become damaged as a result of being gnawed by rats. Regardless of the cause, exposed live wires can cause electric shocks when touched.

Overheating of Cables

Overheating of cables is another electrical hazard and it can be prevented. Overheating is caused by rising temperatures in an electrical circuit. We have learnt that energy can be transferred electrically to the internal stores of devices. $E = I^2Rt$.

Overheating occurs when:

1. the electrical cable passes current that exceeds its limits;
2. a large current flows through the wires due to too many plugs being connected to a socket (overloading); and
3. the contact between a plug and a socket is poor.

In the first two scenarios, too much current is drawn. This leads to overloading. Since the work done $W = I^2Rt$, the amount of energy transferred to the internal store increases rapidly with the current. Hence, overloading causes overheating. Overheated circuits can cause fire and even explosions. Figure 18.8 shows damaged plugs and appliances resulting from an explosion.

Figure 18.8 Overloading a power socket can cause overheating and damage to plugs and appliances.

Damp Environment

A common misconception is that water and electricity should not come in contact due to a risk of electrocution. In fact, pure water does not conduct electricity. The water from taps and other sources usually contains charged ions and impurities that makes it a good conductor of electricity. For this reason, all activities in swimming pools must cease when there is a possibility of thunder strikes.

It is common to find hair dryers or sockets for electric shavers in the toilets of hotels (Figure 18.9). This is a poor environment safety design. Many electrical accidents occur in damp environments. A hair dryer can cause electric shocks if water gets into the hair dryer or if there is damaged insulation. Therefore, do not leave a hair dryer on a wet sink or use one with wet hands.

Figure 18.9 Common electrical hazard in toilets of hotels

In addition to keeping your hands dry when using electrical appliances, we can protect ourselves from electrical shocks by wearing rubber shoes, especially when carrying out electrical repairs or inspection of electrical faults. Electrical shock occurs when an individual is part of an electric circuit and the ground. Rubber shoes act as insulators to cut off the closed path to ground, thereby keeping us safe.

Safety Features to Ensure Safe Use of Electricity

Our homes are installed with a number of safety features to prevent electrical mishaps. Firstly, there is the use of **fuses** and **circuit breakers** to prevent excessive current. Secondly, electrical appliances have **earthed metal casing** or **double insulation** to prevent contact with live wires. Figure 18.10(a) shows an alternating current circuit that has no safety features and are not used in our daily lives. Figure 18.10(b) shows an alternating current circuit with safety features.

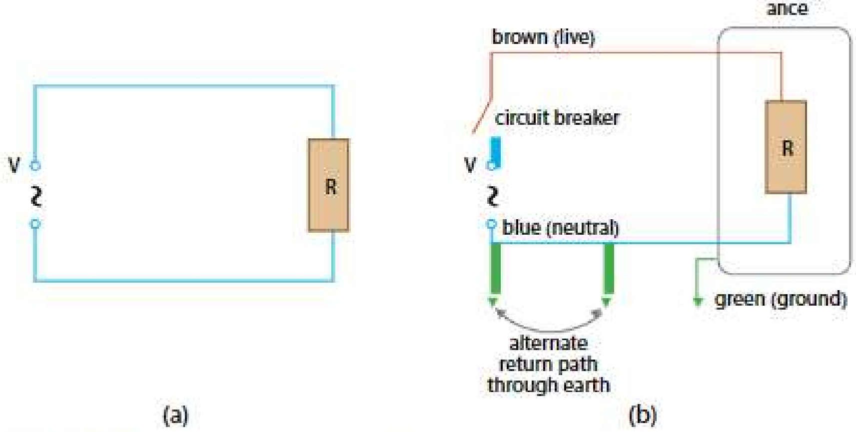
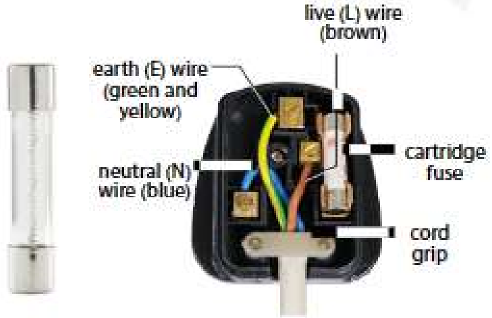


Figure 18.10 An alternating current circuit with (a) no safety features and (b) with safety features

A *fuse* is a safety device added to an electric circuit to prevent excessive current flow. It consists of a strip of fusible wire that will melt when the current flowing through it exceeds a certain value (Figure 18.11(a)). This device limits the amount of current, the value of which depends on its rating. Fuses come with different current ratings. Typical household fuses are rated at 1 A, 2 A, 3 A, 5 A, 10 A and 13 A.

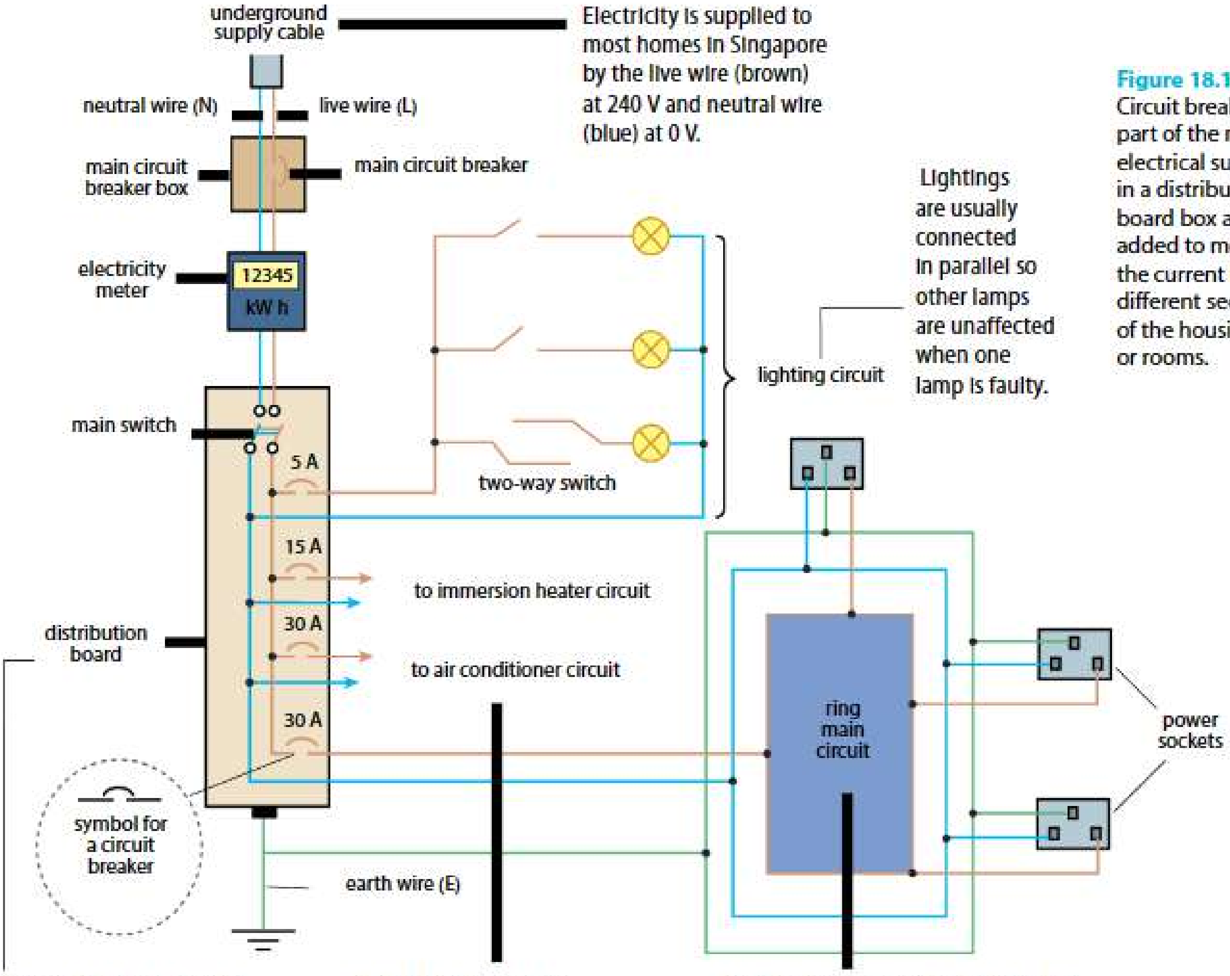
If a 1 A fuse is used in a circuit, the current cannot exceed 1 A. When a fuse limit is reached, the electric circuit is broken until the fuse is replaced with a new one. Fuses are found in the plugs of electric appliances (Figure 18.11(b)).

Likewise, a *circuit breaker* is a safety device to prevent excessive current flow. But unlike fuses, a circuit breaker is not added to the plug of an electric appliance. Circuit breakers are part of the main electrical wiring to an apartment or room, as shown in Figure 18.12.



(a) (b)

Figure 18.11 (a) A fuse consists of a strip of wire which melts, or fuses, and breaks an electric circuit if the current exceeds a safe level. (b) A fuse is found in an electric plug.



Electricity is supplied to most homes in Singapore by the live wire (brown) at 240 V and neutral wire (blue) at 0 V.

Lightings are usually connected in parallel so other lamps are unaffected when one lamp is faulty.

This is a circuit breaker box that contains a main switch and several circuit breakers to different parts of the house.

Water heaters and air conditioners have dedicated circuit breakers because they draw large currents.

Wall power sockets are connected in parallel to different ring circuits in different parts of the house. The earth ring circuit provides additional safety.

Figure 18.12 Circuit breakers are part of the main electrical supplies in a distribution board box and are added to monitor the current in different sections of the housing unit or rooms.

Figure 18.13 Circuit breakers of a distribution board box

Circuit breakers also have current ratings. If the current exceeds its rating, then the circuit breaker will trip, causing an open circuit. Circuit breakers are like on-off switches. When a circuit breaker trips, the faulty appliance causing the trip has to be identified and removed from the circuit. Then, the circuit breaker may be turned on again. Figure 18.13 shows a circuit breaker in a distribution board box.

Worked Example 18D

An electric kettle is rated at 2520 W, 240 V. Calculate the current drawn when the electric kettle is in use. Explain if a 10 A rated fuse is suitable to protect the kettle from overheating.

Answer

The current drawn is:

$$I = \frac{P}{V}$$

$$I = \frac{2520\text{ W}}{240\text{ V}} = 10.5\text{ A}$$

A 10 A fuse would not be suitable because the fuse will blow every time the kettle is switched on.

Worked Example 18E

An electrician has wired the water heater rated at 2400 W, 240 V and electric kettle rated at 1920 W, 240 V to the same circuit breaker. These appliances are connected in parallel. If the circuit breaker has a rating of 16 A, would it trip if both appliances are operating at the same time?

Thought Process

Power is a scalar quantity and adds up like ordinary numbers. If both appliances are being switched on at the same time, we can first find the total power consumed. Then the total power consumed can be used to find the total current required by both appliances.

Alternatively, the individual current required by the appliances can be calculated separately and then added together, since current is also a scalar quantity.
If the total current consumed exceeds the rating of the circuit breaker, then, the circuit breaker would trip.

Answer

If both appliances are operating at the same time,

$$\text{total power } P = 2400\text{ W} + 1920\text{ W}$$
$$= 4320\text{ W}$$

The current drawn is:

$$I = \frac{P}{V}$$

$$I = \frac{4320\text{ W}}{240\text{ V}} = 18\text{A}$$

As the current is higher than the circuit breaker's rating, the circuit breaker will trip when both appliances are operating at the same time.

Another feature of electrical protection in homes is the *earth metal casing*. An earth metal casing is a metal housing that encloses the electrical parts of an appliance, keeping the user safe in the event of an electrical fault. The live current passing through the earth metal casing flows to the ground. Since the earth wire has almost no resistance, a large current flows and causes the circuit breaker to trip or the fuse to blow. This prevents further current flow. Figure 18.14 illustrates how earth metal casings protect a user from electric shocks.

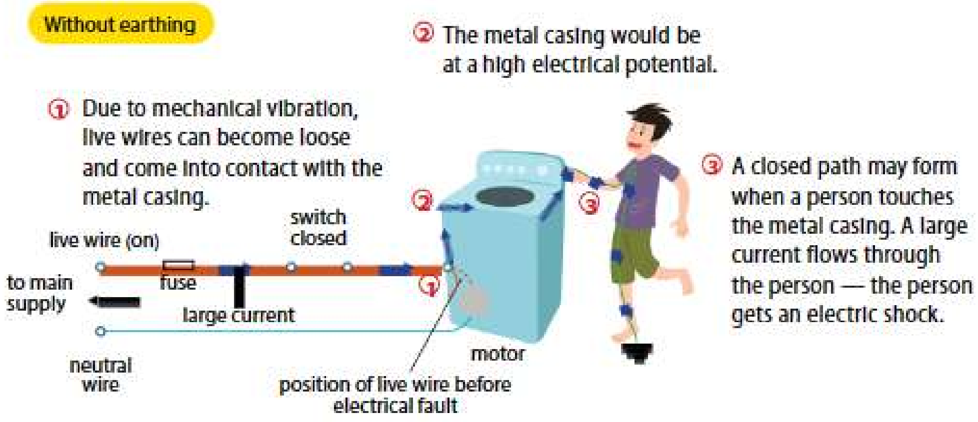


Figure 18.14 (a) The absence of earthing can cause electric shocks.

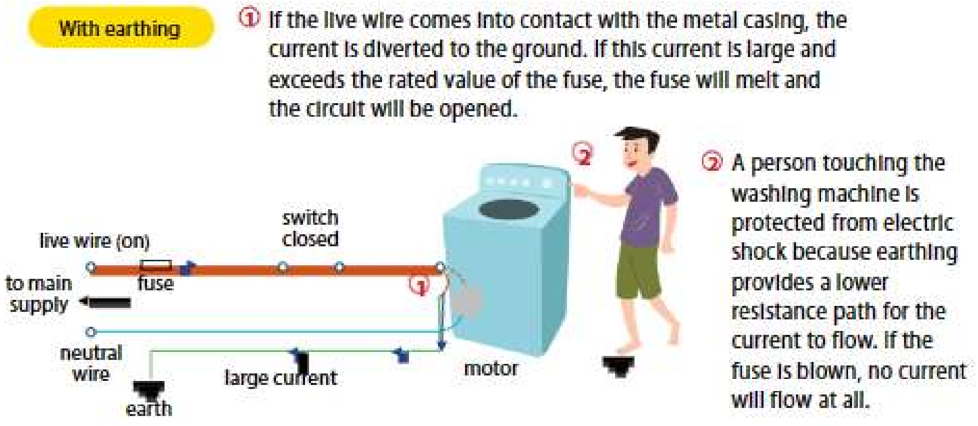


Figure 18.14 (b) The presence of earthing prevents electric shocks.

Not all appliances use earth metal casings. Earth metal casings can increase the cost of the appliances. Some appliances use *double insulation* as a safety feature to keep users safe in the event of a fault. These appliances are enclosed in a plastic casing which is not earthed. Double insulation, as the name suggests, has two layers of insulation to enclose all exposed metalwork and "live" parts.

Figure 18.15 Appliances that use double insulation as a safety feature are marked with a double insulation symbol.

Figure 18.15 shows an appliance that uses double insulation as a safety feature.

Three-pin plugs, or fuse plugs, are commonly used in Singapore. Each pin of the three-pin plug is connected to a different wire, namely earth, neutral and live (Figure 18.16).

Earth wire
The earth wire is yellow and green. It is a safety wire that is needed to earth appliances with a metal case.

Neutral wire
The neutral wire is blue and is kept at zero voltage. It completes the path for current to flow through appliances in the electrical circuit.

Live wire
The live wire is usually brown. It carries both the high voltage and the current.

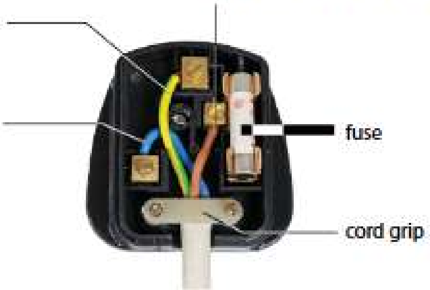
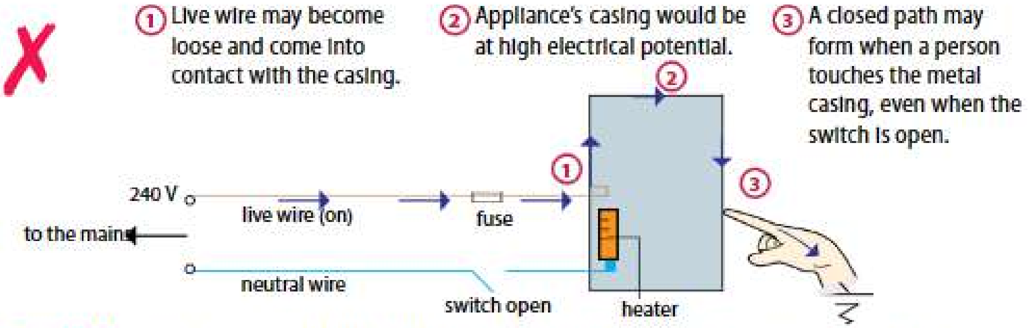


Figure 18.16 A three-pin plug and its internal connections

The earth wires do not have electric current running through them most of the time. However, if there is a sudden electrical surge that causes electric current to flow through them, it can still be dangerous to touch them. Hence, when unsure about whether or not a wire is live, one should always treat the wire as if current is flowing through it.

Switches and safety features such as fuses and circuit breakers have to be connected to the live wire in order to break or complete a circuit. Consider the case in Figure 18.17 where the switch is connected to the neutral wire instead. Then the appliance becomes "live" and can create an electric shock when a person touches it even when the switch is open.

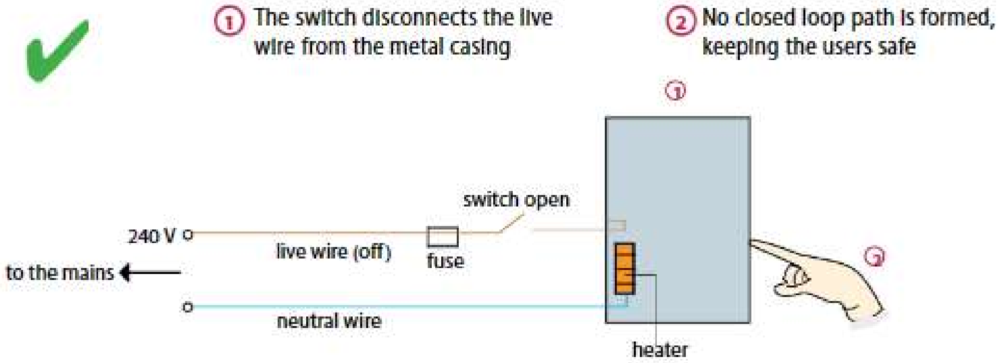

① Live wire may become loose and come into contact with the casing.

② Appliance's casing would be at high electrical potential.

③ A closed path may form when a person touches the metal casing, even when the switch is open.

Figure 18.17 Connecting a switch to the neutral wire does not cut off the supply from the mains to the appliance

On the other hand, if the switch is connected to the live wire, the situation in Figure 18.17 can be prevented. As shown in Figure 18.18, the appliance is disconnected from the mains.


① The switch disconnects the live wire from the metal casing

② No closed loop path is formed, keeping the users safe

Figure 18.18 Connecting a switch to the live wire disconnects the supply from the mains to the appliance

Likewise, having safety features such as a fuse and circuit breaker connected to the live wire instead of the neutral wire allow these devices to cut off the supply from the mains.

Table 18.1 summarises the safety features and their uses to prevent various electrical hazards in homes.

Table 18.1 Safety features and their uses to prevent different electrical hazards.

Safety feature	How It Prevents Electrical Hazard
fuses	used in socket plugs to prevent excessive current
circuit breaker	used in distribution box to prevent excessive current
earthed metal casing	to prevent live wire from causing metal casing to be at a high electrical potential
double insulation	to prevent contact with live wire
earth wire	to earth the metal casing of appliance

Let's Practise 18.2

1 Why do some appliances use a three-pin plug while others use a two-pin plug?
2 In what way is a circuit breaker different from a fuse?

Cool Career

Electrical Safety Officer

An electrical safety officer's job is to ensure electrical safety (Figure 18.20). This could cover certification of safety for new electrical appliances and products or inspection of electrical safety in residential houses or the workplace. The job may also cover planning, developing, and implementing plans, policies and procedures related to electrical safety in places such as theme parks, hotels and shopping malls.

Link

Theory Workbook

Worksheet 18B
Let's Assess
Let's Reflect

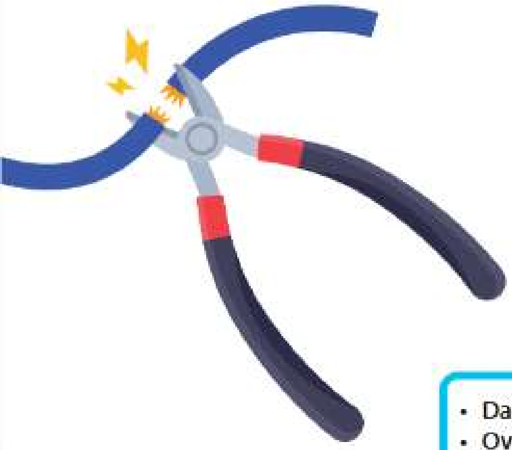
Past to Present

The circuit breaker has gone through a few changes in the last one hundred years. Initially, the circuit breaker was made of only electromechanical parts. This was followed by improvements in design where the circuit breakers were made up of a mix of electromechanical parts and semiconductors.

Now, there are smart circuits breakers that are connected to the Internet. These circuit breakers usually come with an app (Figure 18.19). Users can turn on and off their appliances using the app. The app informs users of the electrical usage per circuit branch in the homes. It can also predict electricity consumption or send mobile alerts to homeowners when the circuit breaker trips.

Figure 18.19 Smart circuit breakers can be controlled using an app on smartphones or tablets.

Let's Map It



Electricity

is a hazard due to

- Damaged insulation
- Overheating of cables
- Damp conditions

thus, we need protective device such as

- Circuit breakers
- Fuses

prevents excessive current when

Connected to a live wire

and additional shielding

- Earth metal casing
- Double insulation

Electrical devices

electric work done E can be determined by

$E = VIt$

where

V = p.d. of electrical component (V)

I = current following through that component (A)

t = time (s)

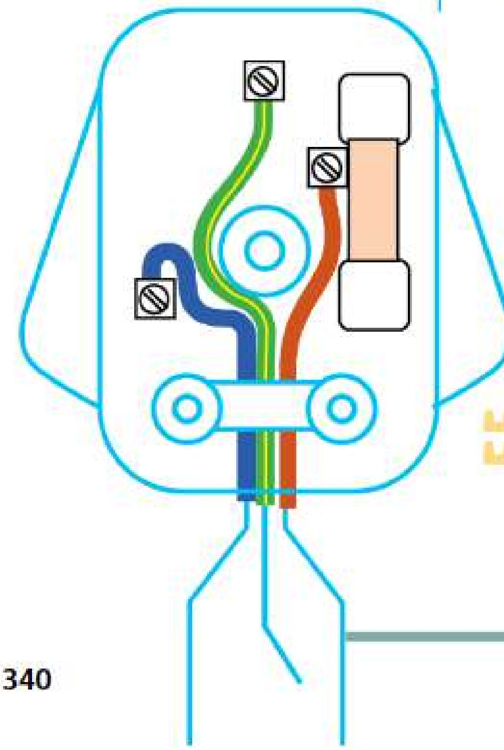
can be

Converted to kW h to find the cost of electricity consumption

related to power by

$E = Pt$

$P = VI$



Let's Review

Section A: Multiple-choice Questions

1 Which one of the following appliances from the same household is the most costly to operate?

○ A A 3600 W air conditioner operating for half a day
○ B A 80 W blender operating for one minute
○ C A 50 W laptop computer operating for eight hours
○ D A 40 W fluorescent lamp operating all day

2 Table 18.2 shows the ratings of some electrical appliances.

Table 18.2

Electrical Appliance	Rating
air conditioner	2.8 kW
lamps	64 W
laptop	80 W

If the cost of electricity is 20 cents per kW h, what is the total cost of operating all three appliances for two hours?

○ A $1.18
○ B $20.36
○ C $58.86
○ D $118

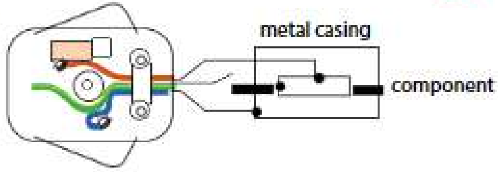
3 Which of the following statement is correct?

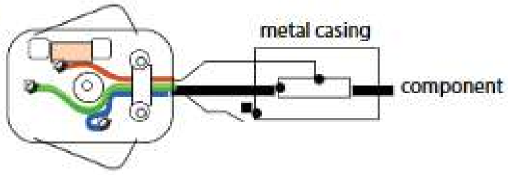
○ A There is no current flowing in the neutral wire when an appliance is in operation.
○ B When there is excess current, a fuse connected to the neutral wire will not melt
○ C There is no current flowing in the live wire when a fuse connect to the live wire has melted
○ D The live wire is connect to the metal casing of an appliance.

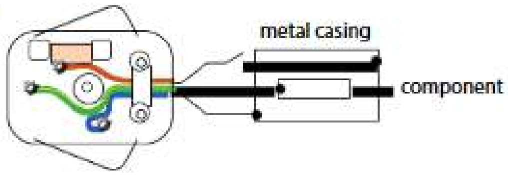
4 The insulated wires of an electric kettle was found to be very warm. This can be prevented by using ________

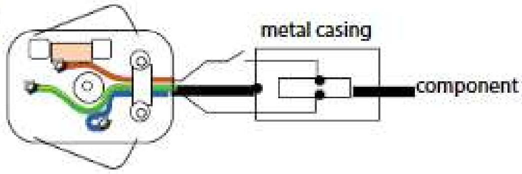
○ A thicker wires
○ B thinner wires
○ C thicker insulation
○ D thinner insulation

5 Which connection is correct?

○ A


○ B


○ C


○ D


Section B: Structured Questions

1 (a) Three unidentified wires X, Y and Z are connected to a 240 V a.c. mains. X is found to have a current of 10 A and a potential of 0 V. Y is found to have a current of 0 A and a potential of 0 V. Z is found to have a current of 10 A and a potential of 240 V. Which wire is live, neutral or earth?

(b) Some countries supply 120 V to their homes. What is the advantage of supplying 120 V instead of supplying 240 V?

2 An induction motor rated at 240 V, 1.5 A operates for 10 hours a day. Find the electrical cost if the electrical tariff is $0.20 per kW h.

3 Figure 18.20 shows a power board that comes with a 13 A fuse.

Figure 18.20

(a) Will the fuse trip if it is operating a 2400 W kettle and 1000 W toaster at the same time off a 240 V mains? Assume that these devices are connected in parallel.

(b) Explain why the current rating of a fuse is usually lower than that of a circuit breaker.

4 In a laundromat, there are three types of washing machines (Table 18.3). These washing machines are connected in parallel to one another and to the mains supply. The voltage of the mains supply is 230 V.

Table 18.3

Type of Washing Machine	Number of Washing Machines	Power of Each Washing Machine / W
5 kg load	10	500
10 kg load	5	1000
15 kg load	2	1500

(a) Calculate the total current when all the washing machines are in used.

(b) Suggest a suitable rating for the fuse of each type of washing machine.

5 In a computer laboratory, there are forty desktop computers and monitors. These desktop computers and monitors were left in stand-by mode for six weeks during the year-end school holidays. A typical stand-by circuit is shown in Figure 18.21.

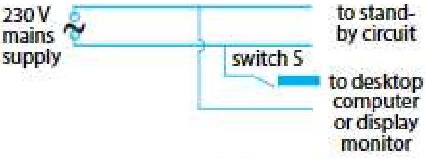


Figure 18.21

These devices are all connected to the 230 V mains.

(a) If the stand-by operating current is 20 mA for each device, calculate the energy consumption in kW h during the year-end school holiday.

(b) If the cost of 1 kW h of energy consumption is 20 cents, calculate the total cost of electricity consumption of this computer laboratory.

(c) In a study room, twenty students crowd into a room lit by a 16 W LED lamp to study for three hours each night. If the electricity consumption by the laboratory is supplied to this room instead, how many hours can the room be lit?

Section C: Free-response Questions

1 Figure 18.22 shows the three-pin plug of an appliance.

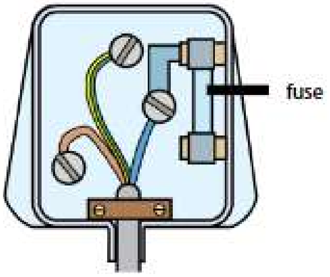


Figure 18.22

(a) What is the purpose of a fuse?

(b) Explain what is wrong with the wiring connection.

(c) Will the appliance still work?

2 Figure 18.23 shows a lamp that operates using a tungsten filament.

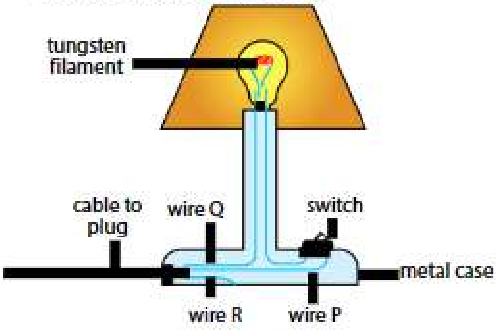


Figure 18.23

(a) If the lamp is connected to a 240 V mains and the resistance of the filament is 50 Ω, what is the power consumed?

(b) Find the electricity cost of operating the lamp for two hours if 1 kW h costs 20 cents.

(c) Which wire, wire P or wire Q, should be connected to the live terminal in the plug?

(d) What is the purpose of wire R?

(e) What danger, if any, will there be if wire P becomes loose and comes into contact with the metal case?

CHAPTER

19 Magnetism

What You Will Learn

- What are the interactions between magnets and between magnets and magnetic materials?
- How do we show the magnetic field around a magnet?

Between 1997 and 2004, Singapore made about one-third of the world's hard disks. That is, on average, about 90 million hard disks every year. Following the computer boom in the 1970s and 1980s, some of the world's largest hard disk companies opened plants in Singapore. Singapore went on to become an important centre for research and development of hard disks.

Do you know that hard disks are essentially made of electromagnets and magnetic recording media? How do magnets and magnetic materials interact with each other?

19.1 What Are the Interactions Between Magnets and Between Magnets and Magnetic Materials?

Learning Outcomes

- State the properties of magnets.
- Describe induced magnetism caused by placing magnetic material close to a strong magnet or within a current-carrying solenoid.
- Distinguish between temporary magnets and permanent magnets in terms of their properties and uses.

Disciplinary Idea

Forces help us understand motion.

Like magnetic poles repel and unlike magnetic poles attract. This results in forces that cause acceleration (motion). We can then apply Newton's laws of motion to describe the motion that is created.

Properties of Magnets

Like poles repel, unlike poles attract

You may have played with toys made of magnets. When you place two pieces of magnets together, they either attract or repel each other. More precisely, the **like poles** of the magnet **repel** while the **unlike poles attract**. These are not the only properties of a magnet.

Magnets have two poles. The magnetic effects are strongest at the poles. When iron filings are sprinkled onto a bar magnet, most of the iron filings are attracted to the two ends of the magnet (Figure 19.1).

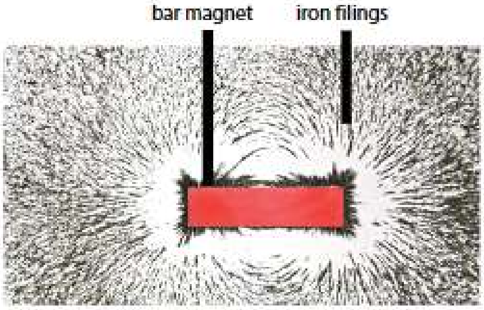


Figure 19.1 More iron filings are attracted to the poles of a magnet.

Rest in North–South Direction

A freely suspended magnet comes to rest in the north-south direction (Figure 19.2). At the equator, the north seeking side of the magnet will point towards Earth's geographic North Pole. We call this side of the magnet the **north pole**. Likewise, the opposite end of the magnet, the south seeking side, is called the **south pole**. A good example of this effect is the needle on a compass.

What if a magnet is suspended at the Earth's geographic North Pole or at the Arctic north? The suspended magnet would be inclined at an angle (Figure 19.3). In fact, the magnet is tilted towards the Earth's magnetic pole since the magnet aligns itself with the Earth's magnetic field.

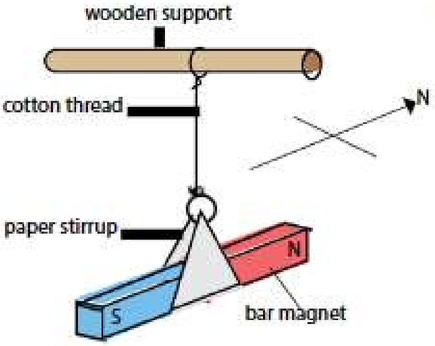


Figure 19.2 A freely suspended magnet always points in the north–south direction.

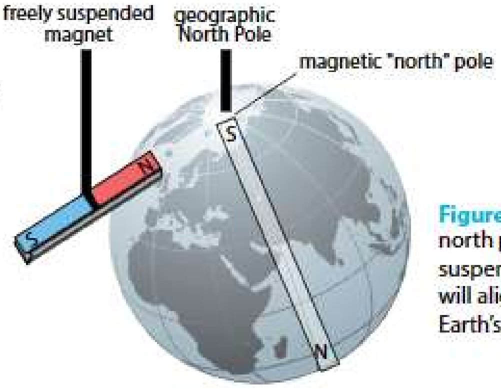


Figure 19.3 The north pole of a freely suspended magnet will align itself with Earth's magnetic field.

Have Two Poles

The magnetic north and south poles of a magnet always *occur in pairs*. When a magnet is broken or divided into two, it will result in two smaller pieces of magnets with both a north and a south pole. If we continue dividing the magnet into smaller pieces, each piece will still be a magnet with two poles (Figure 19.4).

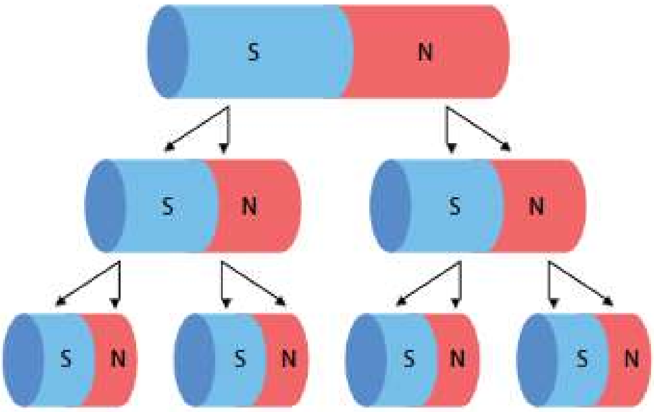


Figure 19.4 Dividing a magnet into smaller piece produces smaller pieces of magnets.

Attract Magnetic Materials

Magnetic attractions do not just occur between magnets. Attraction can also take place between a magnet and an object that is made of an unmagnetised magnetic material. However, repulsion can occur only between two magnets. We can only confirm that an object is a magnet if it repels another magnet (Figure 19.5).

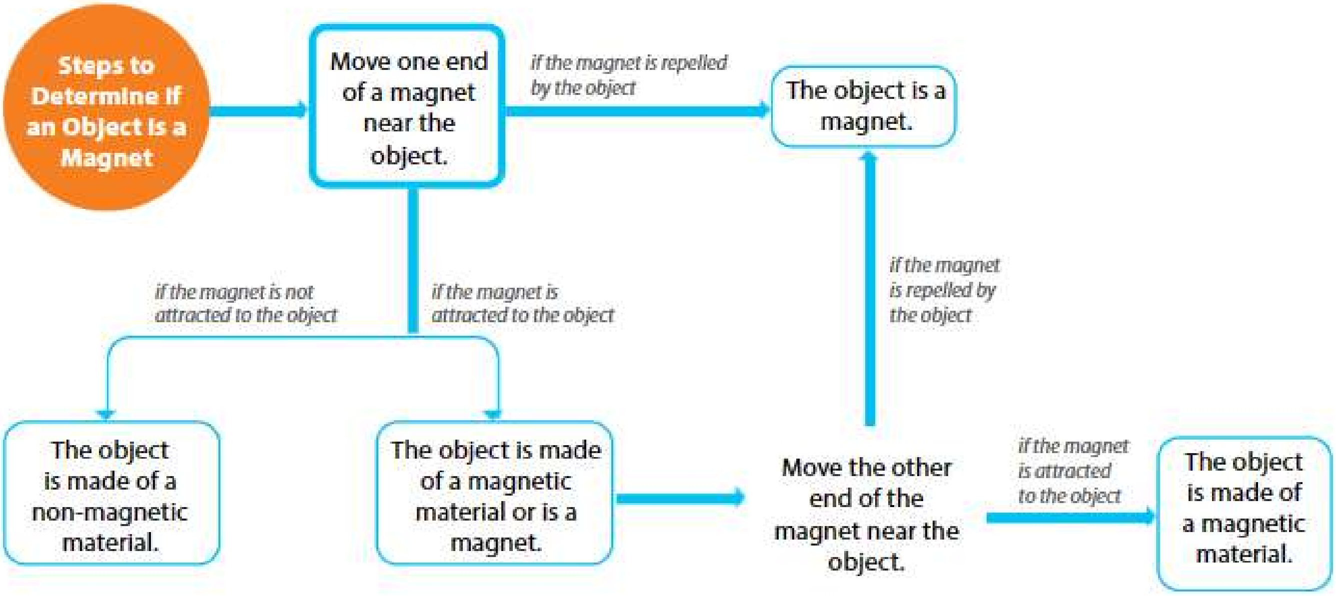


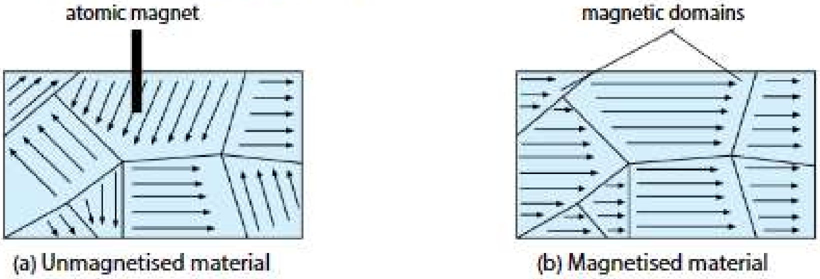
Figure 19.5 How to determine if an object is a magnet

Helpful Note

What gives rise to magnetic properties? Magnets are made up of atoms. At the subatomic level, electrons circulate around the atomic nuclei and spin about their own axes. These movements give rise to an atomic magnet, which is a tiny magnet of subatomic dimensions.

The magnetic domain theory is used to explain why some materials are magnetised and others are not. The theory states that there are regions called *domains* in which the atomic magnets are aligned (Figure 19.6).

- The atomic magnet is represented by an arrow.
- The head of the arrow represents the north pole and the tail represents the south pole.
- The neighbouring atomic magnets have the same magnetic orientation and can be banded together into areas called magnetic domains.



(a) Unmagnetised material

(b) Magnetised material

When a material is not magnetised, the atomic magnets in each domain have different orientations. The net magnetic effect is zero.

When a material is magnetised, the atomic magnets in each domain are aligned in the same direction.

Figure 19.6 Atomic magnets of (a) an unmagnetised magnetic material are not all aligned, whereas in (b) a magnetised magnetic material, they are all aligned.

Using this representation, it is easy to see that if we divide the magnet into two smaller pieces, we would get two magnets with a pair of opposite poles. This explains why the north and south poles always occurs in pairs, even if we break the magnet into smaller piece. Can you also use this representation to explain why a magnet is strongest at its poles?

When two bar magnets are joined together, the overall strength of the combined magnet:
- is stronger than that of one bar magnet; and
- is weaker than the sum of the strength of both magnets.

This is because when two magnets are stuck together, the overall magnetic field is the vector sum of the magnetic field of each magnet. However, the edges of the magnets that are in contact with each other are now one magnet away from the other edge of the magnet. Thus, the field strength is weaker than the sum of the field strength of both magnets.

Disciplinary Idea

Microscopic models can explain macroscopic phenomena.

Atomic magnets (microscopic models) can be used to explain magnetism (macroscopic phenomena) and its properties. Atomic magnets can also be used to explain induced magnetism, as well as magnetised and demagnetised states. This is classified as magnetic domain theory.

Induced Magnetism

You may have observed that a steel nail retains some magnetism when it is previously stuck to a magnet for a long time. This process is known as proximity induced magnetism. Proximity induced magnetism can take place when a magnetic material is in contact or in close proximity to a strong magnet (Figures 19.7 and 19.8). Only materials that can be attracted by a magnet can be magnetised.

▶ **Induction**, or **induced magnetism**, can take place when a magnetic material is placed close to a strong magnet or within a current-carrying **solenoid**.

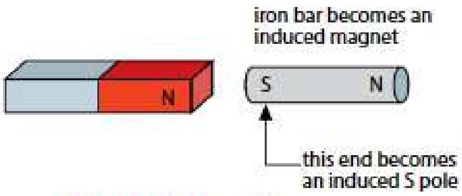


Figure 19.7 Magnetic induction can happen without physical contact.

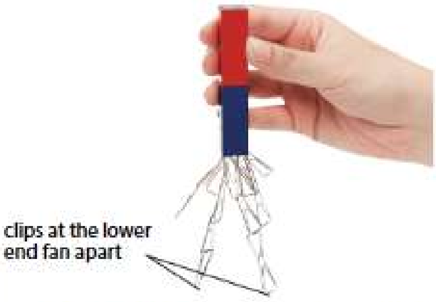
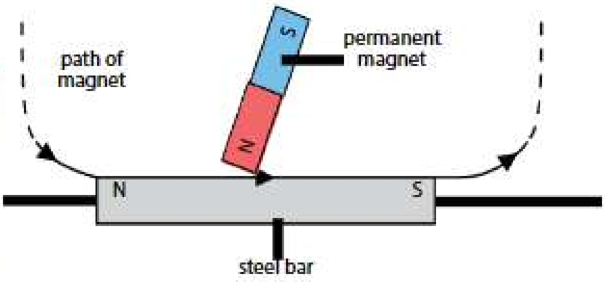


Figure 19.8 A paper clip attracted to a magnet becomes an induced magnet that attract other clips.

A magnetic material can be magnetised when it is stroked with a strong magnet (Figure 19.9).



An unmagnetised steel bar is stroked with one pole of a magnet repeatedly. The same pole must be used throughout.

The magnet must be lifted sufficiently high above the bar after each stroke. An opposite pole will be induced at the end where the magnet leaves the steel bar.

Figure 19.9 Induction or induced magnetism can be achieved through stroking a magnetic material with a magnet.

Disciplinary Idea

Matter and energy make up the Universe.

Some forms of matter (ferromagnetic materials) have strong magnetic properties. They can be magnetised and attract or repel one another.

Word Alert

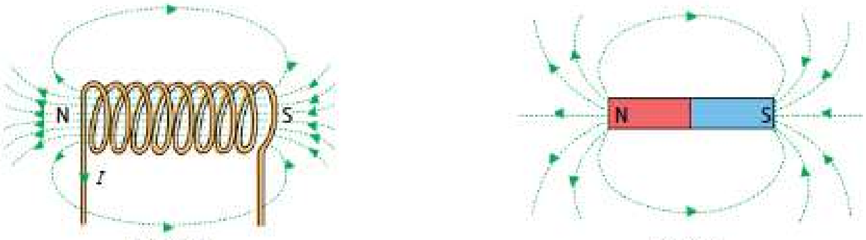
Solenoid: coil of wire used as an electromagnet

Helpful Note

The movement of the magnet in Figure 19.8 pulls the atomic magnets in the steel bar into alignment.

A current-carrying solenoid produces a magnetic field similar to that of a bar magnet (Figure 19.10).

► A **magnetic field** is a region in which the force of magnetism acts.



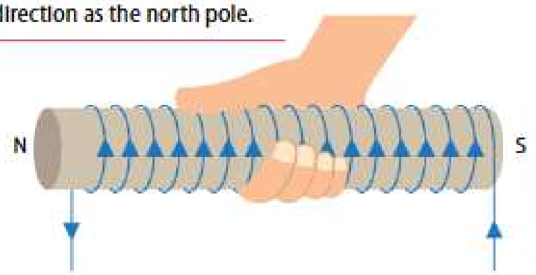
solenoid magnet

Figure 19.10 Magnetic field lines of a solenoid is very similar to that of a bar magnet.

By placing a magnetic material, such as an iron rod, inside the current-carrying solenoid, the magnetic material becomes a magnet.

The direction of the magnetic field produced by a solenoid can be determined using the right-hand grip rule. The right-hand grip rule, also known as the corkscrew rule, is used to show the relationship between current and magnetic field.

To determine the direction of magnetic field when a current flows through a solenoid, imagine gripping the solenoid with our right hand (Figure 19.11).



The thumb points in the same direction as the north pole.

The fingers curl in the same direction as the current flowing through the solenoid.

Figure 19.11 The right-hand grip rule is used to determine the direction of magnetic field of a solenoid.

Link

You will learn that moving charges carry magnetic fields in Chapter 20.

Helpful Note

When a magnetic material is inside a magnetic field, the atomic magnets align themselves in the direction of the magnetic field. The magnetic material becomes magnetised.

Materials that can be attracted by a magnet are called ferromagnetic materials. Examples of ferromagnetic materials are iron, cobalt, nickel and alloys such as steel and alnico.

Disciplinary Idea

Matter interacts through forces and fields.

Magnetic materials and currents can interact with magnetic fields.

Demagnetisation

Figure 19.12 How does a magnet lose its magnetism?

Is it possible to demagnetise a magnet (Figure 19.12)? The answer is yes. This process of demagnetisation can be achieved by:
- placing the magnet in the east-west direction; and
- hitting or heating the magnet.

Placing the magnet in the east-west direction minimises the influence of the Earth's magnetic field during the demagnetisation process (Figure 19.13).

Figure 19.13 Hammering the magnet placed in the east-west direction can cause it to lose its magnetism.

Similarly, dropping a magnet multiple times on a hard surface also causes the magnet to lose its magnetism.

Helpful Note

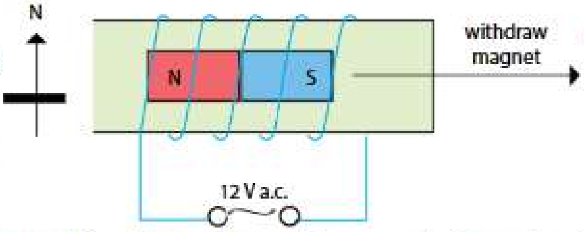
To demagnetise a magnet, the aligned atomic magnets need to return to their random positions. When heating or hitting the magnet, the atoms vibrate. Thus, the atomic magnets will not be aligned and they settle back in different orientations. This demagnetises the magnet.

It is also possible to demagnetise a magnet using a solenoid with an **alternating current**. An alternating current is one that changes direction all the time.

The magnetic field of the solenoid produced by passing alternating current will change direction every time the current changes direction. To demagnetise a magnetised object using a solenoid, we have to:
- place the magnet inside the solenoid in the east-west direction, and
- then gradually reduce the current to zero.

Alternatively, instead of reducing the current to zero, we can also pull the object out of the solenoid until it is some distance away. Figure 19.14 shows how to demagnetise a magnet using a solenoid.

① Apply an alternating current to the magnet that is placed inside a solenoid in the east-west direction.



② With the alternating current still flowing, pull the magnet out of the solenoid slowly until it is far enough from the solenoid.

Figure 19.14 Procedure to demagnetise a magnet using a solenoid

Helpful Note

When demagnetising a magnet using an alternating current, the atomic magnets orientate themselves according to the field. However, since the direction of the magnetic field keeps changing, the atomic magnets become randomised. The magnet is demagnetised.

When subjected to long periods of heat or influence of nearby magnetic fields, magnets can become demagnetised. To prevent this from happening, we make use of iron keepers (Figure 19.15). The magnetic field is retained within the iron keepers to preserve its strength. Keepers also have a safety function. They reduce stray magnetic fields of stored magnets and prevent unwanted magnetised materials from being attracted to the stored magnets.

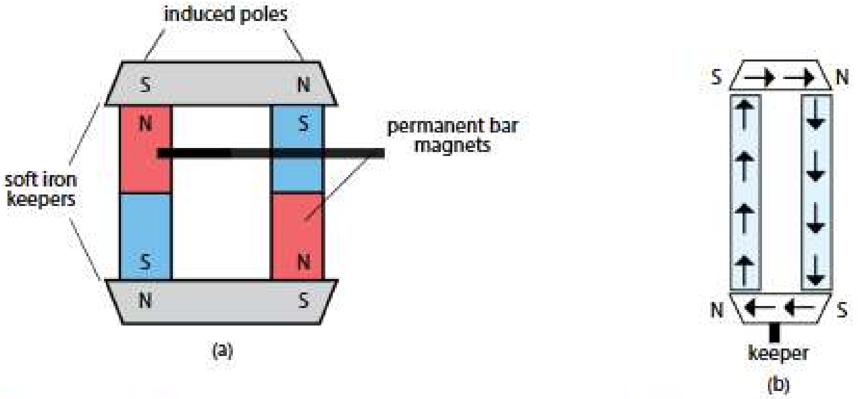


Figure 19.15 (a) Keepers are used to reduce stray magnet fields and help to prevent stored magnets from becoming demagnetised, (b) Illustration of magnetic field lines in iron keepers.

A magnet loses its magnetism when the atomic magnets are no longer aligned. This out-of-alignment happens when magnets are subjected to heating or dropping repeatedly. Heating or dropping causes the atomic magnets to vibrate and settle in their preferred orientation.

Magnetism does not get used up like charges in a battery, nor does it get transferred when attracted to non-magnetic substances or when placed in contact with another magnet (in the case of induced magnetism). However, magnetism does "leak" over time. A magnet subjected to the influence of external magnetic field and temperature variations may lose its magnetism gradually.

Temporary and Permanent Magnets

Some magnets are temporary and others are permanent.

▶ **Temporary magnets** are magnets that retain their magnetism in the presence of an electric current or a permanent magnetic field.

▶ **Permanent magnets** do not require the presence of an electric current or a permanent magnetic field to retain their magnetism.

Magnets are temporary or permanent depending on the materials they are made of.

Soft and Hard Magnetic Materials

There are two types of ferromagnetic materials, soft and hard magnetic materials. The terms "soft" and "hard" do not refer to the hardness of the materials, but to the material's ability to become magnetised and remain magnetised.

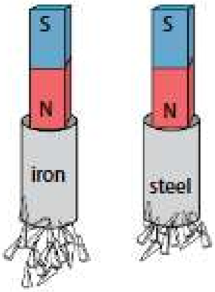
Iron and steel are examples of soft and hard magnetic materials, respectively. Table 19.1 compares these two types of materials.

Table 19.1 Comparison between soft and hard magnetic materials

Magnetic Material	Soft	Hard
Example	soft iron	steel (an alloy of iron)
Properties	easily magnetised and demagnetised	difficult to magnetise and demagnetise
Common Uses	temporary magnets such as electromagnets in junkyards	permanent magnets such as magnetic recording media in hard disk drives

Soft magnetic materials have stronger induced magnetism compared to hard magnetic materials. This can be illustrated with a simple experiment using an iron bar and a steel bar of the same dimensions (Figure 19.16).

1 A magnet is used to hold up one end of the iron bar and the other end of the iron bar is dipped into a dish of paper clips.
2 The magnet is removed and the number of paper clips is counted.
3 Steps 1 and 2 are repeated for steel, using the same magnet. It can be shown that fewer paper clips are attracted to the steel bar in this manner.



More paper clips are attracted to the iron bar than the steel bar.

Figure 19.16 Temporary magnets have stronger induced magnetism compared to permanent magnets.

Iron is not the only magnetic metal. Other elements such as nickel, cobalt, and the rare-Earth metals (notably samarium and neodymium) are also good magnets. Some of the best magnets are alloys (mixtures) of these elements.

Other common metals such as copper, gold, silver, and aluminium are non-magnetic. Most non-metals (including paper, wood, plastic, concrete, glass, and textiles such as cotton and wool) are non-magnetic too.

Worked Example 19A

Suggest some ways to determine the poles of an unmarked magnet.

Thought Process
To determine the poles of an unmarked magnet, we make use of the properties of a magnet. This is because these properties are only for magnets and distinguish magnets from non-magnets.

Answer
Method 1: Use a bar magnet with known poles. Since like poles repel, the north pole of the unmarked magnet repels the north pole of the bar magnet.

Method 2: Use a compass. The south pole of the unmarked magnet will attract the north seeking needle of the compass.

Method 3: If the direction of the geographic north is known, the unmarked magnet can be suspended freely. The magnet will come to rest in the north–south direction and the pole pointing to the north would be the north pole.

Let's Practise 19.1

1 If you are presented with two identical metal bars and are informed that one of them is a magnet, how do you determine which one the magnet is?
2 A steel bar is magnetised by two magnets as shown in Figure 19.17. Mark the poles of the magnetised steel bar.

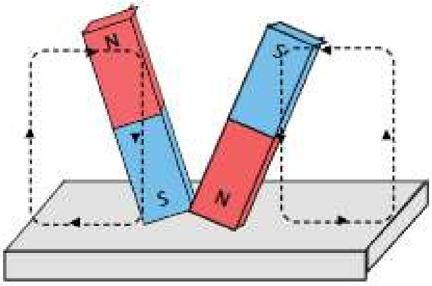


Figure 19.17

Link
Theory Workbook
Worksheet 19A

19.2 How Do We Show the Magnetic Field Around a Magnet?

Learning Outcomes

- Describe how a bar magnet can be used to determine the direction of a magnetic field.
- Draw the magnetic field pattern around a bar magnet and between the poles of two bar magnets.

If we sprinkle iron filings around the bar magnet, the iron filings will fall into lines (Figure 19.18).

The lines are closely packed at either poles of the magnet, but are more spaced out on both sides as well as further away from the magnet. These lines also connect the opposite sides of the poles and are present within the magnet. We call these lines **magnetic field lines**. Magnets create these **spatial** magnetic fields, and the magnetic field lines are a visual tool used to represent magnetic fields.

Word Alert

Spatial: occupying space or is three-dimensional

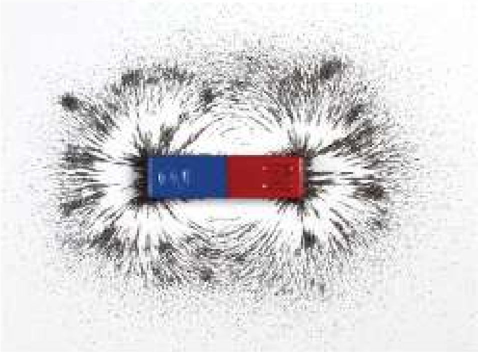


Figure 19.18 Iron filings tracing the magnetic field lines of a bar magnet

From the observations of the iron filings, some characteristics of magnetic field lines are as shown.

- The magnetic field lines never cross one another.
- The magnetic field lines are continuous and they form closed loops.
- The distance between the magnetic field lines represents the strength of magnetic field. The closer the lines, the stronger the magnetic field.

It is common to use a diagram to represent the magnetic field lines (Figure 19.19). By convention, the field lines have arrows that point out from the north pole of the magnet and point into the south pole. Since magnets are stronger at the poles, these field lines are more concentrated at the poles.

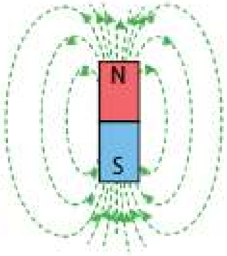


Figure 19.19 Magnetic field lines of a bar magnet are drawn with arrow pointing from the north pole to the south pole

Let's Investigate 19A

Aim
To investigate the magnetic field lines of a magnet using a compass

Procedure

1. Place a bar magnet in the centre of a piece of paper with the north pole pointing to the north (Figure 19.20).
2. Place a compass near one pole of the magnet.
3. Mark the north and south ends of the compass needle with an N and an S respectively.
4. Re-position the compass such that the south needle is pointing to the N marking of the previous position (Figure 19.21).
5. Repeat steps 3 and 4 until several traces have been drawn.

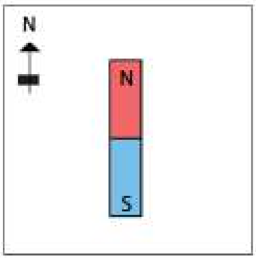


Figure 19.20 The north pole of the magnet points to the north

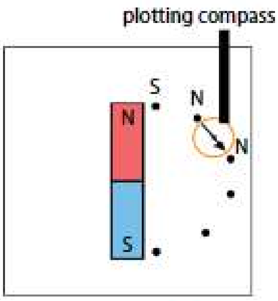


Figure 19.21 Mark the poles of the magnets by compass dots.

Observation
The direction of the field lines is indicated by the direction of the plotting compass needle (Figure 19.22).

Question
Will the magnetic field line be the same if the magnet is placed with the magnet's south pole pointing toward the north? Explain your answer.

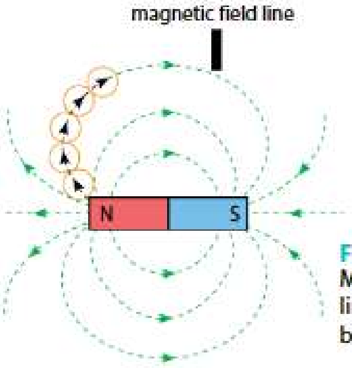


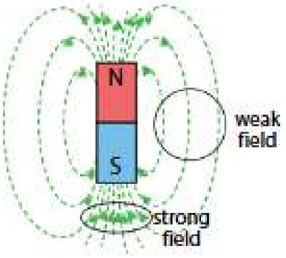
Figure 19.22 Magnetic field lines around a bar magnet

Worked Example 19B

Draw the magnetic field lines of a bar magnet. Indicate in the same diagram a region where the field is weak and the region where the field is strong. You may ignore the effects of Earth's magnetic field.

Thought Process
The strength of a magnetic field is indicated by the proximity of the lines. Magnetic field is stronger where the lines are closer together. Magnetic field is weaker where the lines are further apart and further away from the magnet.

Answer
The density of the field lines indicates the strength of the field.



A uniform magnetic field has field lines (Figure 19.23(a)). The field lines are equally spaced and parallel to one another. A uniform magnetic field exerts a constant magnetic force in the region.

The opposite is true for a non-uniform magnetic field (Figure 19.23(b)). The field lines are not equally spaced and hence are also not parallel to one another. At different points, the magnetic force exerted would be different.

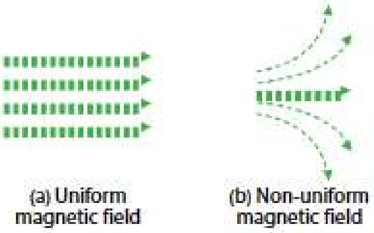


Figure 19.23 A uniform magnetic field and non-uniform magnetic field

Field lines can be used to represent the interaction between two magnets. When two unlike poles are placed next to each other, field lines go from the north pole of one magnet to the south pole of the other magnet (Figure 19.24). This is why unlike poles attract each other.

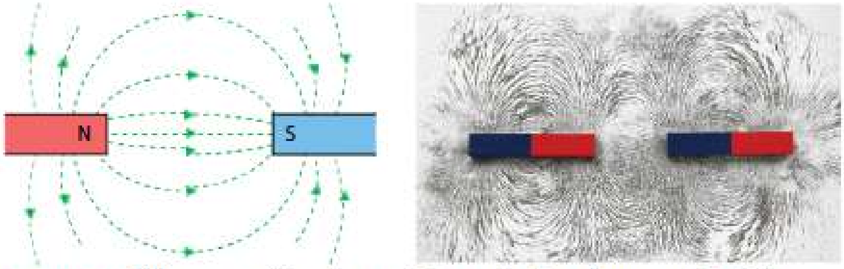


Figure 19.24 When two unlike poles are facing each other, the magnetic field lines of the north pole connect with the magnetic field lines of south pole, attracting each other.

Conversely, when two like poles are placed next to each other, the field lines move away from each other (Figure 19.25). This is the reason why the like poles repel each other.

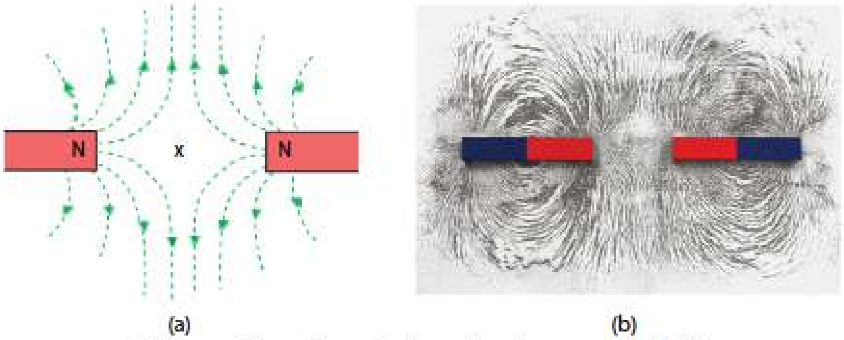


Figure 19.25 When two like poles are facing each other, magnetic field lines move away from each other and cancel each other out, creating a repulsive force.

Point X in Figure 19.25(a) is called a neutral point because the resultant magnetic field in that region is zero. The magnetic fields at point X from each magnet are equal and opposite — they cancel each other.

Disciplinary Idea

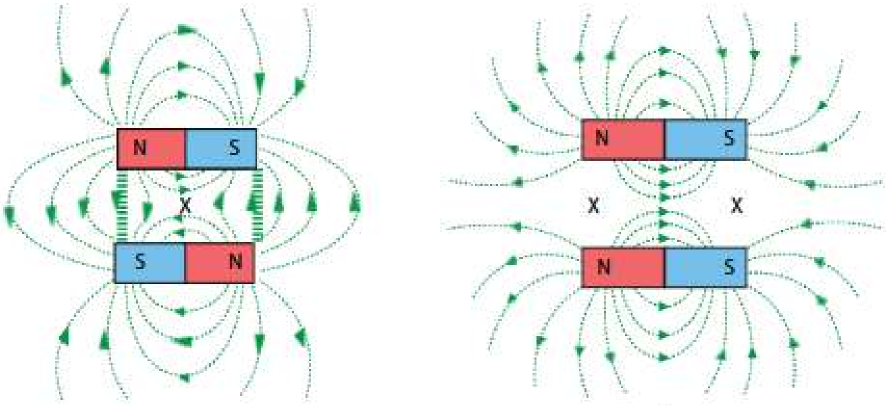
Matter interacts through forces and fields.

A magnetic field is a region in which magnetic materials experience a magnetic force.

The magnetic field is represented by field lines, and the spacing between the field lines represent the strength of the magnetic field. The direction of the magnetic field is given by the arrow.

If two bar magnets are placed side by side, the magnetic field lines will interact with each other. Figure 19.26(a) shows the interaction when the bar magnets are placed side by side, with unlike poles beside each other. The magnetic field lines join together and become denser at the poles.

Figure 19.26(b) shows the interaction when the like poles of both bar magnets are beside each other. This time, the magnetic field lines bend away from each other.



(a) (b)

Figure 19.26 Magnetic field patterns between two bar magnets placed side by side.

The regions marked "X" are neutral regions where the resultant magnetic field lines are zero.

Worked Example 19C

A magnet is placed on top of a turntable (circular rotating platform) and a non-uniform magnetic field is then applied (Figure 19.27). How will the magnet react?

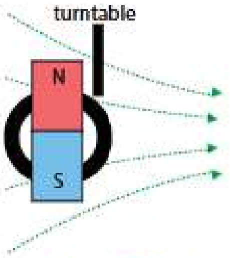


Figure 19.27

Thought Process
Since the non-uniform magnetic field lines point to the right, the direction of the magnetic field is pointing from north (left) to south (right). When a magnet is placed in a magnet field, it will experience a magnetic force. The magnet is free to rotate since it is placed on a turntable and the south pole of the magnet will be attracted towards the left, whereas the north pole of the magnet will be repelled towards the right.

Answer
The magnet will rotate clockwise and come to rest in the horizontal position with its south pole pointing to the left and the north pole pointing to the right.

Let's Practise 19.2

1 Two bar magnets are placed near each other. If the directions of the compass needles are as shown in Figure 19.28, deduce the poles marked X and Y.

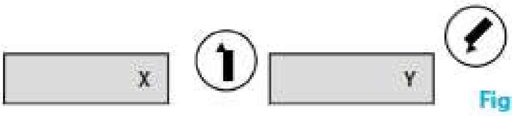


Figure 19.28

2 Four magnetic compasses are placed near an unmarked bar magnet as shown in Figure 19.29. Which compass is faulty?

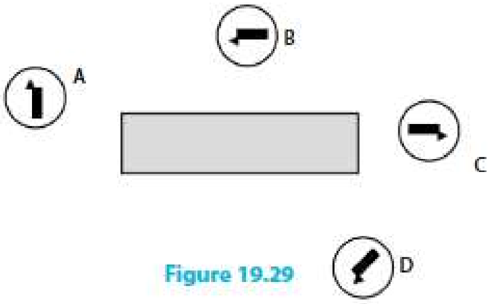


Figure 19.29

Link

Theory Workbook
Worksheet 19B
Let's Assess
Let's Reflect

Tech Connect

Current mass data storage devices such as hard disk drives or magnetic tapes are commonly used around us. These devices read or write data by moving the material (the disk or tape) with a motor across a reader such as a computer.

Racetrack memory is a new form of digital data storage. The racetrack is a ferromagnetic nanowire. In racetrack memory, the material stays in place and the data is moved across the reader without the need to move mechanical parts. The data is carried by a magnetic object called a skyrmion that can be moved by applying an external stimulus, such as a current pulse. The technology could potentially enable handheld devices to store a few thousand movies. It consumes ultralow power and will not wear out. Why are data recorded in 0's and 1's? How does magnetism differentiate 0's and 1's?

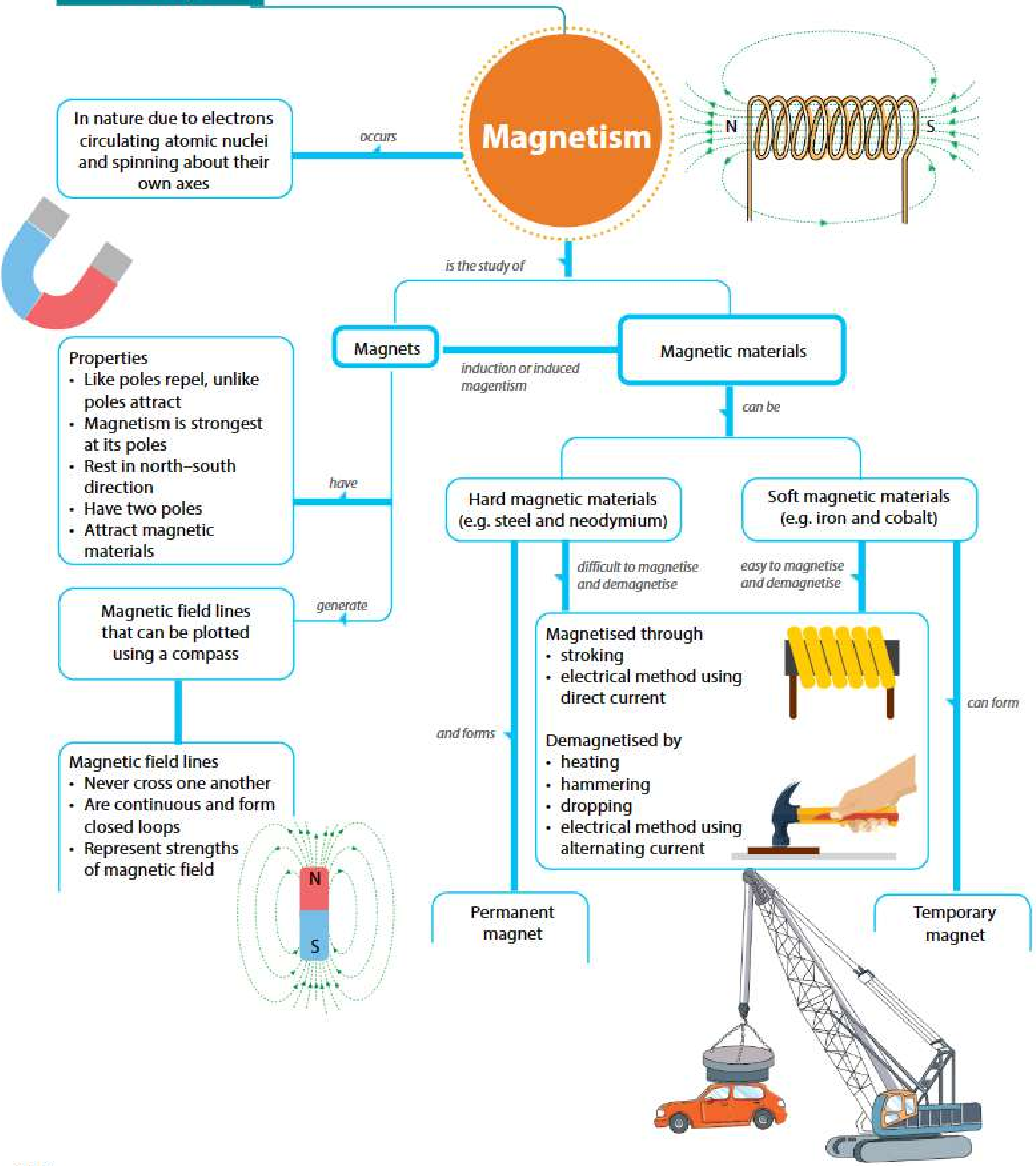
Cool Career

Geomagnetists

Geomagnetists are a specialised type of geologists. They study the magnetic processes of geological features and Earth. Geomagnetism of Earth is a result of Earth's rotation about its axis. The mountain ranges, ocean trenches and shifting tectonics have an effect on the geomagnetic fields of Earth to a certain degree. Studying the magnetic fields of Earth enables companies in the mining, oil and gas industries to predict where natural resources can be found (Figure 19.30).

Figure 19.30 Based on their studies, geomagnetists can predict where minerals such as iron ore can be found.

Let's Map It



Magnetism

occurs

In nature due to electrons circulating atomic nuclei and spinning about their own axes

is the study of

Magnets

induction or induced magentism

Magnetic materials

have

Properties
- Like poles repel, unlike poles attract
- Magnetism is strongest at its poles
- Rest in north–south direction
- Have two poles
- Attract magnetic materials

generate

Magnetic field lines that can be plotted using a compass

Magnetic field lines
- Never cross one another
- Are continuous and form closed loops
- Represent strengths of magnetic field

can be

Hard magnetic materials (e.g. steel and neodymium)

Soft magnetic materials (e.g. iron and cobalt)

difficult to magnetise and demagnetise

easy to magnetise and demagnetise

Magnetised through
- stroking
- electrical method using direct current

Demagnetised by
- heating
- hammering
- dropping
- electrical method using alternating current

and forms

Permanent magnet

can form

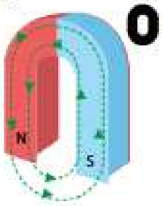
Temporary magnet

Let's Review

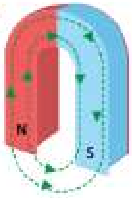
Section A: Multiple-choice Questions

1 Which diagram correctly shows the magnetic field lines of a U-shaped magnet?

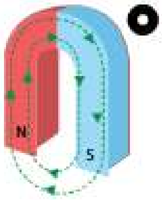
○ A



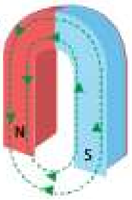
○ B



○ C



○ D



2 A neutral point in a magnetic field is a point at which ________.

○ A the magnetic field is zero
○ B Earth's magnetic field is zero
○ C the resultant magnetic field is zero
○ D the magnetic fields oppose each other

3 The magnetic field inside a long straight current carrying solenoid ________

○ A is zero
○ B decreases at the ends
○ C increases at the ends
○ D is the same at all points

4 A piece of steel is being magnetised by a magnet (Figure 19.31). What are the poles produced at X and at Y?

Figure 19.31

	Pole at X	Pole at Y
○ A	north	north
○ B	north	south
○ C	south	north
○ D	south	south

5 Which of the following statement about magnetic field lines is **incorrect**?

○ A They are visual tools to represent the directional lines present inside and outside the magnetic material that indicate the magnitude and direction of the magnetic force.
○ B The direction of the magnetic field is the tangent to the field line at any point in space.
○ C Magnetic field lines do not cross outside the magnet, but they cross one another inside the magnet.
○ D Magnetic field lines are continuous, forming closed loops without beginning or ending.

Section B: Structured Questions

1 Would you use a soft magnetic material or a hard magnetic material to make the needle of a compass? Explain your answer.

2 Figure 19.32 shows three unmarked ring magnets "floating" on top of one another. Identify the poles of each magnet.

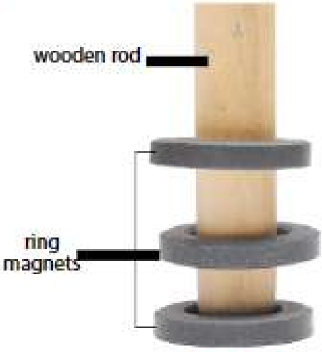


Figure 19.32

3 A thin piece of wood separates a magnet and two iron nails (Figure 19.33). Explain why the pointed tip of the nails point away from each other.

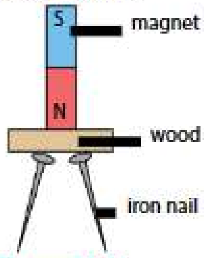


Figure 19.33

4 A bar magnet is resting on a turntable (Figure 19.34). Explain what happens to the needle of the compass when the magnet is rotated in an anticlockwise direction.

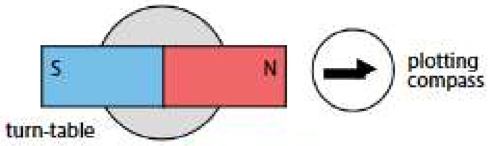


Figure19.34

5 A paper clip was stuck onto a magnet. When the paper clip was removed from the magnet, it was found that the paper clip could deflect the needle of a compass. Explain why.

Section C: Free-response Questions

1 Figure 19.35 shows an electromagnetic crane that is used to move scrap metal from one place to another.

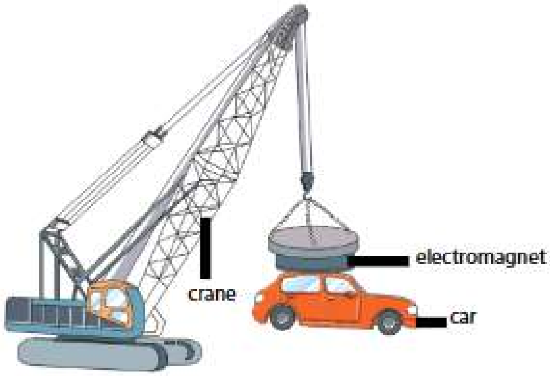


Figure 19.35

(a) Suggest a suitable material for the electromagnet.

(b) Explain why the material selected in (a) is suitable.

(c) The cross-section of the electromagnet is shown in Figure 19.36. The wires are coiled around an iron core. Given the polarity of the induced electromagnet, determine if the current flowing in the clockwise or anticlockwise direction when viewed from the bottom.

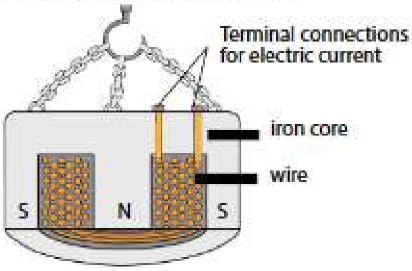


Figure 19.36

(d) Explain how the direction of current is determined.

2 A magnet is placed on the table in Figure 19.37.

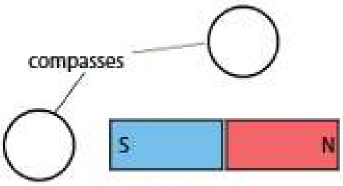


Figure 19.37

(a) Assuming that the effects of Earth's magnetic field are negligible, indicate the directions of the nearby plotting compasses.

(b) A nail is placed near the magnet (Figure 19.38). Explain why the nail is attracted to the magnet.

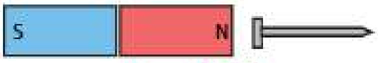


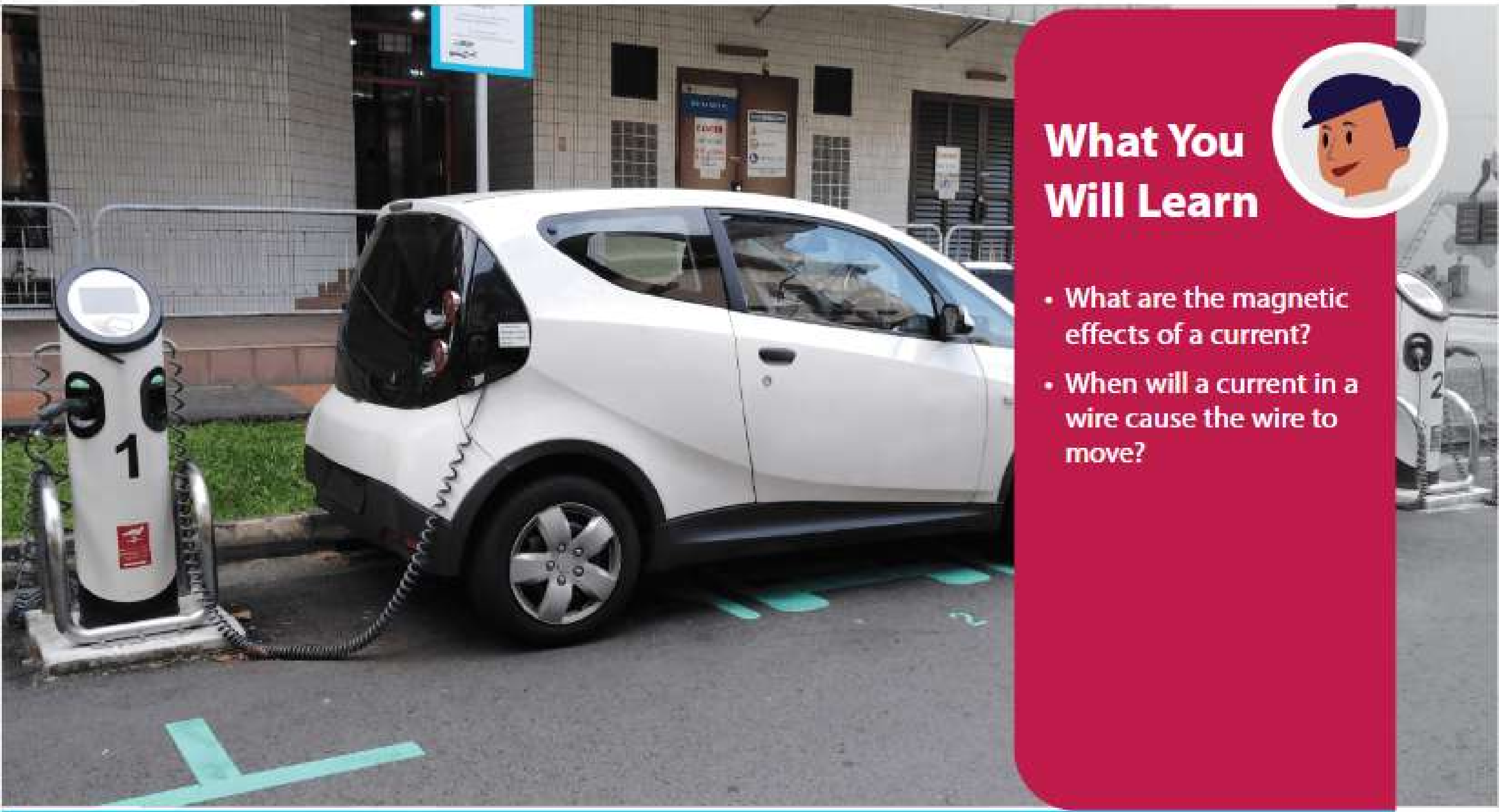
Figure 19.38

(c) Suggest some ways to determine if the nail has been magnetised after it has been removed from the bar magnet.

(d) Suggest how to demagnetise the nail.

CHAPTER

20 Electromagnetism



What You Will Learn

- What are the magnetic effects of a current?
- When will a current in a wire cause the wire to move?

Singapore plans to replace all internal combustion engine vehicles with electric vehicles by 2040. Electric cars run on rechargeable batteries. These batteries power an electric motor, which in turn drives the wheels.

Energy is transferred electrically from the chemical potential store of the battery to the kinetic store of the motor. This process is achieved through electromagnetism, which unifies electricity and magnetism.

Many appliances in your home also work on the principles of electromagnetism. Can you name some of these appliances?

20.1 What Are the Magnetic Effects of a Current?

Learning Outcomes

- Draw the pattern of the magnetic field due to currents in straight wires and in solenoids and state the effect on the magnetic field of changing the magnitude and/or direction of the current.
- Describe the application of the magnetic effect of a current in electromagnets.

If you dismantle an electric toy car or train, you would notice that it has a small motor that runs on two batteries (Figure 20.1(a)). If you pull the motor apart, you would see that it has two pieces of magnets (Figure 20.1(b)). Why does a motor have two magnets and how does electricity from the battery cause the motor to spin?

Figure 20.1(a) Stripped-down toy car

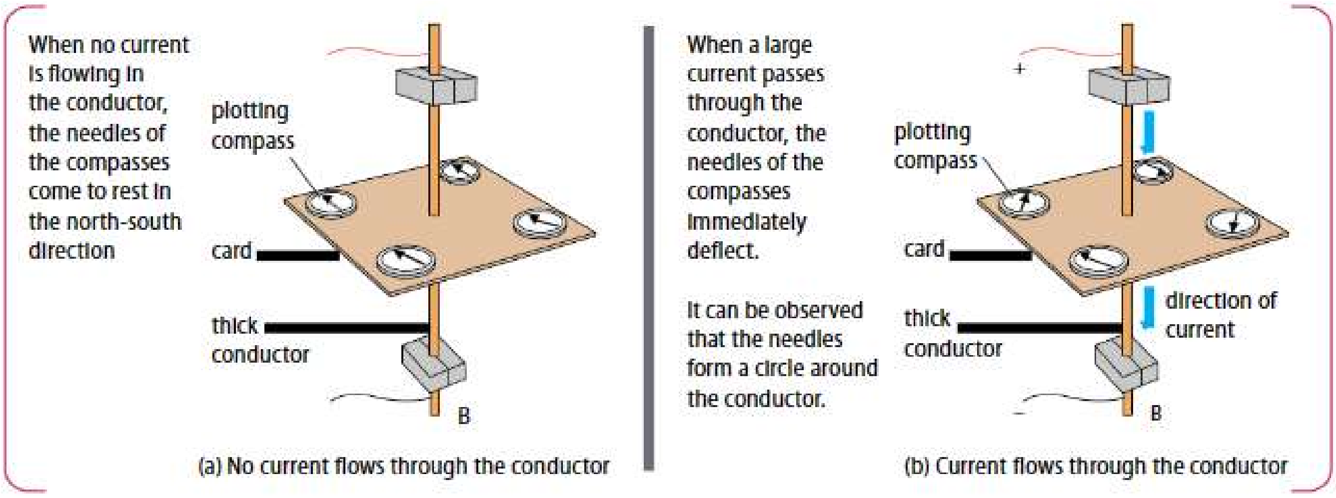
Figure 20.1(b) Stripped-down motor

Magnetic Field Patterns

In 1820, Hans Christian Oersted discovered that electricity and magnetism are linked. Indeed, the source of magnetism is moving electric charges, which in turn produce electricity.

In an experiment, Oersted found that a wire carrying current caused a compass needle to deflect, indicating the presence of a magnetic field. Figure 20.2 shows an experimental set-up similar to that carried out by Oersted. The positions of the needles of the compasses indicate the direction of the magnetic field generated by the current passing through a straight conductor.

Figure 20.2 The positions of the compass needles before and after a current flows through the conductor



When no current is flowing in the conductor, the needles of the compasses come to rest in the north-south direction

(a) No current flows through the conductor

When a large current passes through the conductor, the needles of the compasses immediately deflect.

It can be observed that the needles form a circle around the conductor.

(b) Current flows through the conductor

If the card in Figure 20.2(b) is raised or lowered to a new position, the directions of the needles do not change. This suggests that magnetic field produced by a current-carrying conductor forms a cylinder around the conductor.

If the compasses on the card are repositioned further from the conductor, the needles of the compasses again form a circle around the conductor as before. If the card is moved up and down, the needles remain in their deflected position. This suggests that the magnetic field produced forms concentric cylinders around the conductor.

If the direction of the current is reversed, the needles deflect in the opposite direction (Figure 20.3). Moving the card up and down along the entire conductor shows the same deflections of the needles.

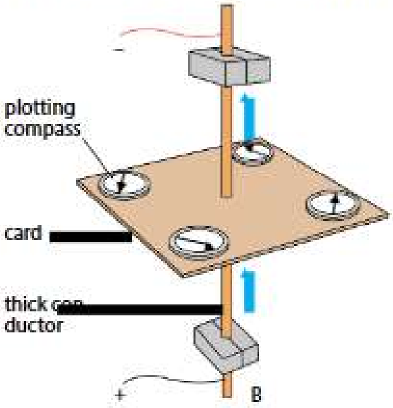


Figure 20.3 The positions of the needles of the compasses deflect in the opposite direction when the current is reversed.

The compasses are then removed and some iron filings are sprinkled evenly over the entire card. The current flowing in the conductor is slowly increased. The iron filings initially form fewer concentric circles around the conductor. As the current is increased further, more concentric circles are formed.

The directions of the needles on the compasses follow the right-hand grip rule. If we grip the conductor with the thumb pointing in the direction of the conventional current, the curl of the fingers shows the direction of the magnetic field (Figure 20.4).

Link

Recall from Chapter 19: The right-hand grip rule was used to determine the direction of the magnetic field of a solenoid.

A word of caution: it is very dangerous to grip a bare wire or conductor when a current is flowing through it.

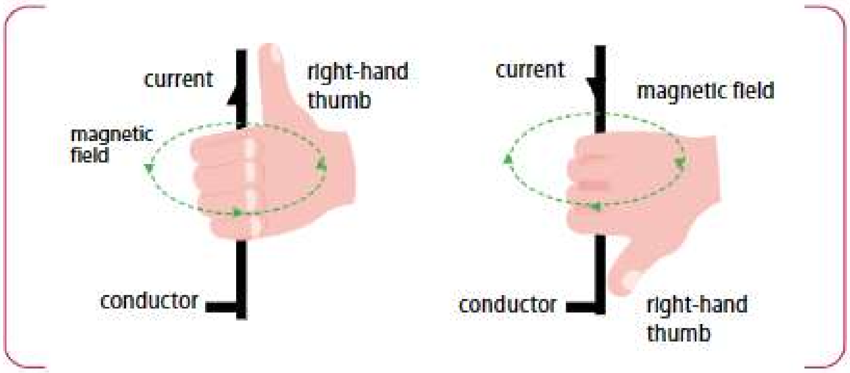


Figure 20.4 If the thumb points in the direction of the current, the curl of the fingers shows the direction of the current.

Helpful Note

We can use the following to remember what the × and • symbols represent.

Imagine the direction of current as an arrow.

- When an arrow moves into the plane of the paper, we can see the tail of the arrow (the cross ×).
- When an arrow moves out of the plane of the paper, we can see the tip of the arrowhead (the dot •).

Thus, we can conclude the following:

- Changing the magnitude of the current changes the strength of magnetic field. The strength of magnetic field increases when the current is increased (Figure 20.5).

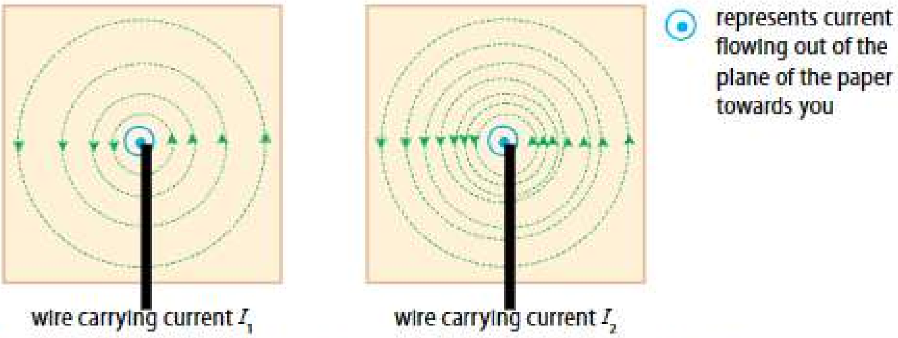


Figure 20.5 Top view of the strength of magnetic field: The strength of magnetic field increases when I_1 is increased to I_2.

- Changing the direction of the current changes the direction of the magnetic field. The direction of the magnetic field is reversed when the direction of current is reversed (Figure 20.6). This direction is given by the right-hand grip rule.

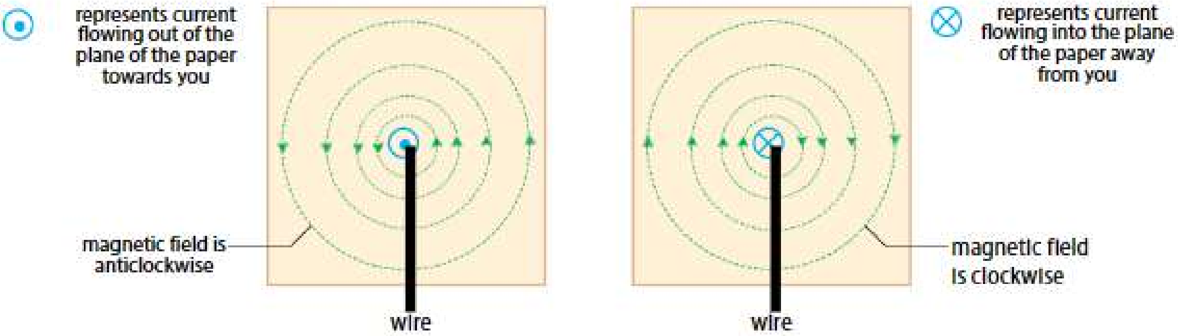


Figure 20.6 Top view of the strength of magnetic field: The direction of the magnetic field is reversed when the direction of the current is reversed.

Notice that in Figures 20.5 and 20.6, the magnetic field lines near the wire are closer together than the ones further away from the wire. This is because the strength of magnetic field is stronger closer to the wire.

This field that is produced by the current is temporary. As soon as the current stops flowing, the magnetic field disappears. Hence, it is possible to use this property to make temporary magnets such as in a solenoid.

Helpful Note

When drawing the magnetic field around a long current-carrying wire, the concentric field lines should be further apart with increasing radius. This is because the strength of magnetic field is stronger closer to the wire.

A solenoid is a long piece of wire wound in a coil. Some solenoids have a soft iron core to enhance the strength of magnetic field. Figure 20.7 shows a solenoid with and without a soft iron core.

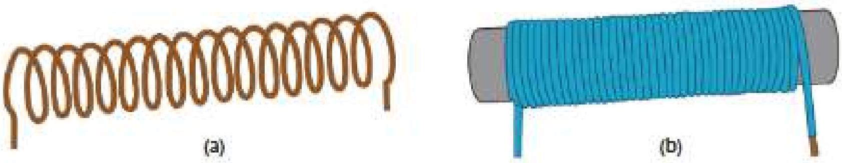


Figure 20.7 Solenoid (a) without soft iron core (b) with soft iron core

Link

Recall from Chapter 19: The magnetic field lines have a pattern similar to a bar magnet.

The polarity of a magnet is determined by the right-hand grip rule.

A current-carrying solenoid is an electromagnet. When a current is passed through a solenoid, a resultant magnetic field similar to a bar magnet is generated. To understand how this magnetic field is formed, consider the magnetic field from each turn of the coil (Figure 20.8).

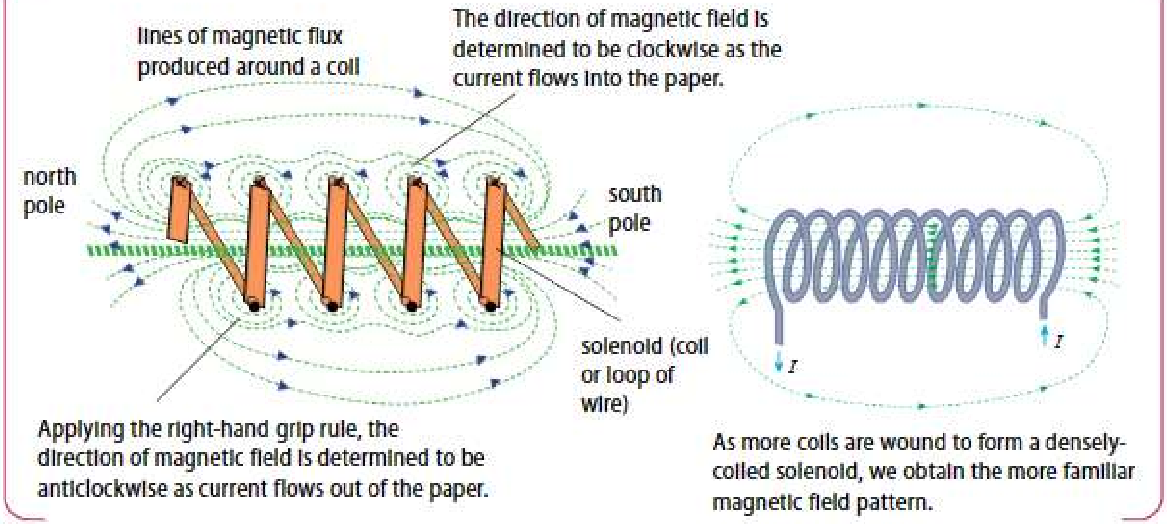


Figure 20.8 (a) Top view of the magnetic field lines of a solenoid, and (b) magnetic field pattern of a typical solenoid

The field lines of each individual turn add up to give the resultant magnetic field. Since the resultant magnetic field is the vector sum of the magnetic field lines of each individual turn, the strength of magnetic field can be increased by increasing the number of turns. In fact, the strength of the magnetic field depends on the number of turns per unit length, or the number of turns for every metre of the solenoid.

In addition, if the current flowing in the solenoid is increased, the strength of magnetic field of each individual turn would increase. This increases the resultant strength of magnetic field. Placing a soft iron core within the solenoid also helps to increase the strength of the magnetic field. This is because the soft iron core tends to concentrate the magnetic field. This strengthens the field since the field lines are much closer together.

The strength of magnetic field 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; and
- placing a soft iron core within the solenoid.

Let's Investigate 20A

Aim

To investigate the magnetic field lines of a solenoid using iron filings

Procedure

1 Set up the apparatus in Figure 20.9.

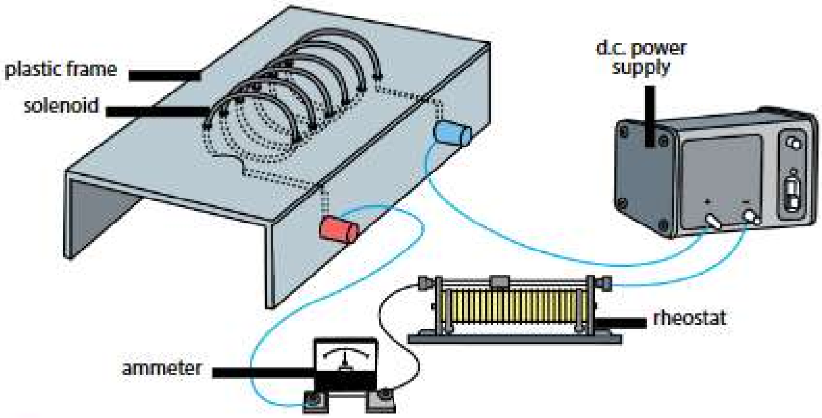


Figure 20.9 Experimental set-up to determine the magnetic field of solenoid

2 Sprinkle some iron filings on the plastic frame.
3 Switch on the power supply.
4 Observe the pattern of the iron filings.
5 Vary the current through the solenoid by adjusting the rheostat.
6 Repeat steps 3 to 5 with a solenoid that has more turns.

Observations

The patterns of the iron filings show the magnetic field lines.

1 The field lines of each turn of the solenoid join together to form a resultant magnetic field lines similar to that of a bar magnet.
2 Increasing the current increases the number of field lines and hence the strength of the magnetic field.
3 A solenoid that has more turns has more field lines when the same current flows through the solenoid.

Questions

1 What happens if you reverse the direction of polarity of the supply?
2 How will the strength of magnetic field change when a soft iron bar is placed inside the solenoid?

Link

Theory Workbook
Worksheet 20A

Electromagnets

A current-carrying conductor in a solenoid is also commonly used in electromagnets. Electromagnets are commonly used in household appliances. An example of an appliance that uses an electromagnet is the circuit breaker shown in Figure 20.10.

① Under normal conditions, when the switch is turned on, current flows through the solenoid.

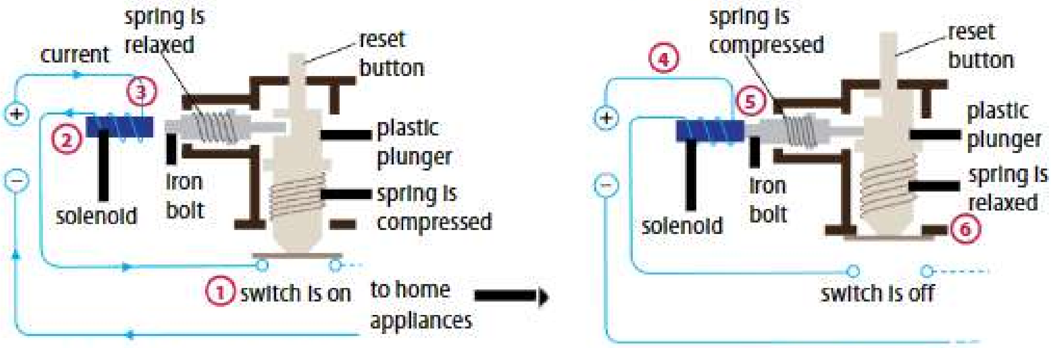
② When the current is below the limit, the magnetic field of the solenoid is weak and does not attract the iron bolt.

③ The solenoid and iron bolt are not in contact. The current flows normally through the circuit.

④ A surge in current occurs when there is a fault.

⑤ If the surge in current exceeds the limit, the solenoid becomes an electromagnet that is strong enough to attract the iron bolt.

⑥ As a result, the plastic plunger is free to move upward as the spring around the plunger extends. This action opens the circuit and cuts the flow of current to the home appliances as well as the solenoid.



(a) Under normal conditions

(b) When a fault occurs

Figure 20.10 How a circuit breaker works

After the fault has been traced, the circuit breaker is switched on again by depressing the reset button. The spring around the iron bolt goes back to its original length and pushes the iron bolt into the catch of the plastic plunger, holding it in place. The circuit breaker is ready to switch off the current in the circuit if there is another surge of current.

Worked Example 20A

Figure 20.11 shows a compass placed on top of a wire AB. What will happen to the compass when current flows from A to B? What will happen if the compass is placed below the wire AB?

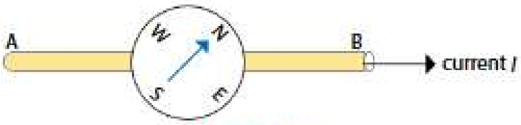


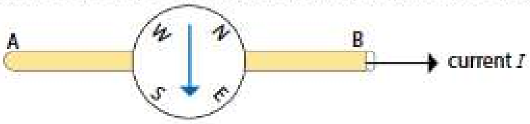
Figure 20.11

Thought Process

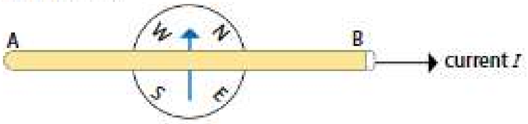
When there is no current flowing, the needle of the compass comes to rest in the north-south direction. When a current flow from A to B, the needle will deflect. The direction of magnetic field is given by the right-hand grip rule. Grip the conductor with your thumb pointing from A to B and the curl of the fingers gives the direction of the magnetic field.

Answer

The deflection of the needle is given by the right-hand grip rule.



When the compass is placed below wire AB, the deflection of the needle is as follows.



Let's Practise 20.1

1 Figure 20.12 shows a current-carrying wire. Draw a top view of the magnetic field pattern that is produced on the paper card.

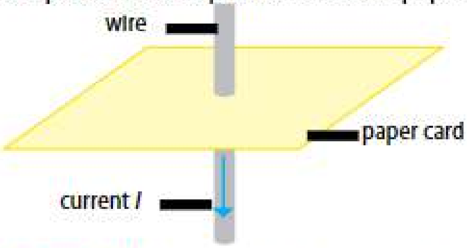


Figure 20.12 Current flowing into paper card

2 Figure 20.13 shows an electromagnet with an iron nail as the core. Describe what happens if:
  (a) the number of turns is increased; and
  (b) another battery is added in series.

3 What would happen if the iron core of a solenoid is replaced by a steel core? Explain your answer.

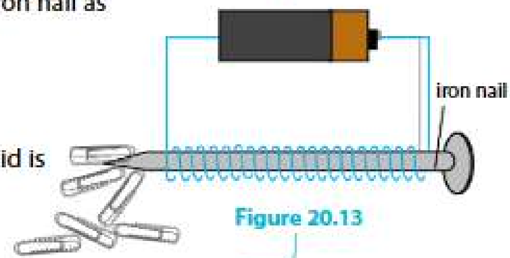


Figure 20.13

Link

Theory Workbook
Worksheet 20B

20.2 When will a Current in a Wire Cause the Wire to Move?

Learning Outcomes

- Describe experiments to show the force on a current-carrying conductor, and on a beam of charged particles, in a magnetic field, including the effect of reversing:
  (i) the current; and
  (ii) the direction of the field.
- Deduce the relative directions of force, field and current when any two of these quantities are at right angles to each other using Fleming's left-hand rule.
- Explain how a current-carrying coil in a magnetic field experiences a turning effect and that the effect is increased by increasing:
  (i) the number of turns on the coil; and
  (ii) the current.
- Describe the action of a split-ring commutator in a two-pole, single-coil motor and the effect of winding the coil on to a soft-iron cylinder.

When a current-carrying conductor is placed inside a solenoid, what is the force it experiences (Figure 20.14)?

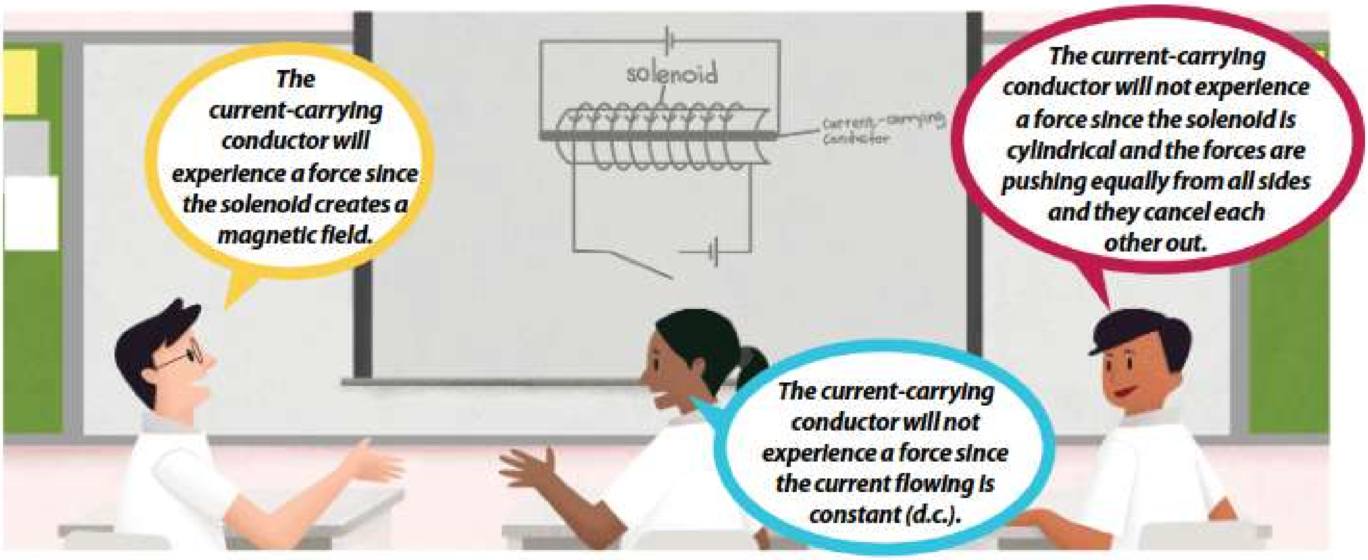


Figure 20.14 Would the conductor in a solenoid experience a force?

A current-carrying conductor will experience a force if the magnetic field applied is perpendicular (or has a component that is perpendicular) to the direction of flow of current. In Figure 20.14, since the magnetic field applied is parallel to the conductor rod, the conductor does not experience a force.

Force on a Current-carrying Conductor

We have seen that a current-carrying conductor can produce a magnetic field. When this magnetic field interacts with another magnetic field, magnetic attraction or repulsion can take place. If the forces of attraction or repulsion are large enough, they will cause a motion. This effect can be demonstrated using the set-up in Figure 20.15.

When the power supply is switched on, the copper wire frame immediately swings (Figure 20.16(a)). If the current is increased, a larger swing is produced (Figure 20.16(b)).

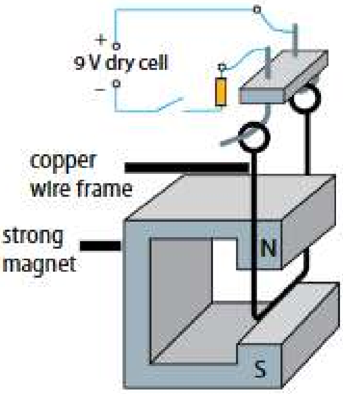
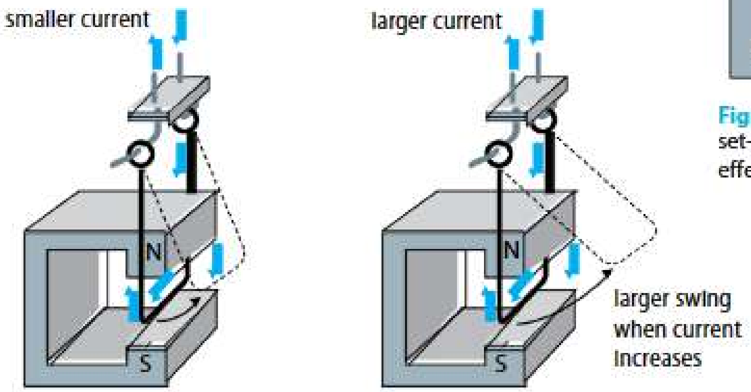


Figure 20.15 Experimental set-up to show the motor effect of electromagnetism



(a) (b)

Figure 20.16 A larger current produces a larger swing.

If we increase the strength of magnetic field by adding more magnets, a larger swing is also produced.

If the connection of the terminals is reversed, the copper wire frame swings in the opposite direction. The copper wire frame will also swing in the opposite direction if the polarity of the magnet is reversed.

In summary, the following conclusions can be made.

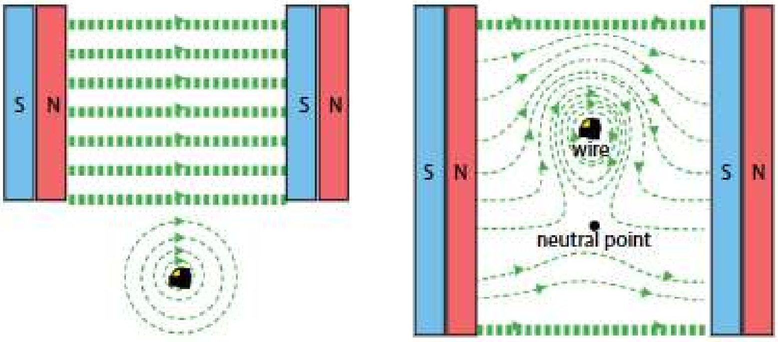
- Increasing the current produces a larger swing.
- Increasing the strength of magnetic field produces a larger swing.
- Reversing the direction of current induces a swing in the opposite direction.
- Reversing the polarity of the magnet also reverses the direction of the swing.

This motion that is created is also known as the **motor effect** or **catapult effect**. When a current-carrying conductor is placed inside a uniform magnetic field, the magnetic fields interact in a manner similar to the pulling of the elastic band of a catapult (Figure 20.17). The current-carrying conductor experiences a force that pushes it out. In Figure 20.15, since the copper wire frame in the set-up is pivoted, it appears to swing out.

Disciplinary Idea

Matters interact through forces and fields.

When a moving charged particle (matter) is placed in an external magnetic field, it experiences a force due to the interaction with the external magnetic field.



(a) Magnetic field before interaction (b) Magnetic field after interaction

Figure 20.17 Magnetic fields interact to create the motor effect or catapult effect.

This phenomenon can also be explained in terms of strength of magnetic field. The magnetic field lines are closer together at the top than they are at the bottom of the conductor (Figure 20.17(b)). This means that the strength of magnetic field is stronger at the top and weaker at the bottom. The wire experiences a force that pushes it downwards.

Helpful Note

We can use the following to help us remember Fleming's left hand rule.

Forefinger — Field
seCond — Current
thuMb — Motion

The direction of the force can be determined using Fleming's left-hand rule. First, the left hand is held out with the forefinger, second finger and thumb perpendicular to each other (Figure 20.18). Next, the first finger is oriented in the direction of the magnetic field from north to south, and the second finger in the direction of conventional current. The resultant force that is induced by the current-carrying conductor will be given by the direction the thumb is pointing to.

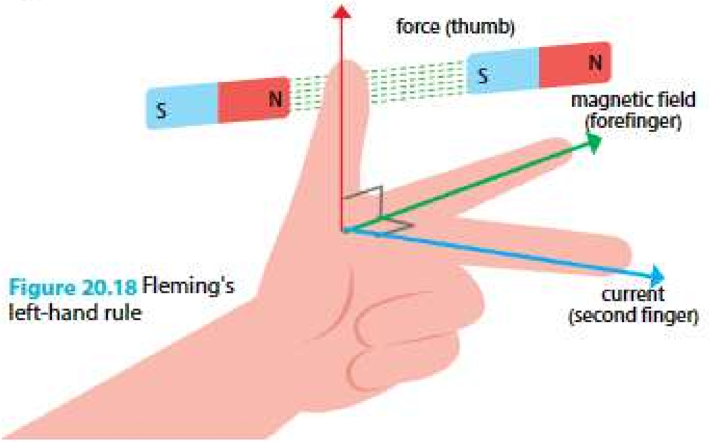


Figure 20.18 Fleming's left-hand rule

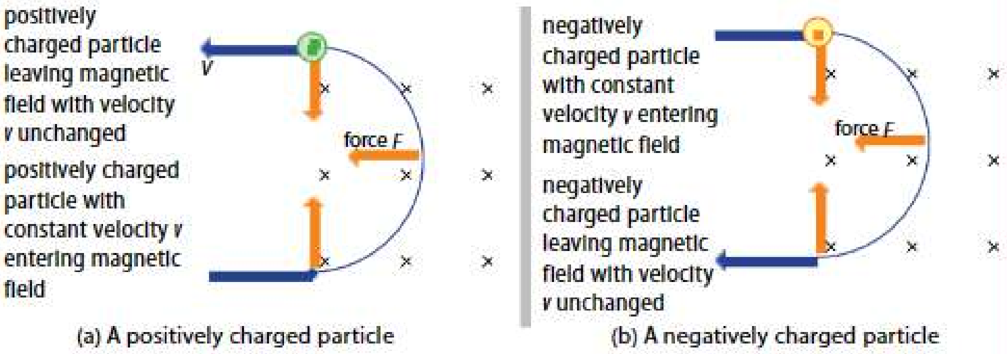
Fleming's left-hand rule is used to find either the direction of the force, magnetic field or current when the directions of two of these are known. The direction of the force, magnetic field or current are at right angles to one another.

Force on a Beam of Charged Particles

A current-carrying wire experiences a force when its current is flowing perpendicularly to the direction of a magnetic field. Similarly, a beam of moving charged particles would also experience a force when a magnetic field is applied perpendicularly to the beam of particles.

Figure 20.19(a) shows the force acting on a positively-charged particle as it moves through a magnetic field. The magnetic field shown is acting into the plane of the paper. The direction of current is the same as the direction of force on the charge, since the charge is positive. As the charge enters the magnetic field, the direction of force on the charge is given by Fleming's left-hand rule and is perpendicular to the path of travel. The resultant path is circular, with the force acting towards the centre of the circle.

Figure 20.19(b) shows the force acting on a negatively-charged particle in the same magnetic field. In this case, the direction of current is opposite to the direction of motion of the charge. Once again, using Fleming's left-hand rule, we can determine the motion as the charge enters the magnetic field. The direction of force on the charge is again perpendicular to the direction of travel, but in the opposite direction to that of Figure 20.19(a). The resultant path is circular, with the force acting towards the centre of the circle.



(a) A positively charged particle entering a magnetic field

(b) A negatively charged particle entering the same magnetic field

Figure 20.19 Oppositely charged particles move in opposite directions in the same magnetic field.

Disciplinary Idea

Microscopic models are often used to explain observable effects.

A stream of moving charges or a current-carrying wire produce a magnetic field. The field interacts with the external fields and the moving charges experience a force due to the external fields. This results in an observable effect, such as the bending of a directed electron beam or a moving conductor, in the presence of an external magnetic field.

Similar to the current-carrying conductor, the force acting on a charged particle:

- increases when the charge on the particle increases;
- increases when the magnetic field increases;
- is in the opposite direction if the particle is oppositely charged; and
- is in the opposite direction if the direction of magnetic field or velocity of charged particle is reversed.

Electric Motors

Having seen how electricity and magnetism produce motion, let us revisit the electric motor mentioned at the beginning of the chapter. In the case of an electric motor, a current-carrying rectangular coil is placed between two permanent magnets (Figure 20.20).

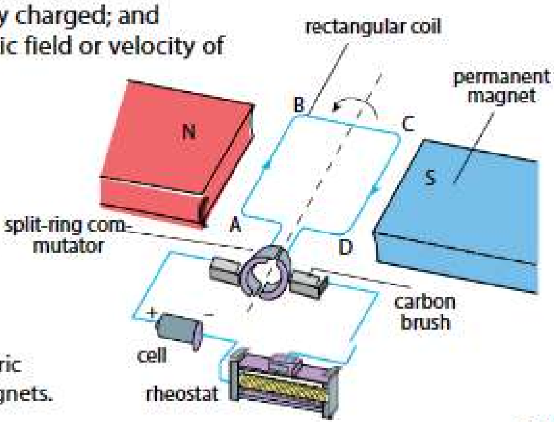


Figure 20.20 Schematic diagram of an electric motor. An electric motor has a current-carrying coil between two permanent magnets.

Link

Recall from Chapter 5: A moment is a turning effect created by a force about a pivot and it generates a rotation.

The current-carrying coil experiences an equal force on parts AB and CD of the wire. This force is created by the motor effect on each side of the coil. The forces produce a turning effect that is equal in magnitude on each wire. This causes the coil to turn in an anticlockwise direction as shown in Figure 20.21.

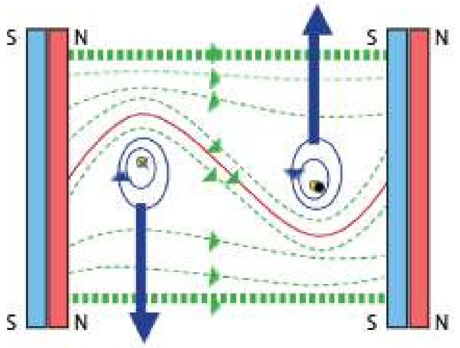


Figure 20.21 Just like a current-carrying conductor in a magnetic field, the coil experiences a pair of forces acting on both sides of the coil.

If the number of turns in the coil increases, the resultant force also increases, since it is the sum of the individual force acting on each turn of the coil.

If we add a soft iron cylinder into the core of the wire coil, the turning effect on the motor would also increase. A soft iron core concentrates the magnetic field lines and thus increases the strength of magnetic field (Figure 20.22). A stronger magnetic field gives rise to a stronger force.

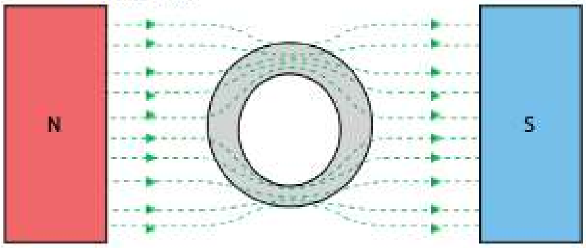


Figure 20.22 A soft iron cylinder concentrates the magnetic field lines and increases the strength of magnetic field.

The turning effect can be increased by:
- increasing the number of turns in the coil;
- increasing the current; and
- adding a soft iron cylinder.

In order to maintain the anticlockwise rotation in Figure 20.20, the current flowing in the coil must always flow clockwise. This is achieved through the use of a split ring commutator. The split ring has two splits or gaps.

As the coil rotates, it momentarily disconnects itself from the carbon brushes. At this point, the current from the cell is cut off from the coil and the momentum of the coil carries it past this position.

Once the coil passes the vertical position, the split ring commutator comes into contact with the carbon brushes again. The current in the coil continues to flow in a clockwise manner.

Link

Practical Workbook
Experiment 20A

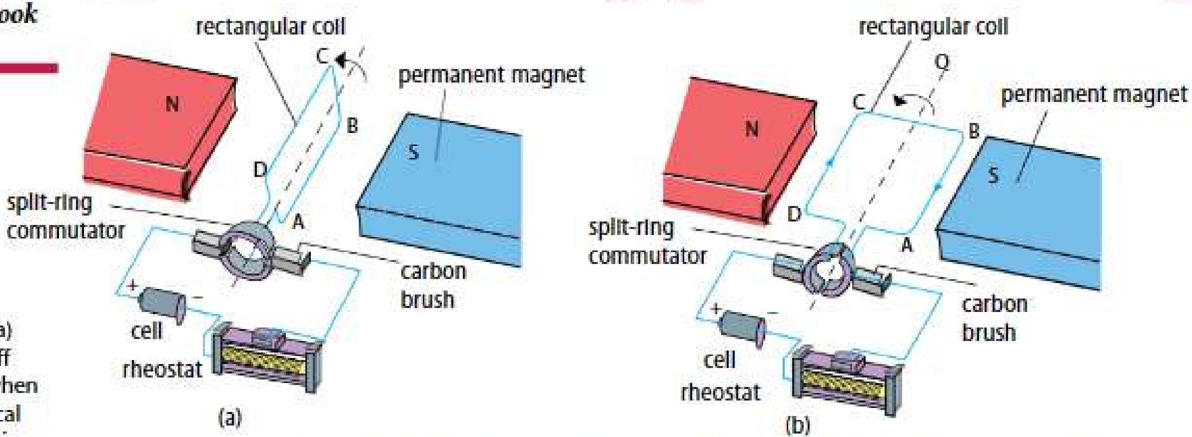


Figure 20.23 (a) Supply is cut-off momentarily when the coil is vertical and (b) current is maintained in a clockwise manner in the coil

The direction of the current flowing through parts AB and CD of the coil has reversed. In Figure 20.20, current flows from A to B and from C to D. After half a revolution, the current flows from B to A and from D to C (Figure 20.23(b)). The split-ring commutator enables this to happen. Therefore, we say that the function of the split-ring commutator is to reverse the direction of the current in the coil every half a revolution.

Worked Example 20B

(a) State what will happen to the soft iron core in Figure 20.24 when the switch is closed, stating the positions of the north and south poles.

(b) Draw a front view of the magnetic field pattern that is produced by the soft iron core.

(c) Explain what will happen to the conductor.

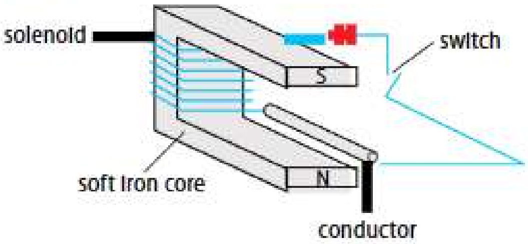


Figure 20.24

Thought Process

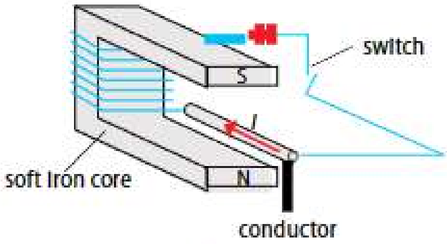
(a) When the switch is closed, current will flow from the positive terminal of the cells. It will pass through the conductor before entering the coils of the solenoid. The direction of the magnetic field can be determined by the right-hand grip rule since the direction of current flowing into the solenoid is known.

(b) The magnetic field lines are drawn from north to south pole.

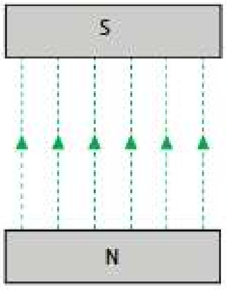
(c) A current-carrying conductor in the presence of a magnetic field will experience a force. The direction of this force is given by Fleming's left-hand rule.

Answer

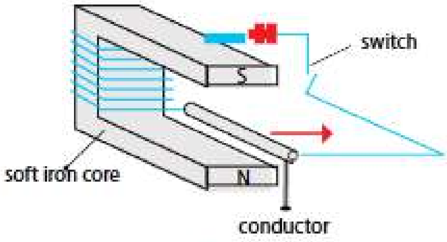
(a) When the switch is closed, the soft iron core becomes magnetised by the solenoid. The north pole is at the bottom and the south pole is at the top as shown on the right.



(b) The magnetic field pattern produced by the soft iron core is shown below.



(c) The current-carrying conductor experiences a force as it is in a magnetic field. The conductor moves to the right based on Fleming's left-hand rule.



Let's Practise 20.2

1 A current-carrying conductor generates concentric magnetic fields (Figure 20.25(a)). Draw the resultant magnetic field when this conductor is placed in a uniform magnetic field in Figure 20.25(b).

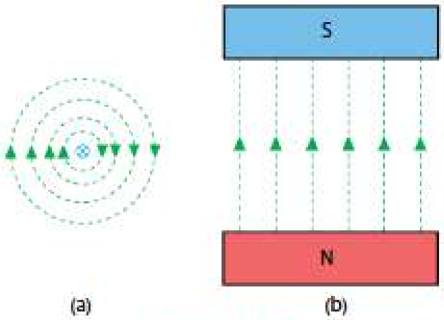


Figure 20.25

2 With reference to Figure 20.25, explain what will happen to the conductor when it is placed in the uniform magnetic field.

Link

Theory Workbook
Worksheet 20C
Let's Assess
Let's Reflect

Past to Present

In 1821, Michael Faraday demonstrated that a vertically suspended wire moves in a circular orbit around a magnet. This was the first electric motor that was ever created (Figure 20.26(a)). Ten years later, Thomas Davenport, a blacksmith, invented the first battery-powered electric motor (Figure 20.26(b)). This electric motor has four coils of wire placed between two electromagnets. Using his electric motor design, Davenport also built a an electric locomotive. The work of Michael Faraday and Thomas Davenport paved the way for the development of the modern electric motors (Figure 20.26(c)). Today, electric motors are used in many different electrical appliances such as drills and blenders.

(a) Faraday's electric motor

(b) First battery-powered electric motor

(c) Modern electric motor

Figure 20.26 Transformation of electric motors

Cool Career

EMI/EMC Engineer

An EMI/EMC engineer conducts tests and ensure EMI/EMC of an appliance is kept within industry standards. What is EMI or EMC?

EMI stands for electromagnetic interference and EMC stands for electromagnetic compatibility. EMI/EMC engineers are needed for the design, testing and for checking the compliance of almost every electronic product. This is because the current flowing in the circuits may introduce undesirable electromagnetic fields that affect the performance or reliability of such products. Figure 20.27 shows a symbol that can be found in home appliances, which is a marking for electromagnetic compatibility.

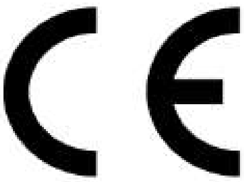
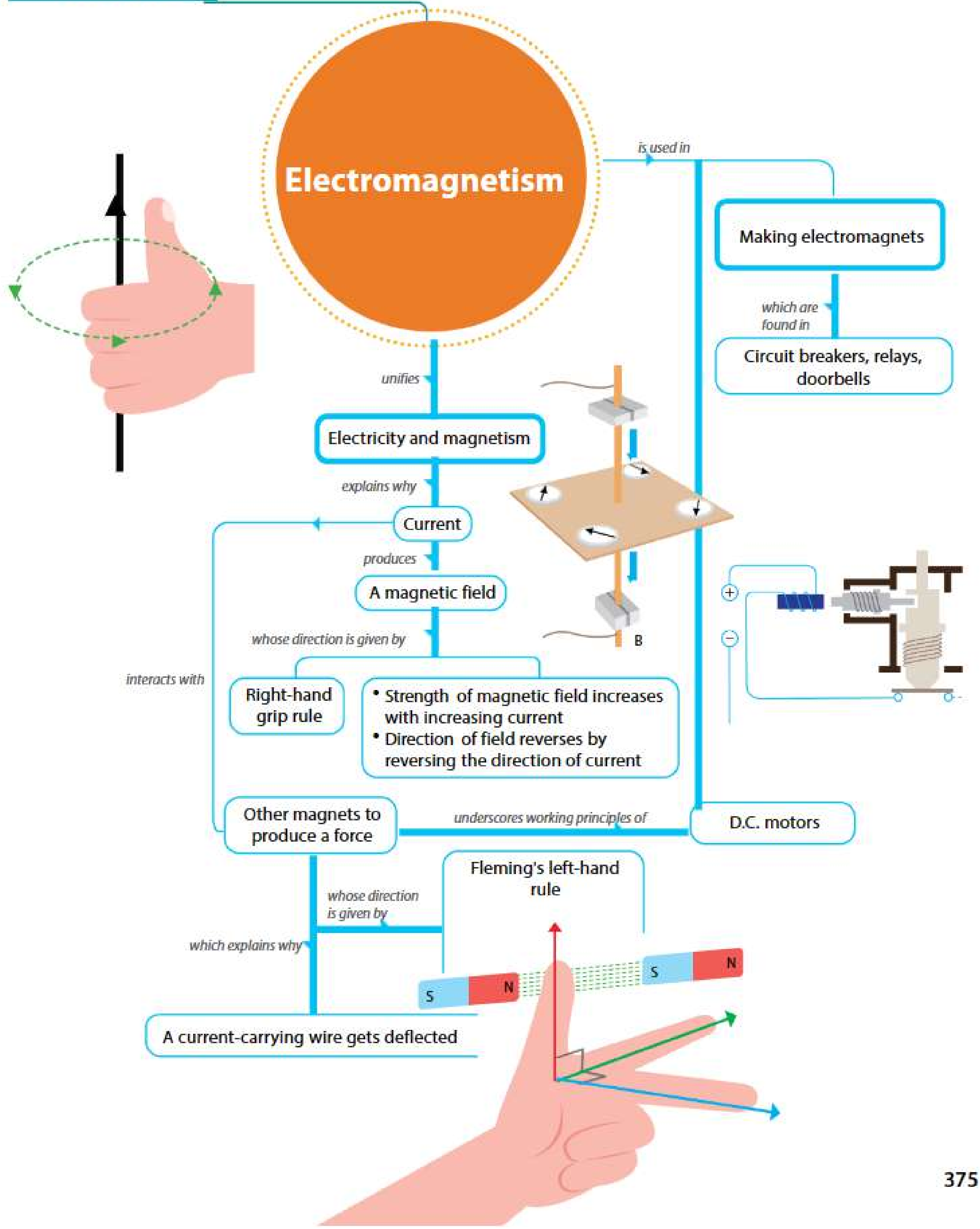


Figure 20.27 A symbol found on home appliances that symbolises electromagnetic compatibility

Let's Map It



Electromagnetism

unifies

Electricity and magnetism

explains why

Current

produces

A magnetic field

whose direction is given by

Right-hand grip rule

- Strength of magnetic field increases with increasing current
- Direction of field reverses by reversing the direction of current

interacts with

Other magnets to produce a force

whose direction is given by

Fleming's left-hand rule

which explains why

A current-carrying wire gets deflected

is used in

Making electromagnets

which are found in

Circuit breakers, relays, doorbells

D.C. motors

underscores working principles of

Let's Review

Section A: Multiple-choice Questions

1 P and Q in Figure 20.28 represent two long parallel straight wires with currents flowing into the plane of the paper. What is the direction of the force exerted on Q?

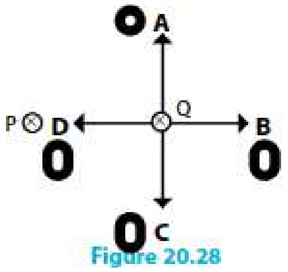


Figure 20.28

2 Why is steel **not** suitable as the core of an electromagnet to separate magnetic metals from other materials in the junkyard?

○ A It has a high density.
○ B It is a hard magnetic material.
○ C It is a good conductor of electricity.
○ D It has a high melting point.

3 An experiment was carried out to investigate the effect of a magnetic field on a current-carrying conductor (Figure 20.29). The set-up was placed on a table.

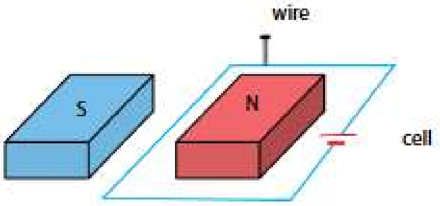


Figure 20.29

No motion was observed because ______

○ A the magnets were too weak
○ B the current was too weak
○ C the polarity of the magnet should have been reversed
○ D the magnets were too far apart

4

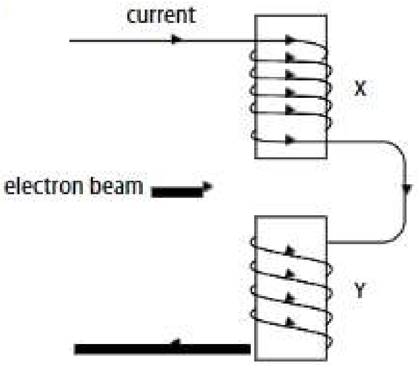


Figure 20.30

In Figure 20.30, the electron beam will experience a force

○ A towards X.
○ B towards Y.
○ C into the paper.
○ D out of the paper.

5 Which two of the following scenarios correctly describes Figure 20.31?

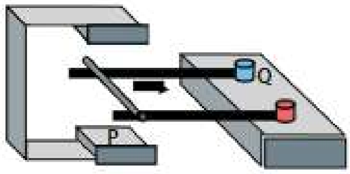


Figure 20.31

1 P is the north pole and Q is a positive terminal.
2 P is the north pole and Q is a negative terminal.
3 P is the sorth pole and Q is a positive terminal.
4 P is the south pole and Q is a negative terminal.

○ A 1 and 3
○ B 1 and 4
○ C 2 and 3
○ D 2 and 4

Section B: Structured Questions

1 Figure 20.32 shows a doorbell. Explain how it operates.

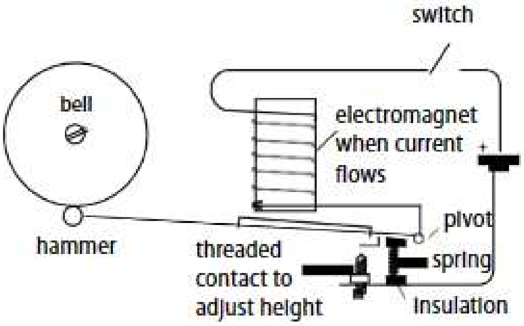


Figure 20.32

2 (a) John wants to make section X of a steel block a north pole and section Y a south pole using a solenoid (Figure 20.33). Explain how it can be done, paying attention to the direction of current.

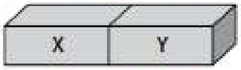


Figure 20.33

(b) In Figure 20.34, draw the magnetic field lines interactions between the bar magnet and the electromagnet.

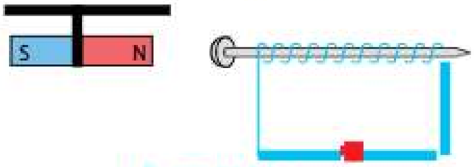


Figure 20.34

3 In Figure 20.35, draw the path taken by the electron beam as it enters a region with magnetic field into the paper.

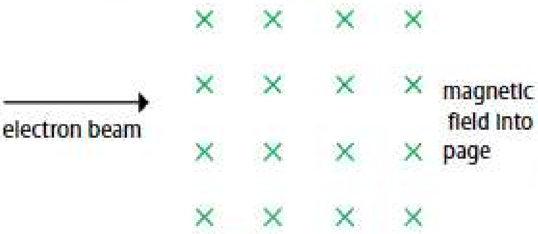


Figure 20.35

4 Two pieces of soft iron are placed inside a coil of wire wrapped around a plastic tube and are not too far apart (Figure 20.36). What will happen to the iron cores when the switch is turned on? Explain your answer.

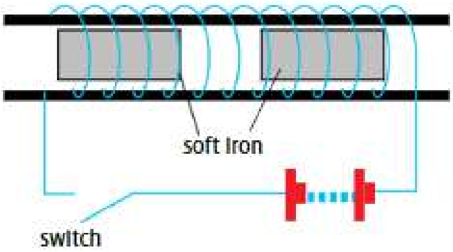


Figure 20.36

5 A student set up the following experiment shown in Figure 20.37.

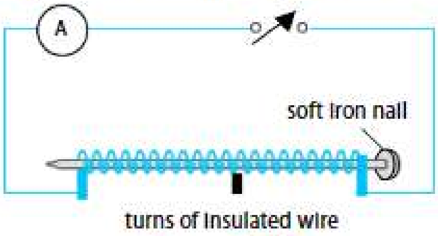


Figure 20.37

First, she investigated the effects of current on the strength of the electromagnet and recorded her results in Table 20.1.

Table 20.1

Current / A	Number of Paper Clips Picked Up By the Electromagnet
0.5	1
1.0	5
1.5	11
2.0	18
2.5	22
3.0	25

(a) What can be concluded from the data collected in Table 20.1? Explain why this is so.

Next, the student investigated the effects on the number of turns on the strength of the electromagnet and recorded her results in Table 20.2.

Table 20.2

Number of Turns	Number of Paper Clips Picked Up By the Electromagnet
10	5
15	11
20	17
25	22
30	27
35	33

(b) What can be concluded from the data collected in Table 20.2? Explain why this is so.

(c) How would her results be affected if she uses a steel nail instead?

Section C: Free-response Questions

1 Figure 20.38 shows an incomplete diagram of a d.c. motor.

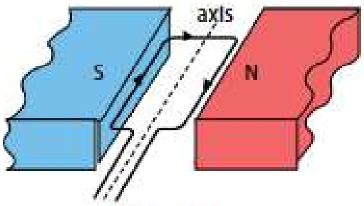


Figure 20.38

(a) Complete the diagram by drawing in the split ring commutator, carbon brushes and d.c. supply.

(b) Determine the direction of motion of the coil.

(c) How can the turning effect of the motor be strengthened?

(d) Suggest how the direction of the motor can be reversed.

2 Figure 20.39 shows an ignition circuit of a vehicle.

(a) Explain how the circuit operates.

(b) Name a material you would use as the core of the electromagnet. Explain your choice clearly.

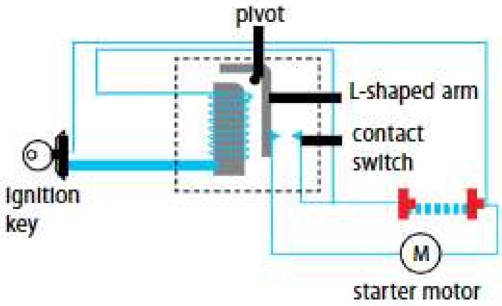


Figure 20.39

CHAPTER

21 Electromagnetic Induction

What You Will Learn

- How are electric currents and magnetic fields related and how do they interact?
- When will movement cause a current to be produced?
- Why is current always generated in alternating form?

This small building on the left is a common sight among housing estates in Singapore. Have you ever wondered what it is?

This is a power substation. Power substations are part of the electrical power transmission and distribution network in Singapore. They are used to step down the voltages transmitted to 230 V. The stepped down voltages are then supplied to our homes.

The change in voltage is achieved through a device known as transformers. Transformers work on the principles of electromagnetic induction. Without this, we will not have the modern convenience of electricity in our homes. What is electromagnetic induction?

21.1 How Are Electric Currents and Magnetic Fields Related and How Do They Interact?

Learning Outcome

- Deduce from Faraday's experiments on electromagnetic induction or other appropriate experiments:
  - (i) that a changing magnetic field can induce an e.m.f. in a circuit;
  - (ii) that the direction of the induced e.m.f. opposes the change producing it; and
  - (iii) the factors affecting the magnitude of the induced e.m.f.

You may have noticed that an electric guitar is different from an acoustic guitar. It does not have a sound hole, but a pick up as shown in Figure 21.1. The pickup is used to produce the sounds of an electric guitar and it works on the principles of electromagnetic induction. What exactly is electromagnetic induction?

Figure 21.1 An electric guitar pickup, which comprises six permanent magnets and coils of wire around a bobbin

Following Oersted's experimental demonstration that a current produces a magnetic field in 1820, several scientists began studying the relationship between electricity and magnetism. Among them was a scientist named Michael Faraday.

Faraday discovered that when he moved a magnet in and out of a coil, it induced a deflection on the galvanometer connected to the coil (Figure 21.2). When the magnet was moved towards the coil, the galvanometer deflected in one direction. When the magnet was moved away from the coil, the galvanometer deflected in the opposite direction. If the magnet was stationary, no deflection was recorded. He concluded that 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.

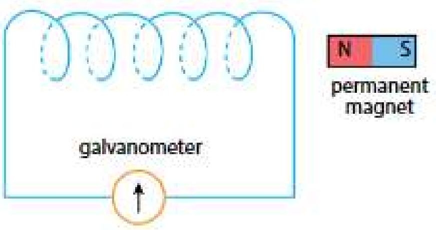


Figure 21.2 Schematics of the experimental set-up by Michael Faraday

Let's Investigate 21A

Aim
To demonstrate the effects of electromagnetic induction

Procedure

1. Set up the apparatus shown in Figure 21.3.
2. Move the south pole of a permanent bar magnet into the solenoid. Take note of any deflection on the galvanometer.
3. Once inside, hold the magnet still and note any deflection on the galvanometer.
4. Move the south pole of a permanent bar magnet out of the solenoid. Take note of any deflection on the galvanometer.
5. Repeat steps 2 to 4 using the north pole of the bar magnet.

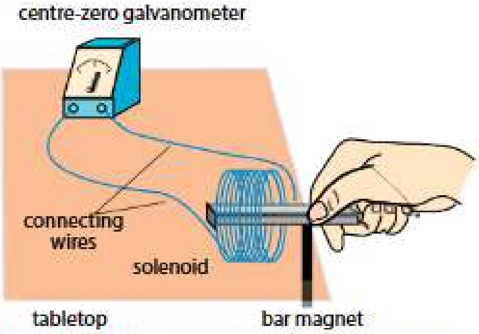


Figure 21.3 Experimental set-up to demonstrate the effects of electromagnetic induction

Observations

1. When the south pole of the magnet is moved towards the solenoid, the galvanometer deflects to one side, indicating the presence of a current.
2. The direction of this induced current creates a south pole in the solenoid that faces the south pole of the moving magnet (Figure 21.4).

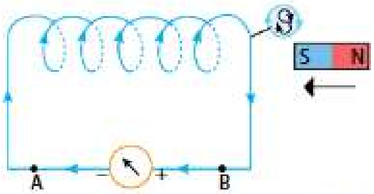


Figure 21.4 The induced current produces a south pole that opposes the movement of the approaching south pole.

3. When the magnet is stationary, the galvanometer does not deflect, indicating that no current is produced.
4. When the south pole of the magnet is withdrawn from the solenoid, the galvanometer deflects in the opposite direction, indicating that the direction of current has reversed. This time, the direction of induced current creates a north pole in the solenoid that faces the south pole of the withdrawing magnet (Figure 21.5).

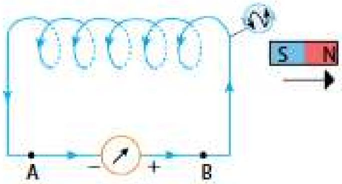


Figure 21.5 The induced current produces a north pole that opposes the movement of the withdrawing south pole.

5 When the north pole of the magnet is moved towards the solenoid, the galvanometer deflects, indicating the presence of a current that will generate a north pole in the solenoid (Figure 21.6)

6 Again, when the magnet is stationary, the galvanometer does not deflect, indicating that no current is produced.

7 When the north pole of the magnet is withdrawn from the solenoid, the galvanometer deflects in the opposite direction, indicating that the current has reversed. This time, the direction of induced current creates a south pole in the solenoid that faces the north pole of the withdrawing magnet (Figure 21.7).

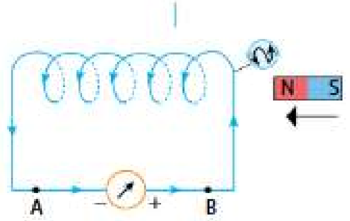


Figure 21.6 The induced current produces a north pole that opposes the movement of the approaching north pole.

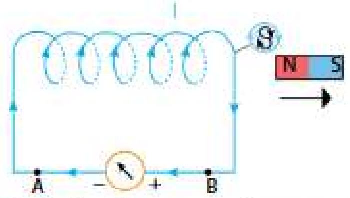


Figure 21.7 The induced current produces a south pole that opposes the movement of the withdrawing north pole.

Questions

1 What happens if the speed of the movement is increased?

2 What happens if a solenoid with more coils is used?

3 What happens if a stronger magnet is used?

Disciplinary Idea

Matter interacts through forces and fields.

In this case, a changing magnetic field, produced by the movement of a magnet, can induce an e.m.f. in an electrical conductor. This is recorded as a deflection in the galvanometer.

The observations in Let's Investigate 21A provide us with a basic understanding 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. **Magnetic flux** is the magnetic field in a given area.

▶ **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.

According to Faraday's law, an unchanging magnetic field will not induce any current. This is why the galvanometer does not deflect when the magnet is inside the coil. This is also why a deflection is observed whenever the magnet is moved, regardless of the direction of movement. It also states that the faster the magnet is moved in and out of the solenoid, the greater the induced e.m.f..

Lenz's law is a consequence of the law of conservation of energy. According to the law of conservation of energy, the total amount of energy in the universe must remain constant. If the magnetic field associated with the current moves in the same direction as the change in magnetic field that created it, these two magnetic fields would combine to create a net magnetic field that would induce a current with twice the magnitude. Energy would have been created. This would violate the law of conservation of energy. Therefore, a small amount of work is done when the magnet is pushed into or pulled out of the coil.

Disciplinary Idea

Conservation laws constraint the changes in a system.

The induced current in the solenoid must oppose the relative motion of the magnet. As a result of this opposition, work is done. The work that is done against magnetic force if transferred electrically to the circuit. This gives rise to the induced current.

The magnitude of the induced e.m.f increases if:

- the speed of the relative motion between the coil and the magnet is increased;
- the number of turns of the coil is increased; or
- the strength of the magnet is increased.

What happens when a magnet is dropped through a copper tube (Figure 21.8)?

Figure 21.8 Dropping a magnet through a copper tube

When a magnet is dropped through a thick copper tube, a current is induced in the copper tube and a magnetic field is generated by the induced current. This induced current produces a magnetic field that opposes the direction of the falling magnet, causing it to slow down.

It is impossible to overstate the significance of Faraday's discovery. Electromagnetic induction makes generators and transformers possible. It is the fundamentals of production and transmission of electricity.

Link

Practical Workbook
Experiment 21A

Let's Practise 21.1

Figure 21.9 shows a bar magnet that is suspended by a spring. The spring is set into oscillation.

1 How would you increase the magnitude of the induced e.m.f. in Figure 21.9?

2 If a galvanometer is connected in series with the solenoid, explain what would be observed.

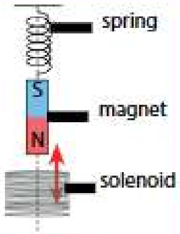


Figure 21.9

Link

Theory Workbook
Worksheet 21A

21.2 When Will Movement Cause a Current to be Produced?

Learning Outcomes

- Describe a simple a.c. generator (rotating coil or rotating magnet) and the use of slip rings (where needed).
- Sketch a graph of voltage output against time for a simple a.c. generator.

In Section 21.1, we saw that a moving magnet induces an e.m.f. or a current in a nearby conductor. Likewise, a moving conductor in the presence of a magnetic field will also produce an e.m.f. or a current in the conductor. This is referred to as the generator effect.

Just as in the motor effect, there is a relationship between the direction of the applied force, the magnetic field and the current. This relationship is given by Fleming's right-hand rule (Figure 21.10).

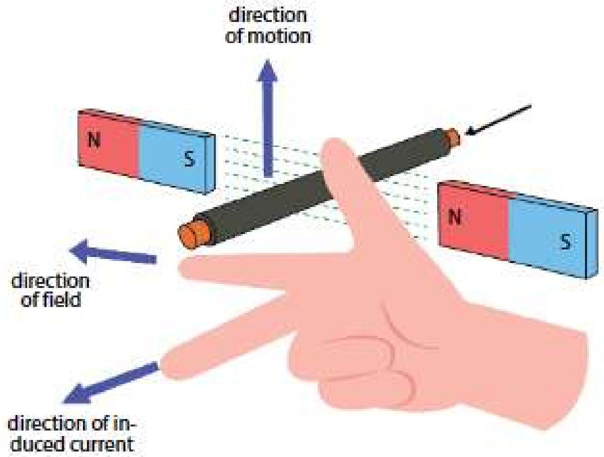


Figure 21.10 Fleming's right-hand rule is used to determine the direction of the induced current.

Helpful Note

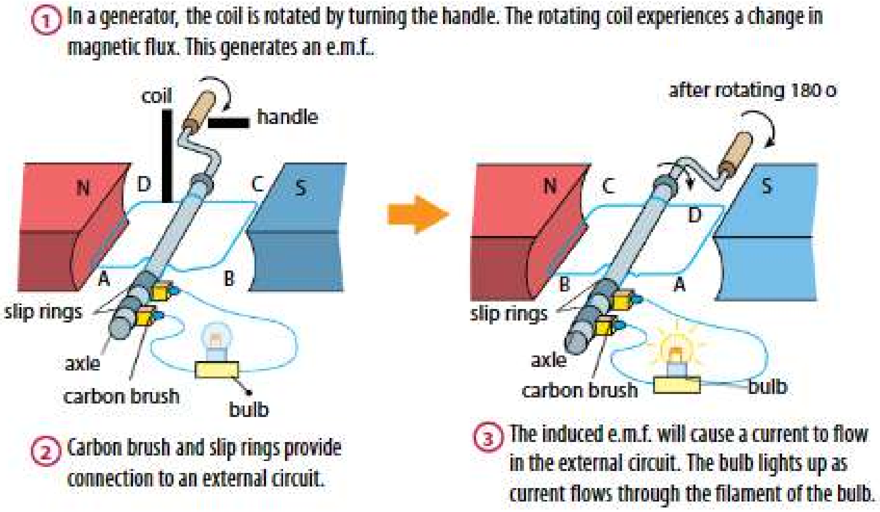
We can use the following to help us remember Fleming's right hand rule.

Forefinger — Field
seCond — Current induced
thuMb — Motion.

The direction of conventional current is determined using Fleming's right-hand rule. First, the right hand is held out with the forefinger, second finger and thumb perpendicular to each other. Next, the thumb is pointed in the direction of motion of the conductor, and first finger in the direction of the magnetic field, from north to south. The direction of conventional current is given by the direction the second finger is pointing to.

Fleming's left-hand rule is used for electric motors, while Fleming's right-hand rule is used for generators. It is important not to confuse the two.

Consider the case of a rectangular coil that is mounted on an axle rotating between two permanent magnets (Figure 21.11).



① In a generator, the coil is rotated by turning the handle. The rotating coil experiences a change in magnetic flux. This generates an e.m.f..

② Carbon brush and slip rings provide connection to an external circuit.

③ The induced e.m.f. will cause a current to flow in the external circuit. The bulb lights up as current flows through the filament of the bulb.

Figure 21.11 Operations of an a.c. generator

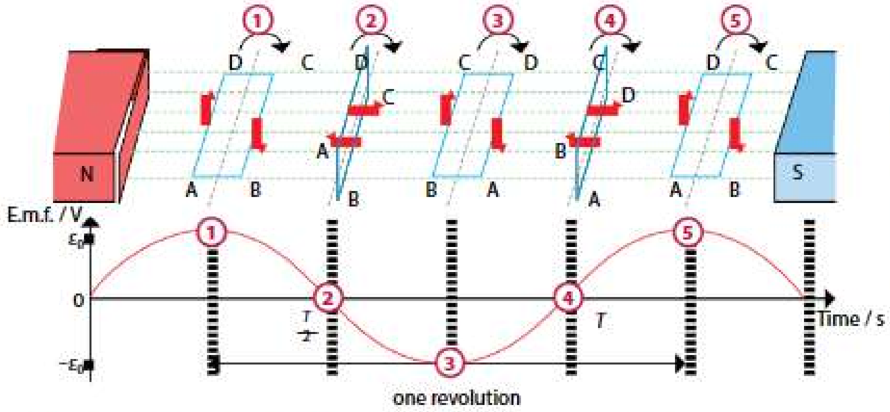
Due to the rotation, a continuous flow of current is induced in the rectangular coil. The direction of the current flow is given by Fleming's right-hand rule and is in the direction of A to D. As the coil flips after half a revolution, the induced current changes direction and is now flowing from D to A. Similarly, the current is initially flowing from C to B. After half a revolution, the current flows from B to C. The current alternates and is known as an **alternating current**.

An alternating current is produced by an alternating induced e.m.f. Therefore, such generators are more specifically termed as alternating current (a.c.) generators or alternators.

An important difference between the d.c. motor and the a.c. generator is the use of slip rings in an a.c. generator. Slip rings are important as they make sure that the ends of the rotating rectangular coil do not get twisted together as the rectangular coil rotates. Slip rings also provide the electric contact with the brushes so that electric current can flow continuously in the a.c. generator.

As the current and voltage of an a.c. generator alternates, the e.m.f. goes through a maximum to zero to minimum transition. Indeed, as the coil rotates through different positions, the amount of induced e.m.f. changes (Figure 21.12 on the next page). The amount of e.m.f. induced also depends on the rate at which the coil cuts the magnetic field lines.

At position ①, the rate at which AD and BC cut the magnetic field lines is the greatest since the movement of the coil is perpendicular to the magnetic field lines. Hence, the magnitude of the induced e.m.f. is also the greatest.



At position ②, AD and BC do not cut the magnetic field lines since the movement of the coil would be parallel to the direction of field lines. Hence the magnitude of the induced e.m.f. is zero.

At position ③, the rate at which AD and BC cut the magnetic field lines is the greatest. However, since the induced current in the coil is flowing in the reverse direction, the induced e.m.f. is also in the opposite direction to that at position ①. The e.m.f. is negative to indicate the change in direction.

At position ④, AD and BC once again do not cut the magnetic field lines. Hence, the magnitude of the induced e.m.f. is zero.

At position ⑤, the coil returns to its starting point after having completed one revolution. The rate at which AD and BC cut the field lines is once again the greatest and the magnitude of the induced e.m.f. is the greatest.

Figure 21.12 A sinusoidal e.m.f. is produced as the coil rotates through different positions

From Figure 21.12, we can see that if the coil is rotated through one complete revolution, the induced e.m.f. also moves through one complete cycle of a sinusoidal wave form. The time it takes to complete one cycle is the periodic time T. The number of revolutions the coil makes in one second is its frequency.

Worked Example 21A

An a.c. generator produces an induced e.m.f. of E_0 V with a periodic time of T s. Draw the waveform if:

(a) the number of turns of the coil is doubled; and

(b) the frequency of the rotation of the coil is doubled.

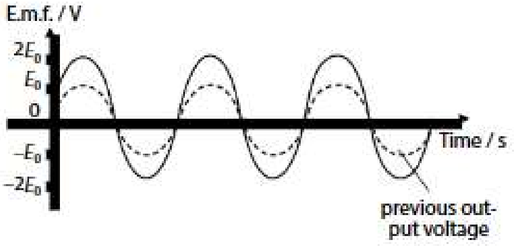
Thought Process

(a) If the number of turns on the coil is doubled, the induced e.m.f. should also be doubled, i.e. $2E_0$. This is because the resultant e.m.f. is the sum of the e.m.f. of the individual turns, which are connected in series. Since the a.c. generator produces a sinusoidal induced e.m.f., the amplitude of the induced e.m.f. should be doubled while the period of the waveform should remain the same.

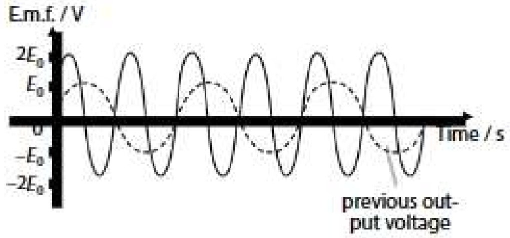
(b) If the frequency of the rotation of the coil is doubled, then the induced e.m.f. should also be doubled, i.e. $2E_0$. This is because the rate of change at which the coil cuts the magnetic field lines is doubled. Since the a.c. generator produces a sinusoidal induced e.m.f., the amplitude of the induced e.m.f. should be doubled. At the same time, since the frequency is doubled, the periodic time should be half the original period time.

Answer

(a) Assuming that the coil was initially in a vertical position, the induced e.m.f. waveform is as follows:



(b) Assuming that the coil was initially in a vertical position, the induced e.m.f. waveform is as follows:



Let's Practise 21.2

1 A small a.c. generator produces a voltage of 40 mV. If the frequency of revolution is 5 Hz, sketch a graph of voltage output against time. Assume that the coil was initially in a horizontal position.

2 Sketch on the same graph in **Question 1**, the voltage output against time for the same a.c. generator if the frequency is halved.

Link

Theory Workbook
Worksheet 21B

Tech Connect

The underlying principle behind wireless charging is electromagnetic induction (Figure 21.13). Alternating current in the transmitter coil of the charging pad produces changing magnetic flux. The changing magnetic flux extends to the receiver coil in the device, inducing current in the receiver coil. When it comes to wireless charging, the first thing that comes to mind is the wireless charging of smartphones. However, wireless charging of electric vehicles is where the current research is focused on (Figure 21.14). This is because wireless charging still has a lot of limitations in the amount of power it can transfer and also the distance from the charger to the device has to be rather short. This technology is not limited to just wireless charging. Can you think of some possible applications of wireless power transmission?

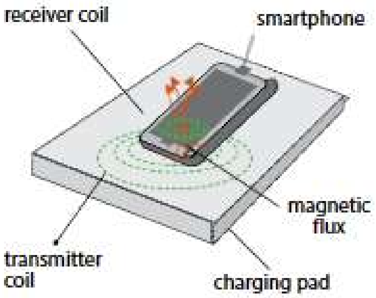


Figure 21.13 Energy is transmitted from the transmitter coil to the receiver coil by electromagnetic induction.

Figure 21.14 Next generation electric vehicles may be wirelessly charged.

21.3 Why Is Current Always Generated in Alternating Form?

Learning Outcomes

- Describe the structure and principle of operation of a simple iron-cored transformer as used for voltage transformations.
- Recall and apply the equations $\frac{V_p}{V_s} = \frac{N_p}{N_s}$ and $V_pI_p = V_sI_s$ to new situations or to solve related problems.
- Describe the energy loss in cables and deduce the advantages of high voltage transmission.

Besides his experiments on the first electric motor and electromagnetic induction, Faraday also created the first ever electric **transformer**. Figure 21.15 shows a schematic diagram of Faraday's set-up.

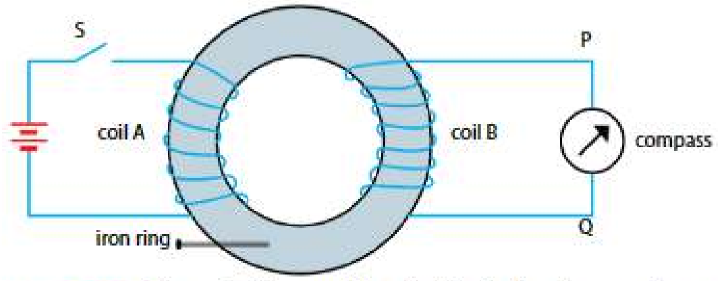


Figure 21.15 Schematic diagram of Faraday's induction ring experiment

A compass is placed on top of wire PQ. If the needle of the compass deflects, it means that there is a current flowing in PQ since a current generates a magnetic field.

Faraday observed that when the switch was closed, the needle of the compass deflected momentarily in one direction and returned to its resting position. When the switch was opened, the needle of the compass deflected momentarily again in the opposite direction and returned to its resting position.

The closing and opening of the switch cause the magnetic field in the ring to change. The strength of magnetic field increases as current flows into coil A and then decreases as current is reduced to zero. These changes in magnetic field induce a current flowing in coil B and cause the needle of the compass to deflect.

When the switch is closed, the induced current in coil B generates a magnetic field that opposes the increase in current in coil A, as described by Lenz's law. When the switch is opened, the induced current in coil B generates a magnetic field that opposes the decrease in current in coil A. Hence, the needle of the compass deflects in different directions.

This experiment came to be known as Faraday's induction ring experiment.

Faraday's induction ring experiment paved the way for the development of transformers.

A transformer is a device that can change a high alternating voltage to a low alternating voltage, or vice versa.

Electricity supply in Singapore is transmitted at 400 kV. The voltage is stepped down through a series of transformers and eventually reaches the homes at 230 V.

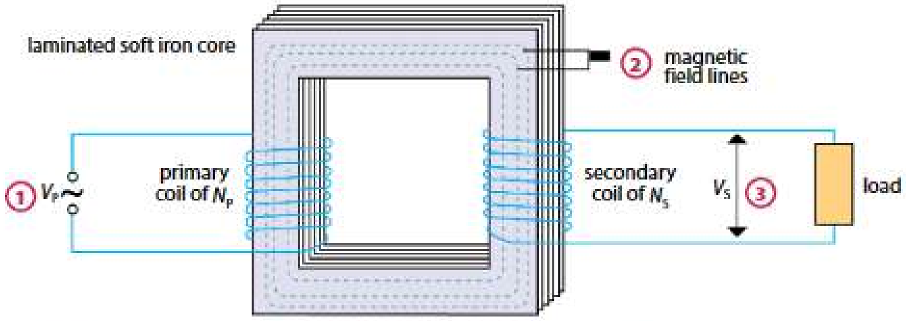
A transformer can change a high alternating voltage (at low current) to a low alternating voltage (at high current) or vice versa.

Figure 21.16 shows the basic structure of a transformer. A transformer is made of two coils of wire called the primary coil and secondary coil. The primary coil is connected to an a.c. input and the secondary coil is connected to a load (output). These coils are wound around a laminated soft iron core.

Disciplinary Idea

Waves can transfer energy without transferring matter.

Changes in magnetic flux linkage can propagate through a vacuum (no medium is required), but the strength of the magnetic fields is greatly enhanced by magnetic materials such as a soft iron core.



① An alternating input V_p causes the magnetic field of the primary coil to increase and decrease continuously.

② The changing magnetic field is directed towards the secondary coil through the laminated soft core.

③ The changing magnetic field induces an e.m.f. V_s and current in the secondary coil.

Figure 21.16 A transfomer is made up of a laminated coil and two coils of wire

The soft iron core is made up of thin sheets of soft iron, laminated together by coats of lacquer. Lamination reduces the transfer of energy to the internal (thermal) store by **eddy currents**, which are local induced electric currents that flow in loops. Lamination cuts off the path taken by an eddy current, keeping these induced currents small. As a result, the unwanted energy transfer is low. Without lamination, large eddy currents are produced and the transfer of energy to the internal store would be larger than with lamination.

Word Alert

Eddy: circular movement

Soft iron is used because it is easily magnetised and demagnetised. If a hard magnetic material is used, the magnetic field lines may not change as they tend to form permanent magnets. The soft iron core also tends to concentrate the magnetic field lines within itself, and this improves the link between the primary and secondary coils.

The changing magnetic field lines in the primary coil is linked to the secondary coil through the soft iron core. This changing magnetic flux induces a voltage and current on the secondary coil. As a result, energy is transferred from the primary coil to the secondary coil.

The voltages of the primary and secondary coils are related by:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

where V_s = secondary (output) voltage (V)
V_p = primary (input) voltage (V)
N_s = number of turns in secondary coil
N_p = number of turns in primary coil

If $N_s > N_p$, the secondary (output) voltage will be greater than the primary (input) voltage. This is a **step-up transformer**.

Conversely, if $N_p > N_s$, the secondary (output) voltage will be smaller than the primary (input) voltage. This is a **step-down transformer**.

We can see from the mathematical relationship that the output voltage depends on the ratio of the number of turns. That is,

$$V_s = \frac{N_s}{N_p} V_p$$

In a transformer, the laws of conservation of energy always applies. A higher output voltage does not mean that energy is created. The rate of energy transferred, or power transferred, from the primary side to the secondary side is governed by the following relationship:

$$V_p I_p = V_s I_s$$

where I_p = primary (input) current (A)
I_s = secondary (output) current (A)

The above relationship holds if and only if there are no energy losses in the system. That is, all the energy that is applied to the primary coils are transferred to the secondary coil. We call such a transformer an ideal transformer.

For an ideal transformer, we can rearrange the relationship such that:

$$\frac{I_p}{I_s} = \frac{V_s}{V_p}$$

Since $\frac{V_s}{V_p} = \frac{N_s}{N_p}$,

$$\frac{I_p}{I_s} = \frac{N_s}{N_p}$$

or

$$I_s = \frac{N_p}{N_s} I_p$$

Link

Recall from Chapter 7: The useful energy output of a machine is always less than the energy input. Some energy is dissipated as wasted energy.

In reality, transformers are not ideal. As a result, the useful output power will be less than the input power. We define the term efficiency η as a ratio of the output power over the input power. That is:

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

In the case where the transformer is ideal, $\eta = 1$ or 100%.

Worked Example 21B

An ideal transformer is connected to the 240 V mains and draws a current of 2 mA. If $\frac{N_P}{N_s}$ is 20, find the output voltage and current.

Answer

Output or secondary voltage is given by:

$$V_s = \frac{V_P}{\frac{N_P}{N_s}}$$

Therefore

$$V_s = \frac{240}{20}$$

$$= 12\text{ V}$$

Since the transformer is ideal, input power equals to output power. That is,

$$V_P I_P = V_s I_s$$

$$240 \times 2 \times 10^{-3} = 12 \times I_s$$

$$I_s = 40\text{ mA}$$

or

$$I_s = \frac{N_P}{N_s} \times I_P$$

$$I_s = 20 \times 2 \times 10^{-3}$$

$$I_s = 40\text{ mA}$$

Motors and generators behave in a similar manner. If you turn a motor, it will generate electricity, and if you apply a voltage to a generator, it will cause the generator to turn. This gives rise to both d.c. and a.c. motors and generators. However, only a.c. generators are used in power stations in the production of electricity. Why is this so?

One of the main challenges in the transmission and distribution of electricity from power stations to households is the loss of power due to ohmic heating ($P = I^2R$) in the cables. If very large currents are transmitted, then losses can be very high due to the squaring effect of current in the power loss equation. For instance, if the current transmitted is 20 kA and the resistance in the cable is 0.01 Ω. Then, even at such a low resistance, the power loss would be 4 MW. This will cause a heating effect in the power cables.

There are two possible solutions to this problem. One solution is to make use of very thick cables. The resistivity of copper is a material property and the length of the cables is fixed by the distance between the power station and the cities. Thus, increasing the cross-sectional area is the only option to reduce the resistance. However, this solution is impractical for several reasons.

- Using very thick cables increases the cost of cables tremendously.
- Thicker cables are heavier and difficult to suspend.
- Even with a very low resistance, ohmic heating can still be substantially high since it is proportional to the square of the current.

The second solution is to reduce the current transmitted. This will reduce ohmic heating of transmission cables. However, to maintain the power that is transmitted, the voltage needs to be increased substantially, since $I = \frac{P_{out}}{V}$. By reducing the current, the power loss, $P_{loss} = I^2R = (\frac{P_{out}}{V})^2R$, is reduced since V is large.

Link

Recall from Chapter 16:
$R = k\frac{l}{A}$

Disciplinary Idea

Conversation laws constrain the changes in the systems.

Energy "losses" during the long-distance transmission of electricity are energy transfers to the internal (thermal) store of the transmission cables.

Figure 21.17 Overhead transmission cables supported by electricity pylons. In Singapore, most transmission cables are underground. Why?

The second solution is more viable. This is why transmission lines have voltages as high as 400 kV a.c.. This very high voltage is then stepped down with transformers. Figure 21.18 shows a typical step-down transformer.

Figure 21.18
Step-down transformer

The reason why only a.c. generators are used in the production of electricity is now clear. If d.c. generators are used, the direct current electricity that is produced cannot be stepped up or down. Then, the power loss during transmission would be very high. Therefore, current produced is always in alternating form.

Helpful Note

Electricity generated by solar panels is in the d.c. form. To obtain a connection to the existing power line infrastructure, electricity generated by solar panels has to be inverted to a.c.. In homes that have solar panels, some of the d.c. output may be connected directly to home appliances such as LED lights. However, most of it would need to be inverted to a.c. before being used.

Worked Example 21C

A power substation supplies 1210 kW at 22 kV to ten blocks of HDB flats. If the cable resistance is 1 Ω, calculate the current flowing in the cable and the power loss.

Answer

The current in the cables is:

$$I = \frac{P_{\text{out}}}{V}$$

$$I = \frac{1210}{22}$$

$$I = 55 \text{ A}$$

The power loss is:

$$P_{\text{loss}} = I^2 \text{R}$$

$$P_{\text{loss}} = 55^2 \times 1$$

$$P_{\text{loss}} = 3025 \text{ W}$$

Let's Practise 21.3

1 An a.c. generator produces an induced e.m.f. of 500 V with a frequency of 50 Hz.

- (a) Draw the waveform of the induced e.m.f. if the e.m.f. is 0 V at time $t = 0$.
- (b) If the induced e.m.f in (a) is stepped-up to 22 kV and the transformer has 100 turns on the primary coil, find the number of turns on the secondary coil.
- (c) If the voltage in (b) is transmitted to a town over a distance of 10 km and the power loss in the transmission cable is 330 W, what is the current flowing in the transmission cable?

Link

Theory Workbook
Worksheet 21C
Let's Assess
Let's Reflect

Problem-based Learning Activity

Eddy currents were once thought of as undesirable wastages of electrical work done. They produce unnecessary heat and, reduce the amount of useful energy transfers. A lot of studies and design of transformers and inductors were based on how to reduce the amount of eddy currents.

However, towards the turn of the last century, a whole new perspective of eddy current emerged. Eddy currents are making their ways into electric trains, cooking utensils, gym equipment and so on.

You are part of a product design team of a company, and you want to explore the applications of eddy currents to generate new product ideas. You may use any one of the following sets of questions to guide you in coming up with your new product ideas. You may do a search on the Internet to find the answers.

Set 1: Electric work done by eddy currents to produce a heating effect
- What are eddy currents and how are they produced?
- How are eddy currents used in cooking?
- What are the advantages and disadvantages of this particular application?
- How would you design your new product? Provide a sketch of your prototype.

Set 2: Electric work done by eddy currents to produce mechanical braking
- What are eddy currents and how are they produced?
- How does eddy current braking work?
- What are the advantages and disadvantages of this particular application?
- What kind of product requires braking or stoppages?
- How would you design your new product? Provide a sketch of your prototype.

Set 3: Electric work done by eddy currents to produce resistive load
- What are eddy currents and how are they produced?
- How are eddy currents used in creating resistive load in gym equipment?
- What are the advantages and disadvantages of this particular application?
- How would you design your new product? Provide a sketch of your prototype.

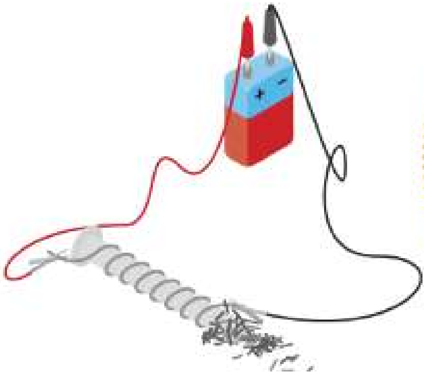
Link

Theory Workbook
Problem-based Learning: Application

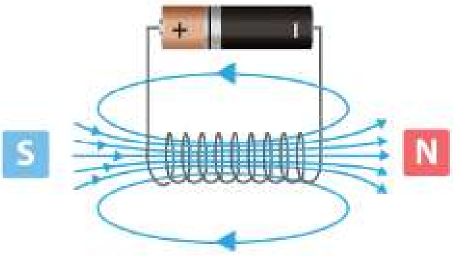
Cool Career

Power Electronics Engineer
Power electronics engineers deal with the changing of electrical power to different forms. They need to know how voltages can be modified so that these voltages are safely used in a device. They often work with other engineers to research, design and test new power electronics designs and technologies. Nowadays, a lot of research by power electronics engineers focus on wireless charging. The immediate application is the electric vehicle. With wireless charging, the electric vehicle can be fully autonomous and would not need a human to plug in a charging cable. The implication of this technology is that all household appliances can be wireless and electric cords will become a thing of the past.

Let's Map It



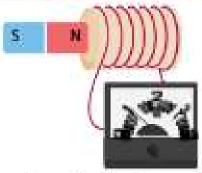
Electromagnetic Induction



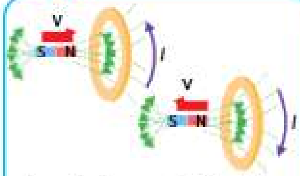
is defined as

The process through which an induced e.m.f. is produced in a conductor due to a changing magnetic field.

obeys



Faraday's Law of electromagnetic induction, which 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.

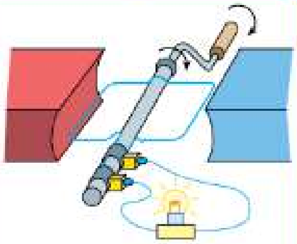


Lenz's Law, which states that the direction of the induced e.m.f., and hence the induced current in a closed circuit, is always such that its magnetic effect opposes the motion or change producing it.

explains why

The magnitude of the induced e.m.f. increases when:
- the speed of the relative motion between the coil and the magnet is increased;
- the number of turns of the coil is increased; and
- the strength of the magnet is increased.

is used in



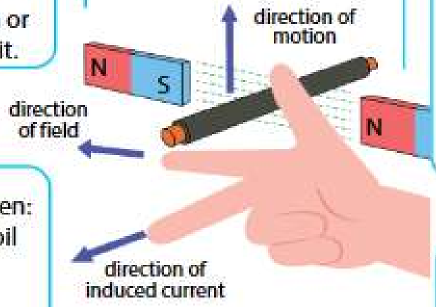
a.c. generators

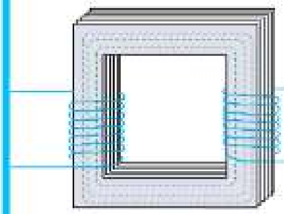
are

Devices that produce an e.m.f. through magnetic field

follow

Fleming's right-hand rule





transformers

are

Devices that can change a high alternating voltage (at low current) to a low alternating voltage (at high current), or vice versa.

use for

- Stepping up voltage to reduce power loss in transmission of electricity
- Stepping down voltages to be supplied to homes

described by

- $\frac{V_p}{V_s} = \frac{N_p}{N_s}$
- For an ideal transformer $V_pI_p = V_sI_s$

Let's Review

Section A: Multiple-choice Questions

1 Figure 21.19 shows a transformer with input voltage of 240 V a.c. and an output voltage of 15 V a.c. If there are 1600 turns on the primary coil, what is the number of turns on the secondary coil?

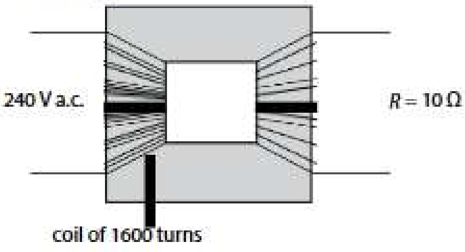


Figure 21.19

○ A 2.5
○ B 22.5
○ C 100
○ D 25600

2 Which of the following does **not** affect the magnitude of the induced e.m.f. of an a.c. generator?

○ A the strength of the permanent magnet
○ B the number of turns in the coil
○ C the resistance of the coil
○ D the presence or absence of an iron core

3 A magnet is moved towards a solenoid as shown in Figure 21.20.

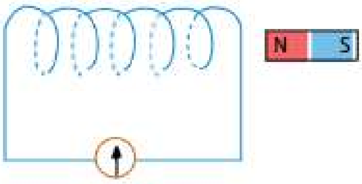


Figure 21.20

Which statement is correct?

○ A The direction of current is given by left-hand grip rule.
○ B No current is induced if a U-shaped magnet is used.
○ C An induced current will flow such that the magnetic field generated by the coil opposes the motion of the magnet.
○ D A magnet that is bigger in size will induce a larger current.

4 Why is electricity transmitted at high voltage along transmission wires?

○ A The high voltage will deter animals from climbing onto the wires.
○ B The high voltage will ensure that there is sufficient current during peak electricity consumption.
○ C The high voltage will deter people from getting near and tampering with the transmission lines.
○ D The high voltage will minimise power loss.

Section B: Structured Questions

1 In Figure 21.21, a magnet is being rotated clockwise.

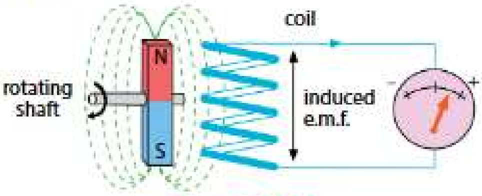


Figure 21.21

(a) Explain why an e.m.f. is being induced.
(b) What happens if the magnet is rotated anticlockwise?

2 Determine the direction of the current flowing in the coil (A to B or B to A) if the magnet is moving away from the coil (Figure 21.22). Explain how you arrive at your answer.

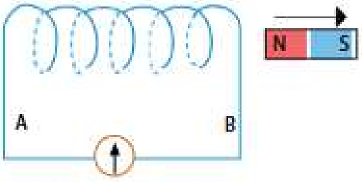


Figure 21.22

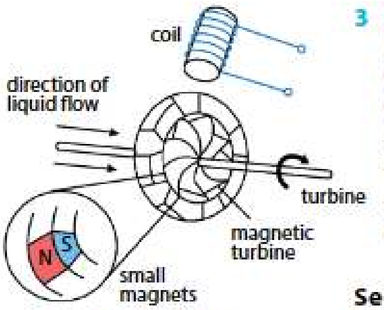


Figure 21.23

3 Figure 21.23 shows a flowmeter which is commonly used in manufacturing plants to measure the flow of liquids in pipes. It comprises a magnetic turbine and a coil. The coil is connected to an a.c. voltmeter. Explain how the flowmeter is able to measure the speed of liquid flow in the pipe.

Section C: Free-response Questions

1 A transmission line is operating at 6.6 kV. An engineer found the resistance of the cable to be 10 Ω and the power loss to be 400 kW. Explain with calculations how this power loss may be reduced if the transmission voltage is increased to 22 kV.

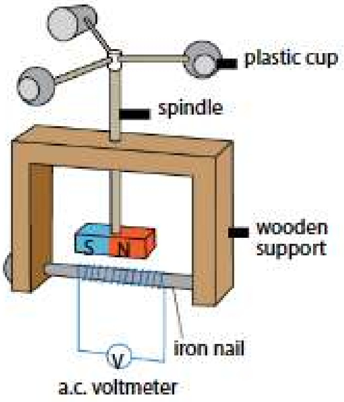


Figure 21.24

2 Figure 21.24 shows a wind turbine made by a student.

(a) Explain why an e.m.f. is induced in the coil when wind is blowing.

(b) How can the induced e.m.f. in the coil be increased?

(c) Sketch the waveform of the induced e.m.f.

(d) Figure 21.25 shows a wind turbine that produces an induced e.m.f. of 660 V. The energy is fed into the 6.6 kV power grid using a transformer.

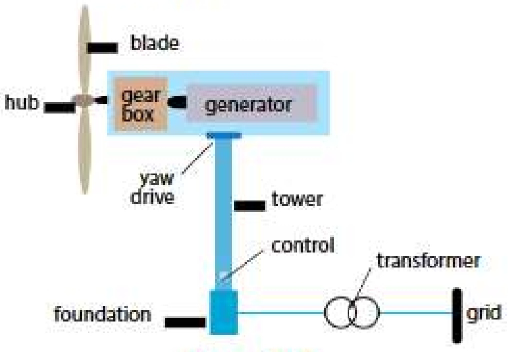


Figure 21.25

(i) What type of transformer should be used?

(ii) If the primary coil has 100 turns, how many turns are there on the secondary coil?

3 Figure 21.26 shows a transmission network with all values of the transmission provided.

Figure 21.26

(a) What types of transformers are transformers A and B?

(b) If transformer A is an ideal transformer, calculate the power loss when the resistance of the transmission cable is 0.01 Ω.

(c) If the primary coil of transformer B has 8000 turns, calculate the number of turns in its secondary coil.

(d) Why is it necessary to step up the voltage from 2 kV to 20 kV?

(e) The distance between transformer A and B is 5 km. Table 21.1 provides the data for two different materials to be used as transmission cables. It is further given that the cross-sectional area of both cables are 3.0×10^{-4} m².

Table 21.1

Cable Material	Resistance per km / Ω/km	Density / kg/m³
aluminium	0.075	2700
copper	0.05	8900

An engineer decided to use copper wires if the transmission cables are to be laid underground and to use aluminium if the cables are to be suspended. Without further calculations, explain the reasons for his decision.

Link

Theory Workbook
Revision Worksheet 5

CHAPTER

22 Radioactivity

What You Will Learn

- What is the composition of an atom?
- What is radioactivity?
- What are nuclear fission and nuclear fusion?
- What are the uses and hazards of radioactivity?

Airborne radioactivity refers to particulate or gaseous radioactive materials that are mixed or suspended in air. In September 2017, an increase in airborne radioactivity was detected in Europe. The increase in airborne radioactivity was likely due to an accident that occurred during the processing of used nuclear fuels.

Although the radioactive isotope, ruthenium-106, was found to be in small quantities, the radiation released still posed a danger to the residents staying within several kilometres of the radioactive source. The extent of the danger is determined by the concentration of the radioactive materials and the energy of the radiation being emitted.

What is an isotope? What are some other factors that affect the extent of the radioactive danger?

22.1 What Is the Composition of an Atom?

Learning Outcomes

- Describe the composition of an atom in terms of a positively charged nucleus and negatively charged electrons.
- Use the terms proton (atomic) number Z, nucleon (mass) number A and isotope.
- Use and interpret the term *nuclide* and use the nuclide notation $^A_Z X$.

Disciplinary Idea

Matter and energy make up the Universe.

Matter is made of atoms that comprise a positively charged nucleus (of protons and neutrons) that is surrounded by negatively charged electrons.

The Atom

In Chapter 8, we learnt about the kinetic particle model. Matter is made up of atoms. An atom is very tiny and typically has a size of 1 × 10^{-10} m. However, atoms are not the smallest possible bits of matter. They are made up of even smaller particles.

An atom consists of a *positively charged* **nucleus** (plural: nuclei) and *negatively charged* electrons moving around the nucleus (Figure 22.1). Strong attractive forces between the positively charged nucleus and negatively charged electrons hold the electrons to the atom.

The nucleus of an atom consists of two types of particles — protons and neutrons. What is the difference between these particles?

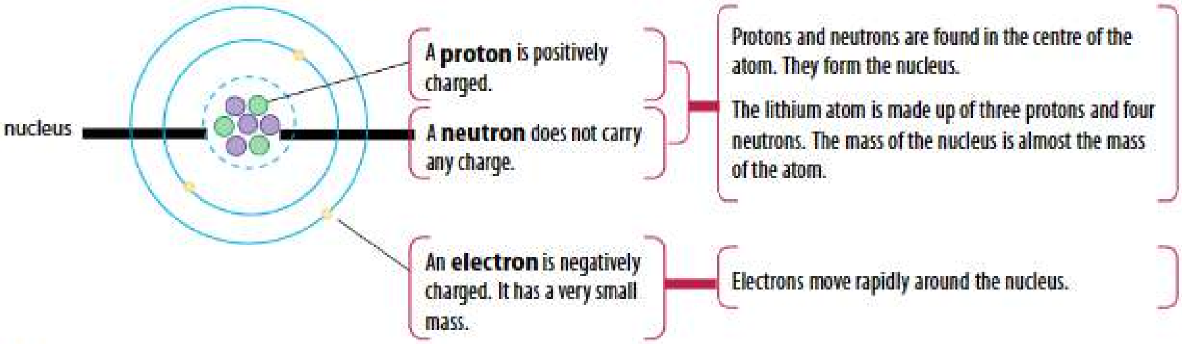


Figure 22.1 Structure of a lithium atom

Link

Chemistry

In Chemistry, we learn about the structure of the atom.

Different atoms contain different numbers of subatomic particles (protons, neutrons and electrons).

Protons, neutrons and electrons are called **subatomic particles**. 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 much smaller than 1 C. Instead of using a specific small number for the charge of an electron, scientists express the charge of small subatomic particles as relative charges (Table 22.1).

Table 22.1 The relative charges of subatomic particles

Subatomic Particle	Relative Charge
electron	−1
proton	+1
neutron	0

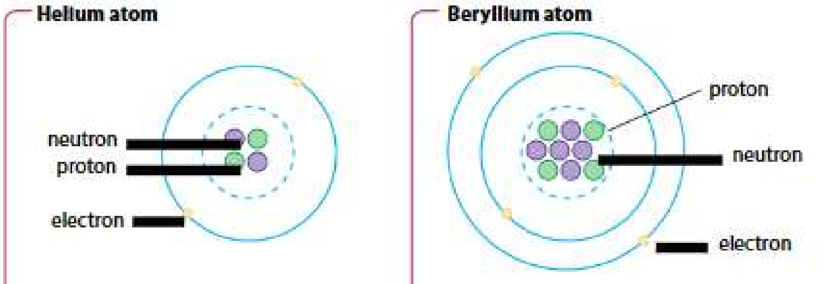
Proton (Atomic) Number *Z*

The **proton number** is the number of protons in an atom.

The symbol Z is used to represent the proton number of an element. The proton number is also known as the **atomic number**.

In a neutral atom, the total positive charge equals the total negative charge. Therefore, in a neutral atom, the number of protons is the same as the number of electrons. For example, the proton number of helium is two. This indicates that a helium atom has two protons and two electrons.

Each element has a unique proton number. No two elements have the same proton number. For example, helium and beryllium have different proton numbers (Figure 22.2).



Contains:
- two protons
- two electrons
- two neutrons

Thus, all atoms with two protons are helium atoms.

Contains:
- four protons
- four electrons
- five neutrons

Thus, all atoms with four protons are beryllium atoms.

Figure 22.2 Helium and beryllium atoms

Nucleon (Mass) Number *A*

Protons and neutrons are also called **nucleons**.

The **nucleon number** is the total number of neutrons and protons in the nucleus of an atom.

The symbol A is used to represent the nucleon number of an element. The nucleon number is also known as the **mass number**. This is because the mass of an atom depends on the mass of nucleons in the nucleus of the atom. The mass of an electron is very small and is thus negligible.

Recall that the number of protons in an atom is the proton number Z. Therefore, we have:

Number of neutrons = nucleon number A – proton number Z in a nucleus

In nuclear physics and nuclear chemistry, the various species of atoms whose nuclei contain a particular number of protons and neutrons are called **nuclides**.

Link

Chemistry

In Chemistry, we learn that an element's nucleon and proton numbers can be represented by ${}^{A}_{Z}X$.

The chemical symbol X is found in the periodic table. In the periodic table, elements are arranged in order of increasing proton number.

The nucleus of an atom can be represented by the **nuclide notation** (Figure 22.3).

Figure 22.3 Nuclide notation

An atom is sometimes represented using only the nucleon number. An example is carbon-12.

Worked Example 22A

The nucleus of a radioactive element is represented by ${}^{235}_{92}U$.

(a) How many protons does the neutral atom contain?

(b) How many neutrons does the nucleus contain?

Answer

(Refer to Figure 22.3 for interpreting the nuclide notation.)

(a) The proton number Z is shown as a subscript. The number of protons is 92.

(b) The nucleon number A is 235. Thus, the number of neutrons is $235 - 92 = 143$.

Isotopes

Figure 22.4 shows the nuclide notations for three atoms of the same element. How many neutrons, electrons and protons does each atom have?

$${}^{12}_{6}C \quad {}^{13}_{6}C \quad {}^{14}_{6}C$$

Figure 22.4 Nuclide notations of three atoms with the same proton number but different nucleon numbers

The atoms have the same proton number. Thus, each atom has six protons and six electrons. They are carbon atoms.

The atoms of the same element have the same number of protons but their numbers of neutrons can be different. There are six neutrons in ${}^{12}_{6}C$, seven neutrons in ${}^{13}_{6}C$ and eight neutrons in ${}^{14}_{6}C$. They are isotopes of the same element.

Isotopes are atoms of the same element that have the same number of protons but different numbers of neutrons.

Isotopes have the same proton number but different nucleon numbers. Many elements have isotopes. Isotopes of the same element have *identical* chemical properties.

Let's Practise 22.1

1 Uranium-235 and uranium-238 are isotopes of the same element. The nucleus of uranium-235 is represented by ${}^{235}_{92}U$.

(a) Define *isotopes*.

(b) State the nuclide notation of the nucleus of uranium-238.

(c) How many neutrons are in the nucleus of uranium-238?

Link

Theory Workbook

Worksheet 22A

22.2 What Is Radioactivity?

Learning Outcomes

- Show an understanding that nuclear decay is a random and spontaneous process whereby an unstable nucleus loses energy by emitting radiation.
- Show an understanding of the nature of alpha (α), beta (β) and gamma (γ) radiation.
- Use equations involving nuclide notation to represent changes in the composition of the nucleus when radioactive emissions occur.
- Show an understanding of background radiation.
- Use the term *half-life* in simple calculations.

Nuclear Decay

Nuclear decay is a random process by which an *unstable* atomic nucleus loses its energy by emission of electromagnetic radiation or particle(s).

Nuclear decay is also known as *radioactive decay* or *radioactivity*. A material containing unstable nuclei is considered radioactive. The instability of the atomic nuclei is because the **nuclear forces** within the nuclei are not enough to bind the nucleons together.

The radiation emitted by a radioactive nucleus is *spontaneous* and *random* in direction (Figure 22.5). The direction of the emissions and the time between emissions cannot be predicted.

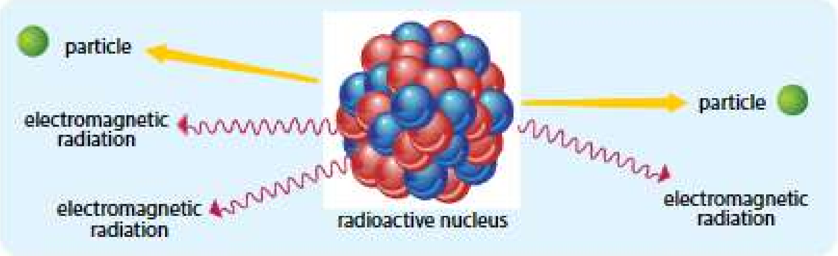


Figure 22.5 The radiation or particles emitted from a radioactive nucleus can occur anytime and in any direction.

In other words, it is not possible:

- to make the radioactive nucleus emit radiation by heating, cooling, chemical means or any other method;
- to predict when a radioactive nucleus will emit radiation; and
- to know the direction in which the emitted radiation will leave a nucleus.

Word Alert

Decay: break down into smaller parts

Disciplinary Idea

Matter interacts through forces and fields.

The instability of atomic nuclei is related to the nuclear forces within the nucleus.

The atom is unstable when the nuclear forces within the nucleus are not enough to bind the nucleons together. This could be due to an excess of protons in the nucleus as the protons (positively charged) exert repulsive forces on one another. To become stable, the atom loses energy by emitting radiation or nucleons.

Three Types of Nuclear Emission

There are three types of nuclear emission: **alpha (α) particles, beta (β) particles and gamma (γ) rays**. Imagine that each nuclear emission is participating in an obstacle race (Figure 22.6). Which nuclear emission will be able to reach the finish line?

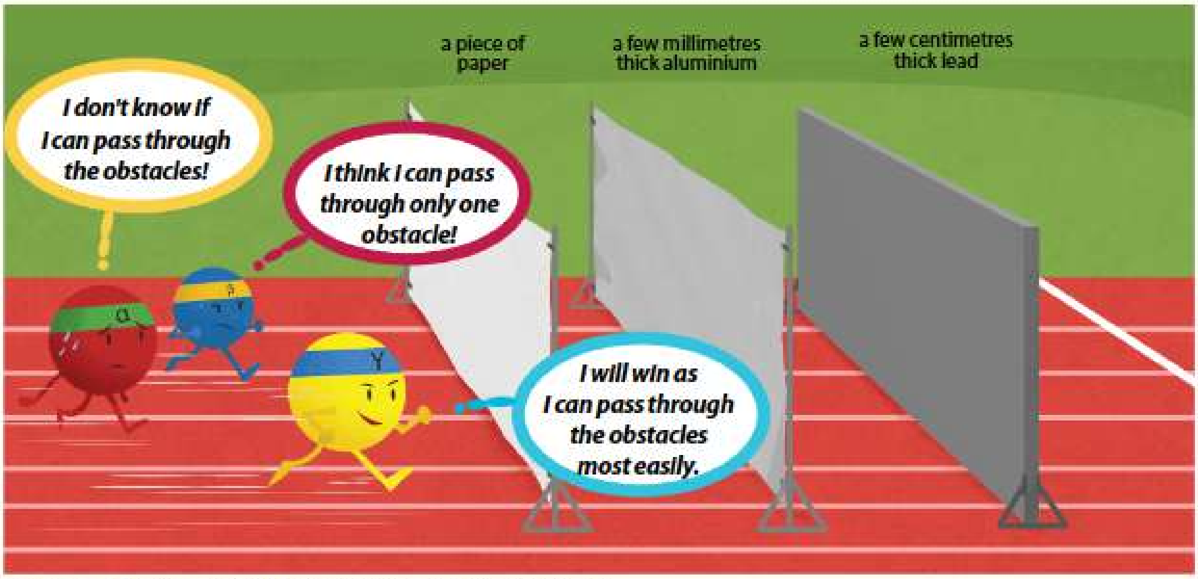


Figure 22.6 Which nuclear emission can reach the finish line?

Different nuclear emissions have different compositions, ionising effects and penetrating abilities (Table 22.2).

Ionisation refers to the ability to eject electrons from atoms to form ions. Since the atoms lose electrons, the number of protons is greater than the number of electrons. Thus, ions carry a charge.

Table 22.2 The three types of nuclear emissions

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. 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  ${}^{0}_{-1}\beta$	An β-particle is a fast-moving *electron* ejected from a radioactive nucleus.	Medium	- Medium - They are absorbed by a piece of aluminium that is a few millimetres thick.
γ-rays 	A γ-ray is *electromagnetic radiation* emitted by a radioactive nucleus with excess energy.	Lowest	- Highest - They pass through most materials easily. They are absorbed by lead that is a few centimetres thick or very thick concrete.

Link

Recall from Chapter 13: Gamma rays have high frequencies and are the most energetic waves in the EM spectrum.

Gamma rays can penetrate deep into the body more easily than other EM waves of lower frequencies.

Disciplinary Idea

Waves can transfer energy without transferring matter.

Gamma radiation is a form of electromagnetic radiation. Gamma rays have the shortest wavelength and the highest frequency among the waves in the EM spectrum. It has high energy.

Disciplinary Idea

Matter and energy make up the Universe.

Some atomic nuclei are unstable and undergo radioactive decay. Some energy from the nuclear store is transferred to the kinetic store of the decay products.

The decay process typically involves the release of α-particles or β-particles, and/or γ-radiation.

The nuclei of the same isotope will emit the same type of nuclear radiation. During α-decay or β-decay, the nucleus changes to that of a different element.

Alpha Decay

When a nucleus undergoes α-decay:

- it emits an α-particle (identical to helium nucleus $^{4}_{2}He$); and
- the nucleon number decreases by four and the proton number decreases by two.

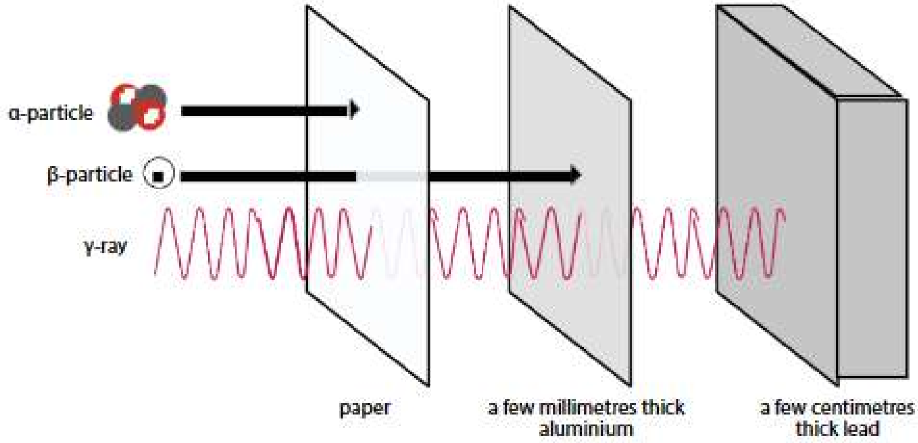
We can use an equation involving nuclide notation to represent the changes in the composition of the nucleus. This is known as the **nuclide equation**. For example, when radium (Ra) emits an α-particle, it decays to radon (Rn).

$$^{226}_{88}Ra \longrightarrow ^{222}_{86}Rn + ^{4}_{2}He$$

The arrow in the equation means "reacts to form". Notice that the total number of nucleons and protons before and after the reaction is the same.

Nucleon numbers: 226 ⟶ 222 + 4
Proton numbers: 88 ⟶ 86 + 2

The total relative charge before and after a nuclear emission should also be the same. Recall that the relative charge on a proton is +1 and the relative charge on a neutron is 0. Thus, the relative charge on the nucleus is the same as the proton number of the nucleus.



Link

Chemistry

In Chemistry, we learn that a balanced chemical equation must contain an equal number of atoms of each element on both sides of the equation.

Disciplinary Idea

Conservation laws constrain the changes in system.

In an atomic reaction, the mass and charge are conserved. The composition of the nucleus changes after the radioactive emission. Hence, changing the type of atom in the reaction.

Conservation of mass: The total number of neutrons and protons before and after the decay is constant.

Conservation of charge: The atomic number has to balance in all nuclear decay processes and reactions.

Note: In a chemical reaction, the number of each type of atoms before and after the reaction remain the same.

Beta Decay

When a nucleus undergoes β-decay:

- it emits a β-particle (an electron); and
- the nucleon number remains the same and the proton number increases by one.

For example, when carbon-14 (radioactive carbon C) emits an β-particle (electron), it decays to nitrogen (N).

$${}^{14}_{6}\mathrm{C} \longrightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e}$$

Gamma Radiation

Very often, when nuclei undergo alpha-decay or beta-decay, gamma radiation is also emitted.

For example, when uranium (U) emits an alpha-particle, it decays to thorium (Th) and two gamma rays of different energies are emitted.

$${}^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He} + 2{}^{0}_{0}\gamma$$

Background Radiation

Radiation is all around us. Visible light and infrared radiation are electromagnetic radiation from the sun. Microwaves and radio waves are radiation used in communication systems. These are non-ionising radiation. They have little biological effects.

▶ **Ionising radiation** is radiation with high energies that can knock off electrons from atoms to form ions.

Very high frequency ultraviolet rays, X-rays and gamma rays are examples of ionising electromagnetic radiation. Highly energetic particles from cosmic rays (from outer space) and from naturally occurring radioactive materials are examples of ionising nuclear radiation.

▶ **Background radiation** refers to nuclear radiation in an environment where no radioactive source has been deliberately introduced.

We encounter background radiation every day. The sources of background radiation can be artificial (man-made) or natural (Figure 22.7).

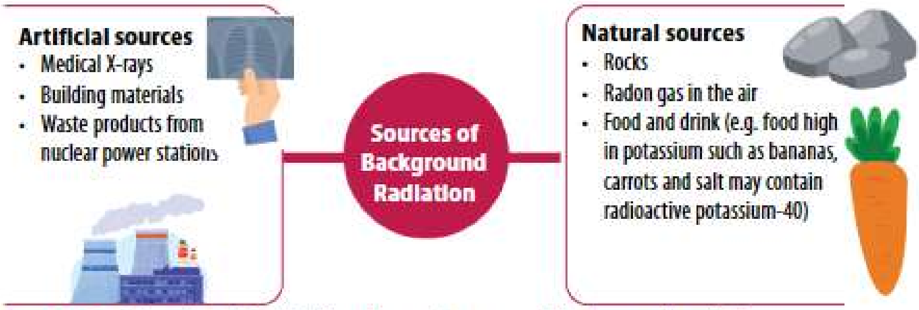


Figure 22.7 Examples of artificial and natural sources of background radiation

Natural background radiation accounts for about 80% of the radiation that we are exposed to. The amount of background radiation we encounter is usually well below the recommended limit of radiation exposure.

Link

Recall from Chapter 13: Ionising waves are those with higher frequencies.

Measuring Ionising Nuclear Radiation

Ionising nuclear radiation can be measured using a Geiger-Muller (GM counter). In one type of GM counter, the detector, counter and display are a single unit. In another type of GM counter, a detector is connected to a counter (Figure 22.8).

Figure 22.8 A GM counter is used to measure ionising nuclear radiation.

The SI unit of the amount of radioactivity is the **Becquerel (Bq)**. The unit is named in honour of Henri Becquerel, a French physicist who discovered radioactivity in 1896.

One becquerel (1 Bq) is equal to 1 disintegration per second. It refers to the amount of ionising radiation released when a radioactive atom (e.g. uranium) spontaneously emits electromagnetic radiation as a result of the radioactive decay.

The measurement of radiation is sometimes expressed as being a *rate of counts per unit time*, also known as the *count rate*. The count rate can be measured using a GM counter. The units for count rate is counts per minute (counts/min) or counts per second (counts/s).

To measure the background radiation, we will need a GM counter and a stopwatch. We can follow these steps:

1. Remove all known radioactive sources.
2. Start the counter and the stopwatch.
3. Stop the counter after 10 minutes and record the number of counts.
   Number of counts per minute = $\frac{\text{number of counts in 10 minutes}}{10}$
4. Repeat your measurement at least once and calculate an average value.

Alternatively, we can 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).

When carrying out any measurements with radioactive sources, we should first measure the background radiation. Subtract this background count rate from the measurements to obtain the corrected count rate for the radioactive source.

Worked Example 22B

(a) A scientist is using a radiation detector connected to a counter to measure the ionising nuclear radiation from a radioactive source. Briefly describe what the scientist should do.

(b) The number of counts from the detector when placed in front of a radioactive source for 30 seconds is 1500. What is the count rate in counts/s?

(c) The background count rate is 18 counts/min. What is the corrected count rate for the radioactive source in counts/min?

Thought Process

(a) The ionising nuclear radiation is measured in counts per minute. To measure the ionising nuclear radiation from the radioactive source only, the background radiation needs to be subtracted from the count rate.

Answer

(a) The scientist needs to measure the background radiation. All known sources of radioactivity must be removed from the room. Record the number of counts on the counter after 20 minutes and determine the background count rate C_b. Then, place the detector in front of the radioactive source. Record the number of counts on the counter after 20 minutes and determine the count rate C_r. The count rate of the radioactive source is $(C_r - C_b)$.

(b) Count rate of the radioactive source in counts/s $= \frac{1500 \text{ counts}}{30 \text{ s}}$

$= 50$ counts/s

(c) Count rate of the radioactive source in counts/min

$= 1500$ counts $\times 2 = 3000$ counts/min

Corrected count rate for the radioactive source $= 3000 - 18$

$= 2982$ counts/min

Helpful Note

Background count rate is typically 18 counts per minute and it does not present a serious health risk to humans.

Half-life

Since nuclear decay is spontaneous, we will not know exactly when a particular nucleus will decay. However, every nuclide has a fixed rate of decay. We can make predictions about the decay of a large number of nuclei of a particular nuclide because it has a fixed half-life.

▶ The **half-life** of a radioactive nuclide is the time taken for *half* the nuclei of that nuclide in any sample to decay.

For example, the half-life of iodine-131 is eight days. Suppose there are 120 million iodine-131 atoms in the beginning. Observe the number of iodine-131 atoms after eight days, 16 days and 24 days. Figure 22.9 shows the results.

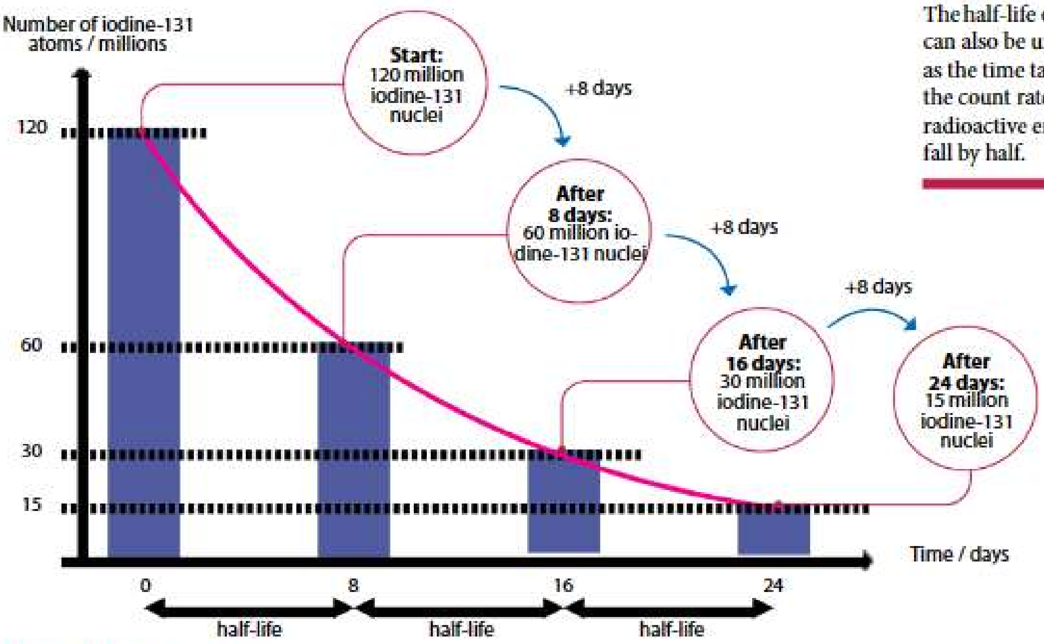


Figure 22.9 Decay curve

Helpful Note

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.

Figure 22.9 is called the **decay curve**. It is the graph of number of atoms or count rate against time. Based on Figure 22.9, we can see that the number of iodine-131 atoms decreases by half every eight days.

Worked Example 22C

The amount of radioactivity of sample X is 600 Bq. If the half-life of sample X is six hours, determine the amount of radioactivity of sample X after 18 hours.

Thought Process

Half-life is the time taken for the amount of radioactivity of the sample to reduce by half.

Answer

Number of half-lives $= \frac{18}{6} = 3$

$$600\text{ Bq} \xrightarrow[\text{half-life}]{\text{one}} 300\text{ Bq} \xrightarrow[\text{half-life}]{\text{one}} 150\text{ Bq} \xrightarrow[\text{half-life}]{\text{one}} 75\text{ Bq}$$

The amount of radioactivity of sample X after 18 hours is 75 Bq.

Worked Example 22D

Figure 22.10 shows the decay curve of a radioactive isotope.

(a) Deduce the half-life of the radioactive isotope.

(b) How long will 2 g of the radioactive isotope take to reduce to 0.25 g?

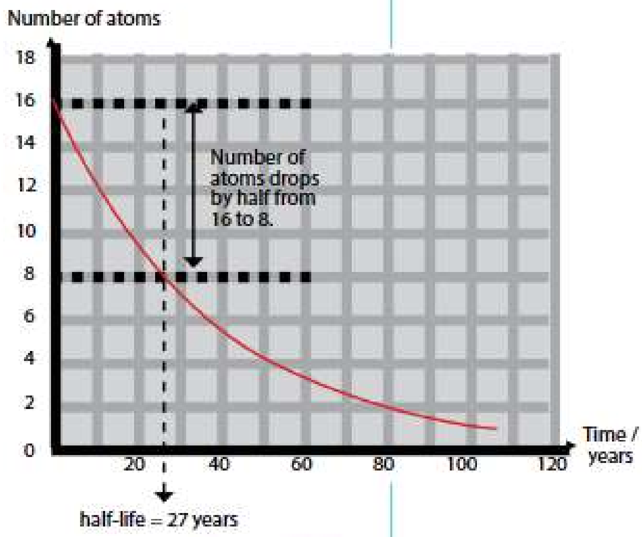


Figure 22.10

Thought Process

(a) Half-life is the time taken for the number of atoms to reduce by half.

(b) To reduce from 2 g to 0.25 g, the radioactive isotope will have gone through three half-lives (2 g ⟶ 1 g ⟶ 0.5 g ⟶ 0.25 g).

Answer

(a) The time taken for the number of atoms to reduce from 16 to 8 is 27 years. Thus, half-life is 27 years.

(b) Time needed = 27 × 3 = 81 years

Worked Example 22E

Figure 22.11 shows the decay curve of a radioactive isotope.

(a) Deduce the half-life of the radioactive isotope.

(b) What would be the approximate number of atoms at the end of 19.5 hours?

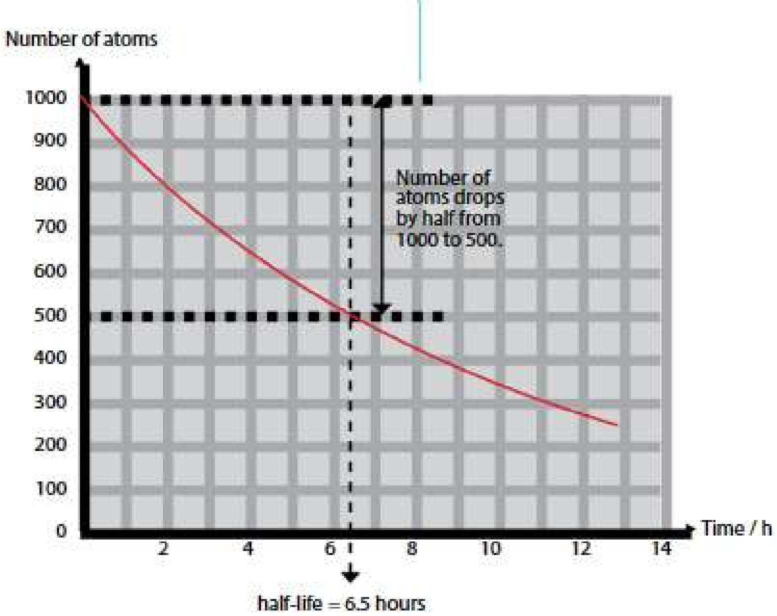


Figure 22.11

Thought Process

(a) Half-life is the time taken for the number of atoms to reduce by half.

(b) To find out the number of atoms after a certain time period, we need to determine the number of half-lives.

Answer

(a) The time taken for the number of atoms to reduce from 1000 to 500 is 6.5 hours. Thus, half-life is 6.5 hours.

(b) Number of half-lives = $\frac{19.5\text{ h}}{6.5\text{ h}} = 3$

Number of atoms = $\frac{1000}{2^3} = 125$

Consider the decay curve in Figure 22.12(a). Why does the count rate remain at about 20 counts/min after some time?

The count rate of a radioactive substance decreases until all the substance has decayed. A typical background radiation count is about 18 counts/min. This implies that the almost constant rate of 20 counts/min is due to the background radiation and the sample has decayed to the point that its radioactivity is negligible. The half-life of the isotope in Figure 22.12(b) is 20 minutes.

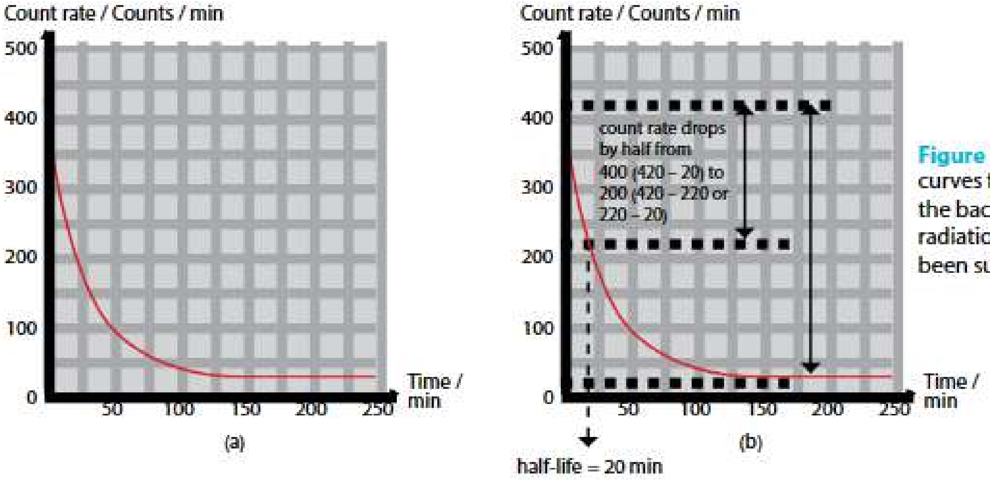


Figure 22.12 Decay curves from which the background radiation has not been subtracted

Let's Practise 22.2

1 (a) What is background radiation?
  (b) The amount of radioactivity of a sample decreases from 252 Bq to 63 Bq in 14 days. What is the half-life of the sample?

2 The thickness of a piece of paper can be monitored by the amount of beta radiation that passes through the paper and reaches the detector.
  (a) Explain why beta radiation is suitable.
  (b) Suggest if the radioactive source used should have a long or short half-life. Explain your answer.

3 The half-life of a radioactive isotope is 15 h. A counter recorded an initial count rate of 10 000 counts/min.
  (a) After how long will the count rate be about 1250 counts/min?
  (b) What will be the count rate at the end of 75 h?

Link

Theory Workbook
Worksheet 22B

Past to Present

In the past, scientists believed that an atom was unchangeable. However, the discovery of radioactive elements, such as uranium, radium and polonium, challenged this idea.

The concept of radioactivity changes these old ideas about atomic structure. Now, we understand that atoms are made up of smaller particles and that these particles can be emitted from an atom. When particles are emitted, a new atom is formed. Many radioactive isotopes have been discovered. Isotopes that emit high-energy radiation have a lot of applications such as in the field of medicine and geology (Figure 22.13).

Figure 22.13 Uranium-238, a radioactive substance, can be used to estimate the age of rocks.

22.3 What Are Nuclear Fission and Nuclear Fusion?

Learning Outcome

- State the meaning of nuclear fission and nuclear fusion and relate these nuclear processes with the release of energy from nuclear fuels.

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 nuclei of various elements.

Word Alert

Probe: examine or investigate in detail

In 1938, scientists conducted an experiment to direct neutrons at the nucleus of uranium-235. The uranium-235 atom, ${}^{235}_{92}U$, has a big nucleus consisting of 235 nucleons. It has 92 protons and 143 (235 – 92) 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 type of nuclear reaction.

Nuclear fission is a process in which the nucleus of an atom *splits* (usually into two parts) and releases a huge amount of energy.

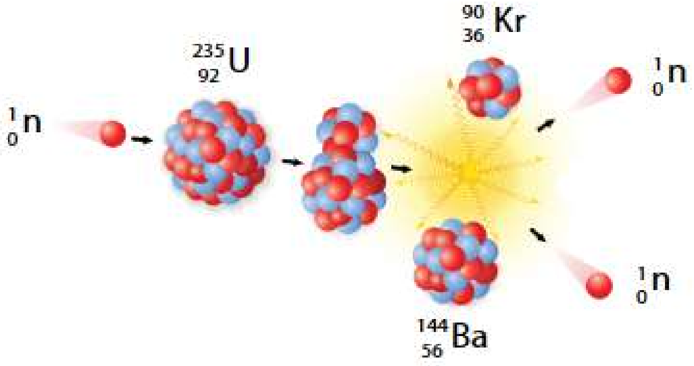
Disciplinary Idea

Microscopic models can explain macroscopic phenomena.

The composition of an unstable radioactive nucleus changes when it undergoes radioactive decay. Thus, the properties of the (daughter) nuclides change.

During nuclear fission, the original atom becomes atoms of two different elements. This is a type of nuclear reaction. The process releases a lot of energy. It can be represented by a nuclide equation (Figure 22.14).

The original atom is called the **parent nucleus**. The parent nucleus decays to form other atoms called the **daughter nuclei**. The daughter nuclei may be stable or may decay further.



$$ {}^{1}_{0}n + \underset{\substack{\downarrow \\ \text{parent} \\ \text{nucleus}}}{{}^{235}_{92}U} \longrightarrow \underbrace{{}^{144}_{56}Ba + {}^{90}_{36}Kr}_{\substack{\downarrow \\ \text{daughter} \\ \text{nuclei}}} + 2\,{}^{1}_{0}n $$

Figure 22.14 During nuclear fission, the uranium nucleus splits into smaller nuclei and releases a large amount of energy.

In a nuclear fission, there are several possible fission products. Therefore, there are several possible nuclide equations.

For example: ${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \longrightarrow {}^{139}_{56}\text{Ba} + {}^{94}_{36}\text{Kr} + 3\,{}^{1}_{0}\text{n}$

It is important to check that the total number of nucleons and the total relative charge before and after the reaction are the same.

Worked Example 22F

In the following nuclide equation, what are the missing nucleon number A and proton number Z?

${}^{219}_{86}\text{Rn} \longrightarrow {}^{A}_{Z}\text{Po} + {}^{4}_{2}\text{He}$

Answer

Before fission, total nucleon number = 219

After fission, total nucleon number = $A + 4$

Equating the total nucleon number before and after fission,

$A + 4 = 219$

$A = 215$

Before fission, total relative charge = 86

After fission, total relative charge = $Z + 2$

Equating the total relative charge before and after fission,

$Z + 2 = 86$

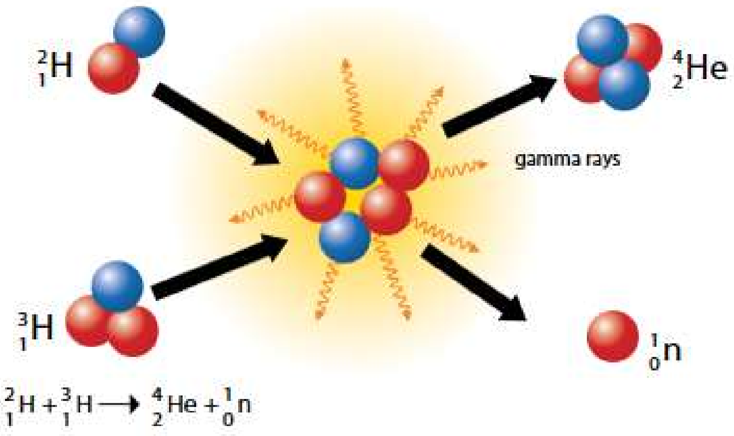
$Z = 84$

Nuclear Fusion

Another type of nuclear reaction is nuclear fusion.

Nuclear fusion is a process in which two light atomic nuclei *combine* to form one heavier atomic nucleus and releases a huge amount of energy.

During nuclear fusion, the two atoms join to become another bigger atom of a different element (Figure 22.15).



${}^{2}_{1}\text{H} + {}^{3}_{1}\text{H} \longrightarrow {}^{4}_{2}\text{He} + {}^{1}_{0}\text{n}$

Figure 22.15 During nuclear fusion, two nuclei (hydrogen-2 and hydrogen-3) fuse together to form a bigger nucleus (helium) and release a large amount of energy (gamma rays).

Disciplinary Idea

Microscopic models can explain macroscopic phenomena.

Isotopes of the same element can have drastically different nuclear properties (properties related to the atomic nuclei such as the force between nucleons and energy required to split a nucleus) because the number of neutrons changes.

For example, the two isotopes of hydrogen in Figure 22.15 have different nuclear properties even though they have similar chemical properties (as the number of electrons is the same). Chemical reactions involve only the electrons.

Energy Changes During Nuclear Processes

Nuclear fuel is a material used in nuclear power stations. Some examples of nuclear fuel are uranium and plutonium. The nuclear fuels undergo nuclear reactions to release energy.

Most nuclear fuels can undergo and sustain nuclear fission. Isotopes such as uranium-233, uranium-235 and plutonium-239 are commonly involved in nuclear fission. When the unstable nuclei of these atoms are hit by a slow-moving neutron, they split. Thus, two daughter nuclei and two or more neutrons are created.

During nuclear fission, energy is transferred from the nuclear store of the unstable nucleus to:

- the kinetic, internal and nuclear stores of the daughter nuclei and neutrons; and
- the internal store of the surroundings.

The internal store of the surroundings is used to heat water so that it changes into steam. The steam turns the turbine to generate electricity (Figure 22.16).

Figure 22.16 Electricity is generated in nuclear power plants by nuclear fission.

Link

Recall from Chapter 7: There are advantages and disadvantages when we harness energy from nuclear fuels.

The neutrons produced in the nuclear fission will go on to split more nuclei. This creates a self-sustaining chain reaction that is controlled in a nuclear reactor (Figure 22.17). The processes involved in mining, refining, purifying, using and disposing of nuclear fuel are collectively known as the *nuclear fuel cycle*.

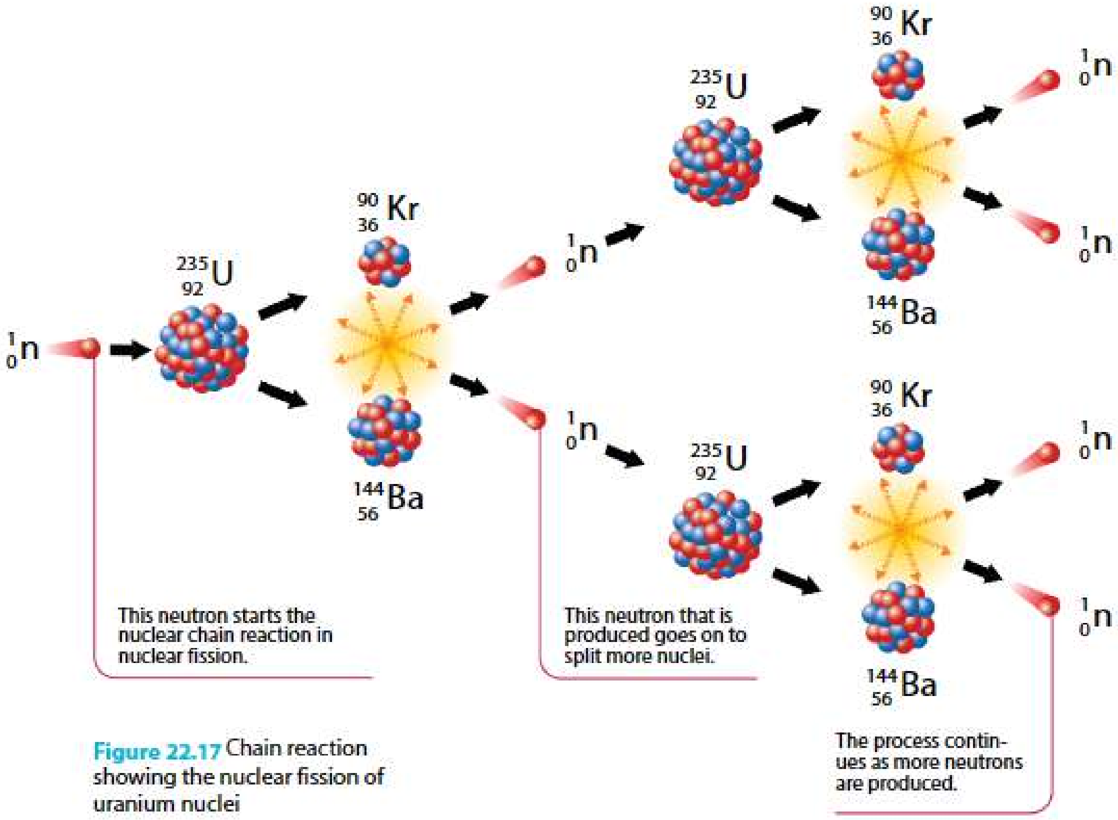


Figure 22.17 Chain reaction showing the nuclear fission of uranium nuclei

Not all types of nuclear fuels generate electrical power from nuclear fission. Electricity can also be generated from nuclear fusion.

During nuclear fusion, energy is transferred from the nuclear stores of the two nuclei to:
- the kinetic, internal and nuclear store of the bigger nucleus; and
- the internal store of the surroundings.

The internal store of the surroundings can be used in the electrical power generation process.

The nuclei of atoms are positively charged. Since like charges repel, it is difficult for two positively charged nuclei to combine, but once combined, nuclear forces hold the nucleus together. A lot of work is done to overcome the repulsive forces between the nuclei during nuclear fusion.

Link
Recall from Chapter 15: Like charges repel each other, while unlike charges attract each other.

Nuclear fusion cannot happen at low temperature and pressure as the two nuclei cannot come into close range of each other due to the repulsive forces. Hence, nuclear fusion requires very high temperatures and pressures and is currently not used in nuclear power plants.

Nuclear fusion can take place in the sun where temperature and pressure are high. Scientists and engineers are working on reactors where nuclear fusion can take place in a safe and controlled manner (Figure 22.18).

Figure 22.18 An experimental device designed to harness the energy from nuclear fusion. More research is needed before it can be used commercially.

Let's Practise 22.3

1 The following shows a nuclide equation.

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \longrightarrow ^{A}_{Z}\text{Zr} + ^{139}_{52}\text{Te} + 3^{1}_{0}\text{n}$$

(a) What nuclear process did $^{235}_{92}\text{U}$ undergo?
(b) What are the missing nucleon number A and proton number Z?

2 Explain why nuclear fusion occurs only at high temperatures and pressures.

Link
Theory Workbook
Worksheet 22C

22.4 What Are the Uses and Hazards of Radioactivity?

Learning Outcome
- Discuss the applications and hazards of radioactivity.

Applications of Radioactivity

Radioactive isotopes have many practical uses. The uses can be broadly categorised into:
- uses related to the damage of cells;
- uses related to radioactive decay and half-life; and
- uses related to the penetrating abilities and ionising effects.

Uses Related to the Damage of Cells

Table 22.3 shows the applications of radioactivity that are related to cell damage.

Table 22.3 Applications of radioactivity that are related to cell damage

	Radiation	Use
Medical	γ-rays	The isotope, technetium-99, is used in the detection of tumours. When a small amount of the isotope is taken into the body, the γ-rays emitted allow images of internal organs to be taken using a medical equipment called a gamma camera (Figure 22.19). This helps in the diagnosis. The isotope has a short half-life (6 hours) so it does not remain in the body for too long.  Figure 22.19 Gamma cameras detect technetium-99 in the body.
	β-particles	The isotope, iodine-131, is used in the treatment of thyroid disorder. When a small amount is taken into the body, it can destroy the thyroid cells including cancer cells. The isotope has a short half-life (8 days) so it does not remain in the body for too long.
	γ-rays	In gamma knife radiosurgery, γ-rays from a radioactive source (cobalt-60) are directed at the brain to destroy brain tumours. The isotope has a long half-life (5.3 years). It takes a long time for the isotope to decay so it remains in the body for a long time. Thus, only a small quantity is needed over a long treatment time.
Safety	γ-rays	Food decays due to the action of microbes. γ-rays can be used to kill the microbes so that the food is safe for consumption and can last longer. The isotope has a long half-life (a few years). It takes a long time for the isotope to decay so only a small quantity is needed over a long time.
	γ-rays	Medical equipment such as syringes and scalpels are kept in sealed packaging and exposed to γ-rays (Figure 22.20). Thus, the microbes present are killed and the equipment is sterile. The isotope has a long half-life (a few years). It takes a long time for the isotope to decay so only a small quantity is needed over a long time.  Figure 22.20 Gamma rays can pass through the packaging to kill any microbes present on the syringes.

Helpful Note

Doctors use radioactive isotopes called tracers to identify abnormal body processes. Tracers emit α-particles, β-particles or γ-rays. They can be used to follow the path of a single element around the body.

Uses Related to Radioactive Decay and Half-life

The decay rates of some radioactive substances are known. We can use this knowledge to determine how old an object or material is (Table 22.4).

Table 22.4 Application of radioactivity that is related to radioactive decay and half-life

	Radiation	Use
Geology	α-particles	The isotope, uranium-238, has a half-life of 4.5 billion years and is found in most rocks. It is used to estimate the age of rocks. The isotope decays to a stable isotope, lead-206. By determining the relative amounts of uranium-238 and lead-206 in a sample, the age of the rock can be known. The greater the amount of lead-206 present, the older the rock.

Uses Related to the Penetrating Abilities and Ionising Effects

Table 22.5 shows the applications of radioactivity that are related to the penetrating abilities and ionising effects.

Table 22.5 Applications of radioactivity that are related to the penetrating abilities and ionising effects

	Radiation	Use
Safety	α-particles	The isotope, americium-241, is used in smoke detectors. When the α-particles emitted fall on the detector, a current flows in the detector as α-particles have high ionising ability. When smoke enters the detector, it easily absorbs the radiation. The flow of current is disrupted and this triggers the detector's alarm (Figure 22.21).  Figure 22.21 A smoke detector's alarm is triggered because the ionising current is interrupted.
Industrial	β-particles or γ-rays	β-particles are used to measure thickness of materials. Manufacturer needs to ensure that the materials are of uniform thickness. β-particles or γ-rays from a radioactive source are directed at the material. A detector measures the amount of radiation passing through. If the material is too thick, the amount of radiation is low and vice versa. The system will need to adjust the thickness of the material. α-particles are not suitable as they will be absorbed by the materials most easily. The type of radiation used, β-particles or γ-rays, depends on the type of materials. β-particles are suitable for thin materials such as paper as γ-rays penetrate through paper regardless of the thickness of the paper. γ-rays are suitable for slightly thicker materials such as metal plates as β-particles cannot penetrate through the thick materials.

Disciplinary Idea

Microscopic models can explain macroscopic phenomena.

The uses and hazards of radioactivity are often related to the ionising effects of radiation. These are partly caused by the interactions of α-particles and β-particles or γ-radiation with electrons in atoms. These particles may carry enough energy to "knock" electrons out of atoms or molecules, thereby ionising them.

Disciplinary Idea
Matter interacts through forces and fields.

Alpha and beta particles are electrically charged, and can interact strongly with biological cells and tissue, causing damage.

Hazards of Radioactivity

While radioactive isotopes are used in the diagnosis and treatment of cancer, they can also damage healthy cells. The energy carried by the radiation can kill cells, and cause mutation and cancer.

In 2011, the Fukushima Daiichi nuclear power plant in Japan was badly damaged by an earthquake and the tsunami that followed. This resulted in the leakage of radioactive substances.

The radioactive substances from the nuclear accident are mainly iodine-131, caesium-137 and strontium-90. β-particles from these substances can easily penetrate human skin and be absorbed in the body. Caesium-137 has a half-life of 30 years and strontium-90 has a half-life of 29 years. Thus, they will remain the environment for a long time.

If the radioactive substances are absorbed in excessive amounts, they can cause cancer and stunt childrens' growth. Thus, residents who lived near the power plant were rapidly evacuated. The Japanese government also started screening fish in the area for radioactive isotopes.

The leaked radioactive substances also affected the plants and animals near the power plant. These organisms could suffer from mutations, stunted growth or reproductive defects.

How can we protect ourselves when handling radioactive substances?

Protecting Ourselves from Radioactive Materials

Limit Contamination

Radiation cannot be seen, smelt or felt, so we may not know that there is a radioactive accident. If we are present at a site where there may have been a radioactive accident, we can take the following precautions.

- Leave the immediate area quickly to avoid being contaminated with radioactive materials. Follow the directions of officials to the nearest safe building or area.
- Remove the outer layer of the clothing. The radioactive materials may be on the clothing. Removing the clothing will reduce the risk of contamination.
- Wash all exposed parts of the body with soap and lukewarm water. This removes radioactive materials that may be present on the body and reduces the risk of contamination.

Reduce Exposure

Figure 22.22 shows four important ways for controlling exposure to ionising radiation.

Reduce exposure time

An experimental set-up should be prepared first before introducing the radioactive source.

Experiments involving radioactive materials should only be carried out in designated locations. These locations should only be used for work that requires the use of ionising radiation.

Increase distance between the 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 the body.

Shielding

Use materials that absorb ionising radiation. For example, wear lead-lined gloves and suits to protect the body.

Use thick concrete walls and lead-lined doors for rooms in which ionising radiation is used.

Storage

Store a radioactive material in a sealed container that will absorb the radiation from the source. This prevents the nuclear radiation from penetrating through the container and escaping into the air.

For instance, a instance of radioactive material must be stored in a lead box. The boxes should also be clearly labelled and kept in a secure place that is not easily accessible by anyone.

Figure 22.22 Ways to reduce exposure to ionising radiation

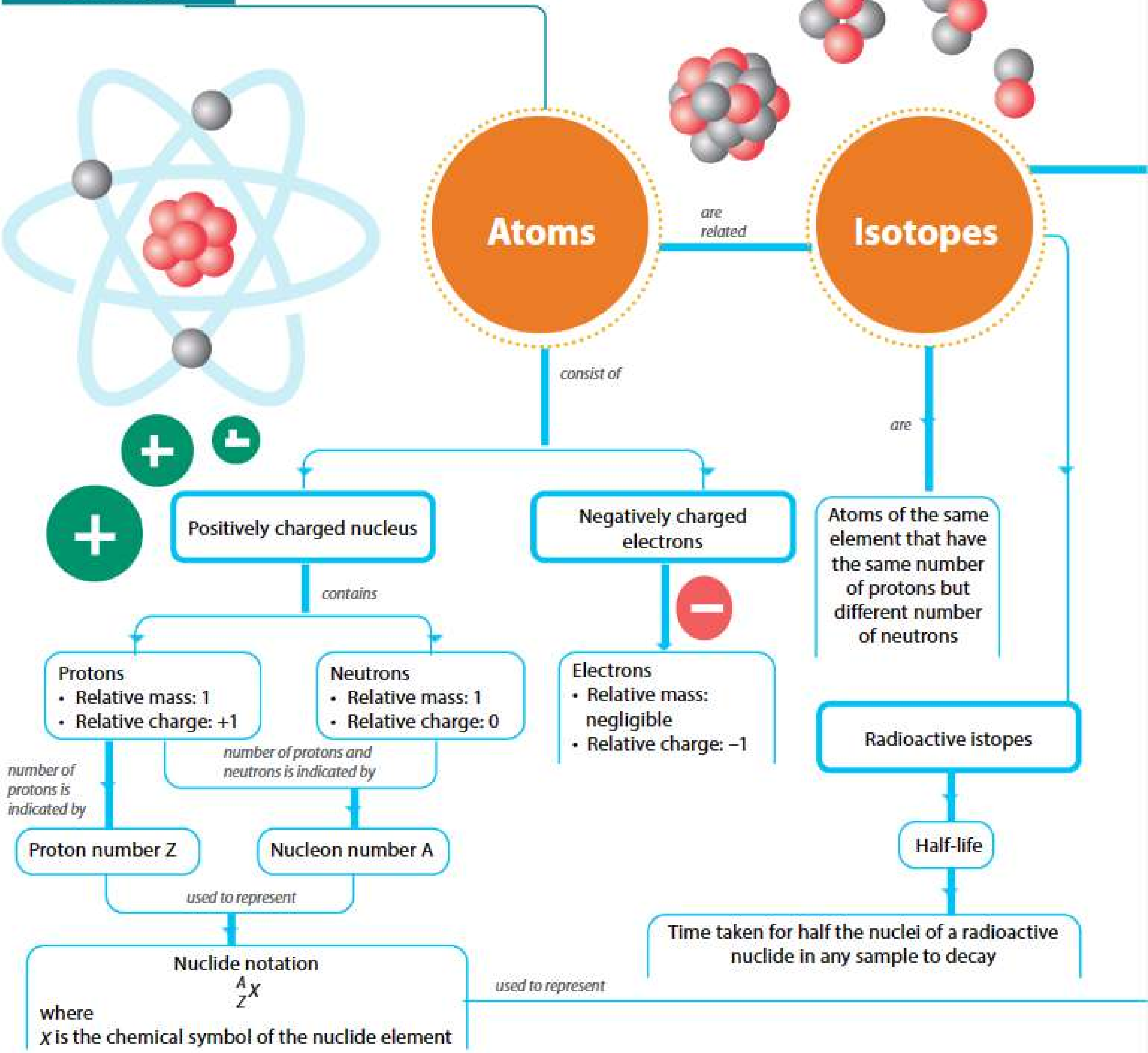
Link

Theory Workbook
Worksheet 22D
Let's Assess
Let's Reflect

Let's Practise 22.4

1 State **one** application of each of the three types of radiation — α-particles, β-particles and γ-rays.
2 State **two** safety measures when handling radioactive materials.
3 State **three** ways to control exposure to ionising radiation.

Let's Map It



Atoms

are related

Isotopes

consist of

Positively charged nucleus

Negatively charged electrons

contains

Protons
- Relative mass: 1
- Relative charge: +1

Neutrons
- Relative mass: 1
- Relative charge: 0

Electrons
- Relative mass: negligible
- Relative charge: –1

number of protons is indicated by

number of protons and neutrons is indicated by

Proton number Z

Nucleon number A

used to represent

Nuclide notation

$^{A}_{Z}X$

where

X is the chemical symbol of the nuclide element

are

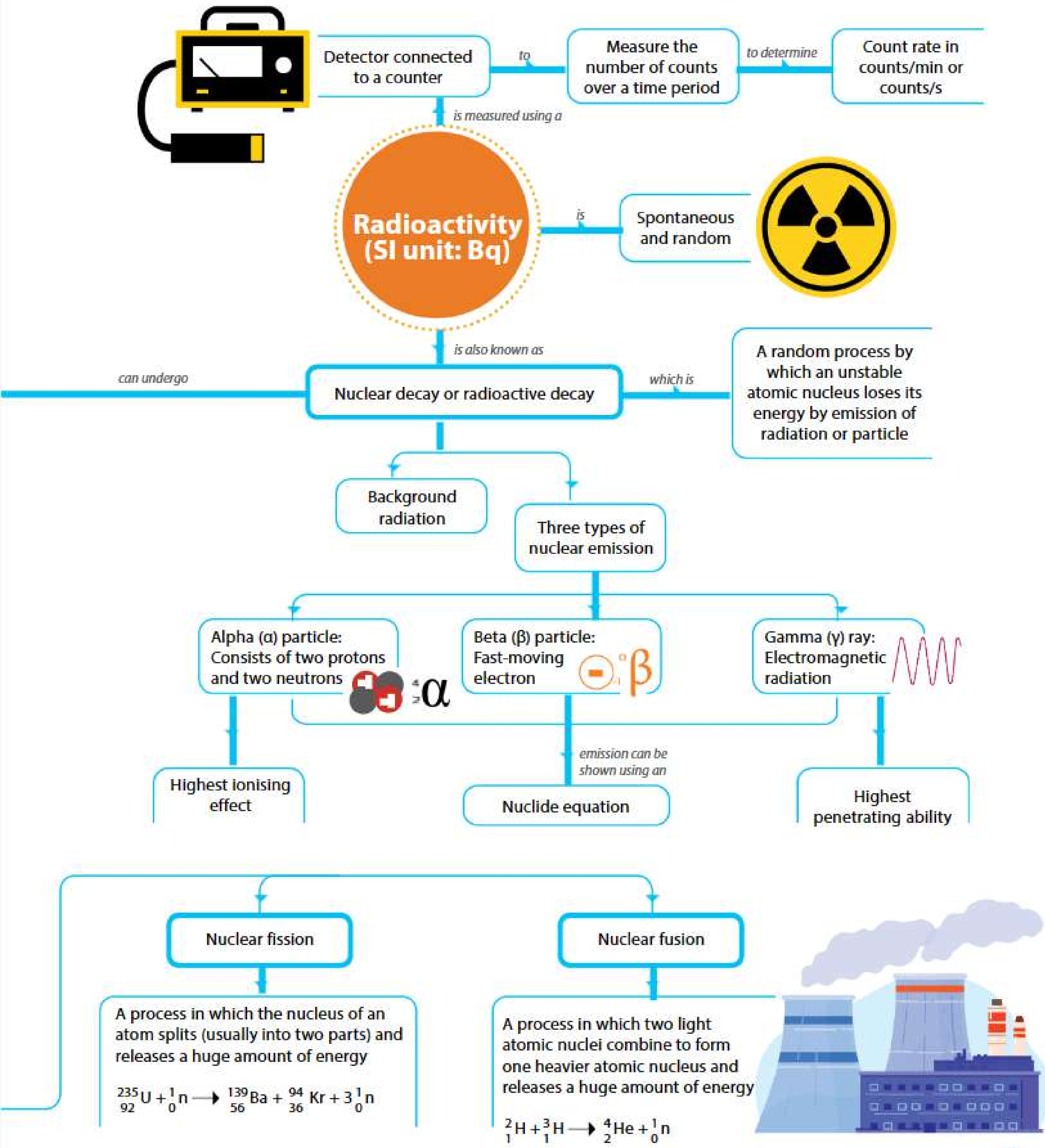
Atoms of the same element that have the same number of protons but different number of neutrons

Radioactive istopes

Half-life

Time taken for half the nuclei of a radioactive nuclide in any sample to decay

used to represent



Detector connected to a counter

to

Measure the number of counts over a time period

to determine

Count rate in counts/min or counts/s

is measured using a

Radioactivity (SI unit: Bq)

is

Spontaneous and random

is also known as

Nuclear decay or radioactive decay

which is

A random process by which an unstable atomic nucleus loses its energy by emission of radiation or particle

can undergo

Background radiation

Three types of nuclear emission

Alpha (α) particle: Consists of two protons and two neutrons $^{4}_{2}\alpha$

Beta (β) particle: Fast-moving electron $^{0}_{-1}\beta$

Gamma (γ) ray: Electromagnetic radiation

Highest ionising effect

emission can be shown using an

Nuclide equation

Highest penetrating ability

Nuclear fission

A process in which the nucleus of an atom splits (usually into two parts) and releases a huge amount of energy

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{139}_{56}Ba + ^{94}_{36}Kr + 3\,^{1}_{0}n$$

Nuclear fusion

A process in which two light atomic nuclei combine to form one heavier atomic nucleus and releases a huge amount of energy

$$^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n$$

Let's Review

Section A: Multiple-choice Questions

1 Which of the following statements correctly describe the structure of an atom?

○ **A** consists of positively charged protons and negatively charged electrons tightly bound together

○ **B** consists of positively charged protons and negatively charged neutrons tightly bound together

○ **C** consists of a positively charged nucleus and negatively charged electrons in orbit around the nucleus

○ **D** consists of a positively charged nucleus and negatively charged neutrons in orbit around the nucleus

2 The nuclide notation for radium-226 is $^{226}_{88}\text{Ra}$. How many electrons are there in a neutral atom of radium-226?

○ **A** 0 ○ **B** 88 ○ **C** 138 ○ **D** 226

3 Table 22.6 shows the count rate of a radioactive substance over two weeks.

Table 22.6

Number of Week	0	1	2
Count Rate / counts/s	3000	2120	1500

What is the count rate at the end of six weeks?

○ **A** 30 ○ **B** 375
○ **C** 500 ○ **D** 1000

4 A radioactive nucleus contains 138 neutrons. The nucleus emits an α-particle. How many neutrons are in the nucleus after it has emitted the α-particle?

○ **A** 136 ○ **B** 137 ○ **C** 138 ○ **D** 139

Section B: Structured Questions

1 An atom of lithium has a nucleon number of 7 and a proton number of 3.

(a) Draw a diagram to represent a neutral atom of lithium showing clearly the electrons, protons and neutrons.

(b) Lithium-6 and lithium-7 are isotopes of lithium.

(i) Define an *isotope*.

(ii) State a difference in the structures between the two isotopes.

2 The background count rate was 20 counts/min. When the radiation detector was placed near the source, the count rate was 800 counts/min. The half-life of the source was 5 minutes.

(a) What was the count rate at the end of 10 minutes?

(b) How long will it take for the count rate on the detector to decrease to 118 counts/min?

3 The following equation shows the nuclear fission of plutonium-239, $^{239}_{94}\text{Pu}$.

$$^{239}_{94}\text{Pu} + ^{1}_{0}\text{n} \longrightarrow ^{134}_{54}\text{Xe} + ^{A}_{Z}\text{Zr} + 3\,^{1}_{0}\text{n}$$

(a) What are the missing nucleon number A and proton number Z?

(b) The half-life of plutonium-239 is about 24 000 years. What are the dangers of using plutonium-239 with a long half-life?

4 What are some precautions to take when using radioactive substances?

Section C: Free-response Question

1 The figures on the dial of a watch are painted with a luminous radioactive substance. A scientist places the watch in front of a radiation detector and places a sheet in between the detector and the watch. She noticed that there is:

- a considerable decrease in the count rate (but above the background count rate) when the sheet is a 1-cm-thick lead;
- no change in count rate when the sheet was a piece of paper; and
- a very slight decrease when the sheet is a 1-mm-thick aluminium.

(a) What is the type of radiation coming from the watch?

(b) Explain why wearing this watch is a health hazard if the back of the watch is made of 1-mm-thick steel.

Link
Theory Workbook
Revision Worksheet 6

Answer Key

Chapter 1: Physical Quantities, Units and Measurements

* Only answers to multiple-choice questions and numerical answers are included.

Let's Practise 1.1and 1.2

2 6.02×10^{23}

Let's Practise 1.3

2 4.0 s

Let's Practise 1.4

2 Velocity = 30 km/h
3 Displacement = 1.41 km due north-east

Let's Review

Section A: Multiple-choice Questions

1 B 2 C 3 D

Section B: Structured Questions

1 (b) 1.3×10^3 kg
3 (c) 22 km
5 (c) Displacement = 15.6 km due north-west

Section C: Free-response Questions

1 $g = 9.9$ m/s^2

Chapter 2: Kinematics

Let's Practise 2.1

1 (a) 72 km/h
  (b) 20 m/s

Let's Practise 2.3

2 (b) 50 m/s
  (c) 125 m

Let's Review

Section A: Multiple-choice Questions

1 B 2 D 3 A 4 D 5 A

Section B: Structured Questions

1 (b) (i) 3.33 km/h
    (ii) 2.67 km/h
    (iii) 3.08 km/h
3 (a) From $t = 12$ s to $t = 16$ s
  (b) 20 m/s^2
  (c) (i) 520 m
    (ii) 32.5 m/s
4 (a) 3.5 m/s^2
  (b) (ii) 22.5 m/s
  (c) 337.5 m

Section C: Free-response Questions

1 (b) 0.40 m/s
  (c) 0.60 m to the right of B
  (d) Acceleration = 0 m/s^2
  (e) −0.20 m/s^2

Chapter 3: Dynamics I: Mass and Weight

Let's Practise 3.2

3 100 N

Let's Review

Section A: Multiple-choice Questions

1 A 2 B 3 B 4 A

Section B: Structured Questions

2 2750 N

Chapter 4: Dynamics II: Forces

Let's Practise 4.1

2 2.5 m/s^2
3 5770 N

Let's Practise 4.2

2 Weight $W = 17.3$ N (downward direction)

Let's Practise 4.3

1 50 N

Let's Review

Section A: Multiple-choice Questions

1 A 2 B 3 A 4 B 5 C

Section B: Structured Questions

1 (b) (i) 10 m/s^2
    (ii) 100 kg
    (iii) 0.0002 N
2 3.66 m/s^2
3 (b) (i) 500 N
    (ii) 2500 N
    (iii) 1250 N
5 2.0 m/s^2

Section C: Free-response Questions

2 $T_2 = W = 100$ N along the horizontal
  $T_1 = 142$ N at 45 ° to the horizontal

Chapter 5: Turning Effects of Forces

Let's Practise 5.1

1 28.6 N
2 1.0 m towards the pivot

Let's Practise 5.2

2 25 N

Let's Review

Section A: Multiple-choice Questions

1 C 2 B 3 B 4 B 5 A

Section B: Structured Questions

3 0.30 N
5 (b) 50 N/m
  (c) 5.0 N

Section C: Free-response Questions

1 (b) $M = 40\,000$ N m
  Direction of moment of the ramp: clockwise
2 (a) 12 N
  (c) 2.31 N

Chapter 6: Pressure

Let's Practise 6.1

2 $\frac{z}{x^2}$ Pa
3 Maximum pressure = 1.33 kPa
  Minimum pressure = 0.667 kPa

Let's Practise 6.2

1 80 N
2 13.9 N

Let's Practise 6.3

1 (b) 106 kPa
  (c) 67.4 cm

Let's Review

Section A: Multiple-choice Questions

1 A 2 D 3 D 4 D 5 D

Section B: Structured Questions

2 875 kg/m^3
3 9420 N
4 (b) 320 kPa
5 (a) 100 800 Pa
  (b) 2000 kg/m^3

Section C: Free-response Questions

1 (c) 200 N
2 (a) 750 kg/m^3

Chapter 7: Energy

Let's Practise 7.1

2 (a) 900 J
  (b) 30 m/s

Let's Practise 7.2

1 (b) (i) 24 J
    (ii) 24 J
2 (a) 100 W
  (b) 1.8 MJ
3 (b) 70%

Let's Review

Section A: Multiple-choice Questions

1 D 2 A 3 B 4 C 5 B 6 C

Section B: Structured Questions

3 (a) 2.0×10^{-3} J
  (b) 1.5×10^{-3} J
4 (b) (i) 9.0 J
    (ii) 12 J

Section C: Free-response Questions

1 (b) 300 kJ
  (c) (i) 240 kJ
    (ii) 17.9 m/s
2 (a) (i) P: 30.4%; Q: 12.5%; R: 40.4%; S: 35.7%; T: 20.5%
  (b) 868.1 MW

Chapter 8: Kinetic Particle Model of Matter

Let's Review

Section A: Multiple-choice Questions

1 D 2 C 3 B 4 A 5 D

Chapter 9: Thermal Processes

Let's Review

Section A: Multiple-choice Questions

1 A 2 D 3 B 4 B 5 D

Chapter 10: Thermal Properties of Matter

Let's Review

Section A: Multiple-choice Questions

1 C 2 A 3 B 4 D

Section B: Structured Questions

1 (a) 643 750 J
  (b) 565 kJ
2 10.9 °C
3 9.3 °C
4 (a) 2260 J
  (b) 51.4 °C
  (c) 11.1

Chapter 11: General Wave Properties I: Introduction

Let's Review

Section A: Multiple-choice Questions

1 A 2 D 3 B 4 C 5 D

Section B: Structured Questions

1 (a) 15 m
  (b) 5.0 m/s
  (c) 0.333 Hz

Chapter 12: General Wave Properties II: Sound

Let's Review

Section A: Multiple-choice Questions

1 B 2 C 3 D 4 A

Section B: Structured Questions

1 (b) 420 m; 540 m
2 (b) 4.0 cm

Chapter 13: Electromagnetic Waves

Let's Review

Section A: Multiple-choice Questions

1 A 2 C 3 D 4 B 5 C

Section B: Structured Questions

2 (a) 0%
  (b) 30%
5 (a) 1.0×10^{6}
  (b) 3.3×10^{-6} s or 3.3 μs
  (c) 82.5×10^{-6} m

Chapter 14: Light

Let's Practise 14.2

1 1
2 1

Let's Practise 14.4

1 (a) 0.80 cm, 3.0 cm
2 (a) 6.0 cm, 6.0 cm

Let's Review

Section A: Multiple-choice Questions

1 D 2 B 3 A 4 C 5 C

Section B: Structured Questions

3 (a) 24.6 °
4 (a) 48.8 °

Chapter 15: Static Electricity

Let's Practise 15.1

2 6.25×10^{18} electrons

Let's Review

Section A: Multiple-choice Questions

1 C 2 A 3 A 4 B 5 D

Chapter 16: Current of Electricity

Let's Practise 16.1

2 180 W

Let's Practise 16.2

1 100 Ω
2 72 Ω

Let's Review

Section A: Multiple-choice Questions

1 D 2 C 3 D 4 C 5 D

Section B: Structured Questions

2 1.0×10^{-3} C
3 9.4 m
4 (a) 7.5 Ω

Section C: Free-response Questions

1 (b) 57.6×10^{3} C
  (c) 672 kJ
2 (a) 30 C
  (b) 10 V
  (d) 22.5 C
  (e) 53.3 Ω

Chapter 17: D.C. Circuits

Let's Practise 17.1

1 (a) 3.0 Ω
(b) Voltage across 1 Ω resistor = 0.50 V
Voltage across 2 Ω resistor = 1.00 V
2 14 Ω

Let's Practise 17.2

1 I_1 = 1.5 A; I_2 = 0.50 A
Potential difference = 1.5 V
2 15 V

Let's Practise 17.3

1 Current = 0.10 A
P.d. across 5 Ω resistor = 0.50 V
P.d. across 15 Ω resistor = 1.5 V
2 (a) Effective resistance = 10 Ω
(b) Current drawn = 0.20 A

Let's Practise 17.4

1 Voltage = 0.57 V; Current =1.14 mA
2 20 000 Ω

Let's Review

Section A: Multiple-choice Questions

1 B 2 D 3 C 4 A

Section B: Structured Questions

1 1.2 V
2 12 V
3 (a) 2.0 V
(b) 1.5 V
4 (a) 0.50 Ω, 0.33 Ω
(c) 0.25Ω
5 (a) 0.50A
(b) 1.0 A

Section C: Free-response Questions

1 (a) 2.5 Ω
(b) 2.0 A
(c) I_1 = 1.33 A; I_2 = 1.0 A; V_1 = 4.0 V; V_2 = 1.0 V
2 (c) 4.0 V
(d) 4.8 V

Chapter 18: Practical Electricity

Let's Practise 18.1

1 2400 W
2 $3.84

Let's Review

Section A: Multiple-choice Questions

1 A 2 A 3 C 4 A 5 D

Section B: Structured Questions

2 $0.72
4 (a) 56.52 A
(b)

Type of Washing Machine	Fuse Rating / A
5 kg load	3
10 kg load	5
15 kg load	10

5 (a) 8.83 kW h
(b) $1.77
(c) 55.2 hours

Section C: Free-response Questions

2 (a) 1152 W
(b) $0.46

Chapter 19: Magnetism

Let's Review

Section A: Multiple-choice Questions

1 A 2 C 3 D 4 C 5 C

Chapter 20: Electromagnetism

Let's Review

Section A: Multiple-choice Questions

1 D 2 B 3 C 4 D 5 C

Chapter 21: Electromagnetic Induction

Let's Practise 21.3

1 (b) 4400
  (c) 15 mA

Let's Review

Section A: Multiple-choice Questions

1 C 2 C 3 C 4 D

Section C: Free-response Questions

1 (d) (ii) 1000
2 (b) 1 MW
  (c) 100

Chapter 22: Radioactivity

Let's Practise 22.1

1 (b) $^{238}_{92}\text{U}$
  (c) 146 neutrons

Let's Practise 22.2

1 (b) 7 days
3 (a) 45 h
  (b) 312.5 counts/min

Let's Practise 22.3

1 (b) $A = 94$; $Z = 40$

Let's Review

Section A: Multiple-choice Questions

1 C 2 B 3 B 4 A

Section B: Structured Questions

2 (a) 215 counts/min
  (b) 15 min
3 (a) $A = 103$
  $Z = 40$

Quick Revision Guide

Chapter 1: Physical Quantities, Units and Measurements

- A **physical quantity** is a quantity that can be measured. It consists of a numerical magnitude and a unit.
- Each complete to-and-fro motion is one **oscillation**.
- The **period** of a simple pendulum is the time taken for one complete oscillation.
- **Scalar quantities** are physical quantities that have only magnitude.
- **Vector quantities** are physical quantities that have both magnitude and direction.
- **Speed** is the distance moved per unit time.

► $\textbf{Speed} = \dfrac{\textbf{distance}}{\textbf{time taken}}$

- **Velocity** is the rate of change of displacement.

► $\textbf{Velocity} = \dfrac{\textbf{displacement}}{\textbf{time taken}}$

Chapter 2: Kinematics

- **Average speed** assumes that an object travels at the same speed throughout the entire distance.

► $\textbf{Average speed} = \dfrac{\text{total distance travelled}}{\text{total time taken}}$

- **Average velocity** assumes that an object travels at the same velocity throughout the entire displacement.

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

- **Acceleration** is the rate of change of velocity.

► $\textbf{Acceleration} = \dfrac{\textbf{change of velocity}}{\textbf{time taken}}$

- **Uniform acceleration** is a constant rate of change of velocity.

► $a = \dfrac{\Delta v}{\Delta t} = \dfrac{v - u}{t_v - t_u}$ where Δv = change in velocity (m/s)
Δt = time interval between t_u and t_v (s)
v = final velocity (m/s)
u = initial velocity (m/s)
t_v = time at which an object is at final velocity v (s)
t_u = time at which an object is at initial velocity u (s)

- The **gradient of a displacement–time graph** of an object gives the velocity of the object.
- The **gradient of a velocity–time graph** of an object gives the acceleration of the object.
- The area **under the velocity–time graph** gives the displacement of the object.

Chapter 3: Dynamics I: Mass and Weight

- **Mass** is a measure of the amount of matter in a body.
- **Weight** is the gravitational force acting on an object that has mass.

► $W = mg$ where W = weight (N)
m = mass (kg)
g = gravitational field strength (N/kg)

- A **gravitational field** is a region in which a mass experiences a force due to gravitational attraction.
- **Gravitational field strength** g is defined as the gravitational force per unit mass placed at that point.

Chapter 4: Dynamics II: Forces

- **Newton's First Law of Motion** states that every object will continue in its state of rest or uniform motion in a straight line unless a resultant force acts on it.
- The **inertia** of an object refers to the reluctance of the object to change its state of rest or motion, due to its mass.
- **Newton's Second Law of Motion** states that when a resultant force acts on an object of a constant mass, the object will accelerate in the direction of the resultant force.

► $F = ma$ where F = resultant force (N)
m = mass of object (kg)
a = acceleration of object (in m/s^2)

- **Newton's Third Law of Motion** states that if body A exerts a force F_{AB} on body B, then body B will exert an equal and opposite force F_{BA} on body A.
- **Friction** is the contact force that opposes or tends to oppose motion between surfaces in contact.
- When the air resistance acting against an object equals its weight, the object starts to travel at a constant speed known as **terminal velocity**.

Chapter 5: Turning Effects of Forces

- The **moment of a force** M, or torque, about a pivot is the product of the force F and the perpendicular distance d from the pivot to the line of action of the force.

► $M = Fd$ where F = force applied (N)
d = perpendicular distance from the pivot to the line of action of the force (m)

- The **principle of moments** states that when a body is in equilibrium, the sum of clockwise moments about a pivot is equal to the sum of anticlockwise moments about the same pivot.

Sum of clockwise moments about any pivot = Sum of anticlockwise moments about the same pivot

- The **centre of gravity** of an object is an imaginary point where the entire weight of the object seems to act.
- The **stability** of an object is a measure of its ability to maintain its original position.

Chapter 6: Pressure

- **Pressure** is the force acting per unit area.

▶ $P = \frac{F}{A}$ where P = pressure (Pa)
F = force (N)
A = contact area (m^2)

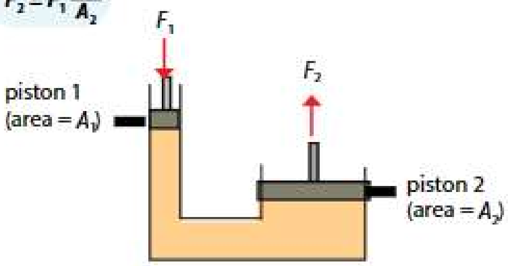
▶ $P = h\rho g$ where h = height (m)
ρ = density (kg/m^3)
g = gravitational field strength (N/kg)

- **Density** is defined as mass per unit volume.

▶ $\rho = \frac{m}{V}$ where ρ = density
m = mass (kg)
V = volume (m^3)

- **Pascal's principle or Pascal's law**: If a pressure is applied to an enclosed liquid, the pressure is transmitted to all other parts of the liquid undiminished.

▶ $F_2 = F_1 \frac{A_1}{A_2}$



Chapter 7: Energy

- To calculate the **amount of energy in the kinetic store** of a body moving at speed v, we use the following:

▶ $E_k = \frac{1}{2}mv^2$ where E_k = energy in the kinetic store (J)
m = mass of the body (kg)
v = speed of the body (m/s)

- To calculate the **amount of energy in the gravitational potential store** of a body at a height h above the ground, we use the following:

▶ $E_p = mgh$ where E_p = energy in the gravitational potential store (J)
m = mass of the body (kg)
g = gravitational field strength (N/kg)
h = height (m)

- The **principle of conservation of energy** states that energy cannot be created or destroyed. It can be transferred from one energy store to another during an event or process. Energy can be transferred from one store to another. The total energy of an isolated system is constant.
- **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.

▶ $W = Fs$ where W = work done by a constant force F (J);
F = constant force (N);
s = distance moved by the object in the direction of the force (m).

- **Power** is defined as the work done or energy transferred per unit time.

▶ $P = \frac{W}{t} = \frac{E}{t}$ where P = power (W)
W = work done (J)
E = energy transferred (J)
t = time taken (s)

- The **efficiency** of a machine can be calculated using:

▶ $\text{Efficiency} = \frac{\text{useful energy output}}{\text{total energy input}} \times 100\%$

Chapter 8: Kinetic Particle Model of Matter

- The **kinetic particle model of matter** is made up of tiny particles that are in continuous motion.
- The random motion of particles in a fluid is called **Brownian motion**.
- **Temperature** rises with the average kinetic energy of the particles in a body and vice versa.
- At the particle level, **pressure** is the average force exerted by the particles per unit area.

Chapter 9: Thermal Processes

- **Thermal equilibrium** describes a state in which two or more objects have the same temperature and that there is no net transfer of energy between them.
- **Conduction** is a process of energy transfer where energy is transferred through the passing on of vibrational motion from one particle to another.
- **Convection** is a process of energy transfer by means of convection currents of a fluid (liquid or gas), due to a difference in density.
- **Radiation** is the process of energy transfer by electromagnetic waves. It does not require a medium.

Chapter 10: Thermal Properties of Matter

- **Internal energy** consists of the kinetic energy associated with the random motion of the particles and the total potential energy between the particles in the system.
- **Heat capacity** C of an object is the change of its internal energy per unit change in its temperature.

▶ $C = \frac{Q}{\Delta\theta}$ where Q = change in internal energy (J) by energy transfer
$\Delta\theta$ = change in temperature (K or °C)

- **Specific heat capacity** c of a material is the change of its internal energy per unit mass for each unit change in its temperature.

▶ $C = \frac{C}{m} = \left(\frac{Q}{m\Delta\theta}\right)$ where C = heat capacity (J/K or J/°C)
Q = change in internal energy (J) by energy transfer
m = mass of substance (kg)
$\Delta\theta$ = change in temperature (K or °C)

- The energy Q transferred by heating to an object of heat capacity C so that the object has a temperature change $\Delta\theta$, is:

▶ $Q = C\Delta\theta$

- For a substance made of a uniform material of mass m, specific heat capacity c, and a temperature change $\Delta\theta$, the energy Q transferred by heating is:

▶ $Q = mc\Delta\theta$

- **Latent heat** L is the energy released or absorbed to change the state of a substance, at constant temperature.
- **Latent heat of fusion** L_f is the amount of energy transferred to change a substance between the solid and liquid states, at constant temperature.
- **Specific latent heat of fusion** l_f is the amount of energy transferred per unit mass of a substance to change between the solid and liquid states, at constant temperature.

▶ $L_f = l_f m$ where L_f = latent heat of fusion (J)
l_f = specific latent heat of fusion (J/kg)
m = mass of substance (kg)

- **Latent heat of vaporisation** L_v is the amount of energy transferred to change a substance between the liquid and gaseous states, at constant temperature.
- **Specific latent heat of vaporisation** l_v is the amount of energy transferred per unit mass of a substance to change it between the liquid and gaseous states, at constant temperature.

▶ $L_v = l_v m$ where L_v = latent heat of vaporisation (J)
l_v = specific latent heat of vaporisation (J/kg)
m = mass of substance (kg)

- The internal energy of the substance increases when it is heated.
- The internal energy of the substance decreases when it is cooled.

Chapter 11: General Wave Properties I: Introduction

- A wave is a disturbance that propagates through space, carrying energy with it but not matter. The periodic and repetitive motion of any selected point in a wave is known as **vibrations** or **oscillations**.
- A **transverse** wave has a direction of vibration that is perpendicular to the direction of wave travel.
- A **longitudinal** wave has a direction of vibration that is parallel to the direction of wave travel.
- **Displacement** of any point on the wave is a vector pointing from its rest position to the point.
- **Amplitude** of a wave is its maximum magnitude of displacement from its rest position.
- **Crests** are the highest points of a transverse wave. **Troughs** are the lowest points of a transverse wave.
- **In phase** describes two points on a wave that always have the same direction of motion (moving in step).
- **Wavelength** λ is the shortest distance between two points which are in phase along the wave's direction.
- The **period** T is the taken by each point on the wave to complete one oscillation.
- The **frequency** f is the number of oscillations each point completes per second.

▶ $f = \frac{1}{T}$ where f = frequency (Hz)
T = period (s)

- **Wave speed** v is the distance travelled by a wave per second.

▶ $v = \frac{\lambda}{T}$ where v = wave speed (m/s)
λ = wavelength (m)
T = period (s)

- A **wavefront** is an imaginary line joining all adjacent points that are in phase.

Chapter 12: General Wave Properties II: Sound

- **Sound** is a longitudinal wave travelling in the air, created by a vibrating source.
- Compressed regions are called **compressions** and the extended regions are called **rarefactions**.
- **Loudness** is related to the amplitude of a sound wave — the larger the amplitude, the louder the sound.
- **Pitch** is related to the frequency of a sound wave — the higher the frequency, the higher the pitch.
- The audible range of humans is 20 Hz to 20 000 Hz. Frequencies below 20 Hz are called infrasound and frequencies above 20 000 Hz are called **ultrasound**.
- An **echo** is the repetition of a sound due to the reflection of sound.
- **Echolocation** is the location of objects using reflected sound.

Chapter 13: Electromagnetic Waves

- Arrangement of electromagnetic waves in order of frequency or wavelength:

Electromagnetic Wave	Frequency	Wavelength
radio waves	lowest	longest
microwaves		↑
infrared	↓	
visible light		
ultraviolet		
X-rays		
gamma rays	highest	shortest

- **Ionising waves** are those with higher frequencies and hence higher energies.
- All electromagnetic waves are **transverse** waves.
- All electromagnetic waves travel with the same speed of **3×10^8 m/s in a vacuum**.
- The **wave speed** equation, $v = f\lambda$, applies to all electromagnetic waves.
- When an electromagnetic wave travels from a vacuum to other media, the **wave speed and wavelength decrease. The frequency stays the same** as at the source when the wave goes into a different medium.
- Electromagnetic waves **undergo reflections and refractions**.
- Electromagnetic waves **transfer energy**.
- All material bodies **emit a range of electromagnetic waves**. In general, higher temperature bodies tend to emit more and higher frequency electromagnetic waves.

Chapter 14: Light

- The **first law of reflection** states that the incident ray, reflected ray and the normal at the point of incidence lie in the same plane.
- The **second law of reflection** states that the angle of incidence θ_i is equal to the angle of reflection θ_r.
- The image of a point object in a plane mirror is always as far behind the mirror as the object is in front of the mirror.
- **Refraction** is the bending of light as light passes from one optical medium to another.
- The **first law of refraction** states that the incident ray, refracted ray and the normal at the point of incidence all lie in the same plane.
- The **second law of refraction** states that for two given media, the ratio of the sine of angle of incidence to the sine of the angle of refraction is a constant, that is, $\frac{\sin i}{\sin r}$ = constant.
- The **refractive index** n of a medium is defined as the ratio of the speed of light in a vacuum to the speed of light in that medium.

▶ $n = \frac{c}{v}$ where c = speed of light in a vacuum
v = speed of light in the medium

▶ $n = \frac{\sin i}{\sin r}$ where i = angle of incidence in a vacuum
r = angle of refraction in the medium

- The principle of reversibility of light rays states that regardless of how many times a light ray has been reflected or refracted, it will follow the same path when its direction is reversed.
- **Critical angle** θ_c is defined as the angle of incidence in an optically denser medium for which the angle of refraction in the less dense medium is 90 °.
- **Total internal reflection** is the complete reflection of a light ray in an optically denser medium at the boundary with an optically less dense medium.

▶ $\sin c = \frac{1}{n}$ where c = critical angle
n = refractive index of the medium

- **Focal length** f is the distance between the optical centre and the principal focus point.
- A **real image** can be formed on a screen placed at the image plane but a **virtual image** cannot be formed on a screen placed at its image plane.

Chapter 15: Static Electricity

- **Like charges repel** each other while **unlike charges attract** each other.
- **Electric field** is a region in which an electric charge experiences an electric force.

Chapter 16: Current of Electricity

- **Electric current** is the rate of flow of charge with respect to time.

▶ $I = \frac{Q}{t}$ where I = current (A)
Q = charge (C)
t = time taken (s)

- The direction of flow of positive charges is described as the **conventional current**.
- The **electromotive force (e.m.f)** of an electrical source is the work done by the source in driving a unit charge around a complete circuit.

▶ $E = \frac{W}{Q}$ where E = e.m.f. of the electrical source (V)
W = work done (J)
Q = amount of charge (C)

- When cells are arranged in **series**, the resultant or total e.m.f. is the sum of the individual e.m.f. of each electrical source.
- When cells are arranged in **parallel**, the resultant e.m.f. is equal to that of a single electrical source.
- The **potential difference (p.d.)** across a component in a circuit is the work done per unit charge in driving charges through the component and that it is measured in volts.

▶ $V = \frac{W}{Q}$ where V = potential difference of voltage across a component (V)
W = work done (J)
Q = amount of charge (C)

- The **resistance *R*** of a component is the ratio of the potential difference V across it to the current I flowing through it.

▶ $R = \frac{V}{I}$ where R = resistance of the component (Ω)
V = p.d. across the component (V)
I = current flowing through the component (A)

- The **resistivity** of a substance depends on what the material is composed of.

▶ $R = k\frac{l}{A}$ where R = resistance of the component (Ω)
k = constant
l = length of wire (m)
A = cross-sectional area of wire (m^2)

When a material exhibits this linear relationship between p.d. V and current I, it is said to be **ohmic**.

- The resistances of **non-ohmic conductors** change as their temperature changes.

Chapter 17: D.C. Circuits

- In a **series circuit**, the current at every point is the same.
- In a **series circuit**, the **total potential difference** supplied to the circuit V_c is equal to the sum of the individual potential difference across the resistors.

▶ $V_c = V_1 + V_2 + \ldots + V_n$

- In a series circuit, the **effective resistance R_e** is equal to the sum of the individual resistance.

▶ $R_e = \frac{V_c}{I} = R_1 + R_2 + \ldots + R_n$

- In a **parallel circuit**, the total current flowing into or out of the parallel branches is equal to the sum of the individual current in each parallel branch.

▶ $I = I_1 + I_2 + \ldots + I_n$

- In a **parallel circuit**, the p.d. across the parallel branches is the same.
- In a parallel circuit, the **reciprocal** of the effective resistance of resistors $\frac{1}{R_E}$ is equal to the sum of the reciprocal of the individual resistances.

▶ $\frac{1}{R_e} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$

- A **potential divider** is a voltage divider, which makes use of voltage drop across resistors in series to divide voltage.
- **Transducers** convert changes in the physical condition, such as pressure, temperature or light into electrical signals so that these physical conditions can be measured.

Chapter 18: Practical Electricity

- **Electric work done *W*** can be calculated using:

▶
$$\begin{aligned} W &= VIt \\ &= I^2Rt \quad (\text{since } V = IR) \\ &= \frac{V^2}{R}t \quad (\text{since } I = \frac{V}{R}) \end{aligned}$$

- **Power *P*** can be calculated using:

▶
$$\begin{aligned} P &= VI \\ &= I^2R \quad (\text{since } V = IR) \\ &= \frac{V^2}{R} \quad (\text{since } I = \frac{V}{R}) \end{aligned}$$

Chapter 19: Magnetism

- **Induction**, or **induced magnetism**, can take place when a ferromagnetic material is placed close to a strong magnet or within a current-carrying solenoid.
- A **magnetic field** is a region in which the force of magnetism acts.
- **Temporary magnets** are magnets that retain their magnetism in the presence of an electric current or a permanent magnetic field.
- **Permanent magnets** do not require the presence of an electric current or a permanent magnetic field to retain their magnetism.

Chapter 20: Electromagnetism

- The **strength of magnetic field** increases when **current** is increased.
- The **direction of the magnetic field** is reversed when the current is reversed.
- The **strength of magnetic field 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; and
  - placing a soft iron core within the solenoid.
- A current-carrying conductor will experience a force if the magnetic field applied is perpendicular (or has a component that is perpendicular) to the direction of flow of current. This is known as the **motor effect**.
- The direction of the force can be determined using **Fleming's left-hand rule**.
- The **turning effect** on a current-carrying wire in a d.c. motor can be increased by:
  - increasing the number of turns in the coil;
  - increasing the current; and
  - adding a soft iron cylinder.
- The function of the **split-ring commutator** is to reverse the direction of the current in the coil every half a revolution.

Chapter 21: 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.
- **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. **Magnetic flux** is the magnetic field in a given area.
- **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.
- **Fleming's left-hand rule** is used for electric motors, while **Fleming's right-hand rule** is used for generators.
- A **transformer** is a device used in the transmission of electricity. It can change a high alternating voltage (at low current) to a low alternating voltage (at high current) or vice versa.
- The **voltages** of the primary and secondary coils are related by:

▶ $\frac{V_p}{V_s} = \frac{N_p}{N_s}$ where V_s = secondary (output) voltage (V)
V_p = primary (input) voltage (V)
N_s = number of turns in secondary coil
N_p = number of turns in primary coil

- In an **ideal transformer**, all the energy that is applied to the primary coil are transferred to the secondary coil.

▶ $V_pI_p = V_sI_s$ where V_p = primary (input) voltage (V)
I_p = primary (input) current (A)
V_s = secondary (output) voltage (V)
I_s = secondary (output) current (A).

The efficiency of a transformer can be calculated using the following equation:

▶ $\eta = \frac{\text{output power}}{\text{Input power}} \times 100\%$

Chapter 22: Radioactivity

- The **proton number** is the number of protons in an atom. It is also known as **atomic number**.
- The **nucleon number** is the total number of neutrons and protons in the nucleus of an atom. It is also known as mass number.

  Number of neutrons in a nucleus
  = nucleon number *A* – proton number *Z*
- **Isotopes** are atoms of the same element that have the same number of protons but different numbers of neutrons.
- **Nuclear decay** is a random process by which an unstable atomic nucleus loses its energy by emission of electromagnetic radiation or particle(s).
- There are three types of nuclear emission: **alpha (α) particles**, **beta (β) particles** and **gamma (γ) rays**.
- **Ionising radiation** is radiation with high energies that can knock off electrons from atoms to form ions.
- **Background radiation** refers to nuclear radiation in an environment where no radioactive source has been deliberately introduced.
- The **half-life** of a radioactive nuclide is the time taken for half the nuclei of that nuclide in any sample to decay.
- **Nuclear fission** is a process in which the nucleus of an atom splits (usually into two parts) and releases a huge amount of energy.
- **Nuclear fusion** is a process in which two light atomic nuclei combine to form one heavier atomic nucleus and releases a huge amount of energy.

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