CHAPTER

11

General Properties of Waves

PHYSICS WATCH

Scan this page to watch a stadium wave in action.

QUESTIONS

- Why can the motion created by the people be described as a wave?
- How could you measure the speed of this wave?
- How is the motion of the people related to the motion of wave?

Have you seen sports fans doing 'the wave' inside a stadium? This wave has many names depending on the location of the stadium. It is popularly known as the Mexican wave after soccer fans in many parts of the world watch it for the first time during the 1986 World Cup in Mexico. Some people call it *la ola*, which means *wave* in Spanish. We can refer to it in general as the stadium wave.

When you find yourself with thousands of people in a major sporting event, have some fun. Start the *la ola*. You don't need water to do it!

11.1 Introducing Waves

In this section, you will learn the following:

- Describe what is meant by a wave motion.
- Know that waves transfer energy without transferring matter.
- Know that for a transverse wave, the direction of vibration is at right angles to the direction of propagation.
- Understand that electromagnetic radiation, water waves and seismic S-waves (secondary) are known as transverse waves
- Know that for a longitudinal wave, the direction of vibration is parallel to the direction of propagation
- Understand that sound waves and seismic P-waves (primary) are known as longitudinal waves

PHYSICS WATCH

Scan this page to watch a clip on wave motion.

When we think of the word *waves*, what often comes to mind is sea waves. Besides sea waves, there are other types of waves, such as sound waves and radio waves. What do all these waves have in common? What are the characteristics of a wave?

What is wave motion?

Wave motion is made up of periodic motion or motion repeated at regular intervals.

For example, the swinging motion of a pendulum bob (Figure 11.1), from the extreme left to the extreme right and back to its starting position, is said to be periodic. One complete cycle of such motion is known as an **oscillation** or a **vibration**. The source of any wave is an oscillation or a vibration.

A wave is a disturbance that *transfers energy* from one place to another. It *does not transfer matter* during the energy transfer (Figure 11.2).

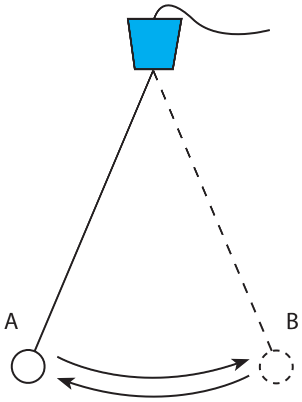


Figure 11.1 *An oscillation is completed when the pendulum bob moves from A to B, and then back to A.*

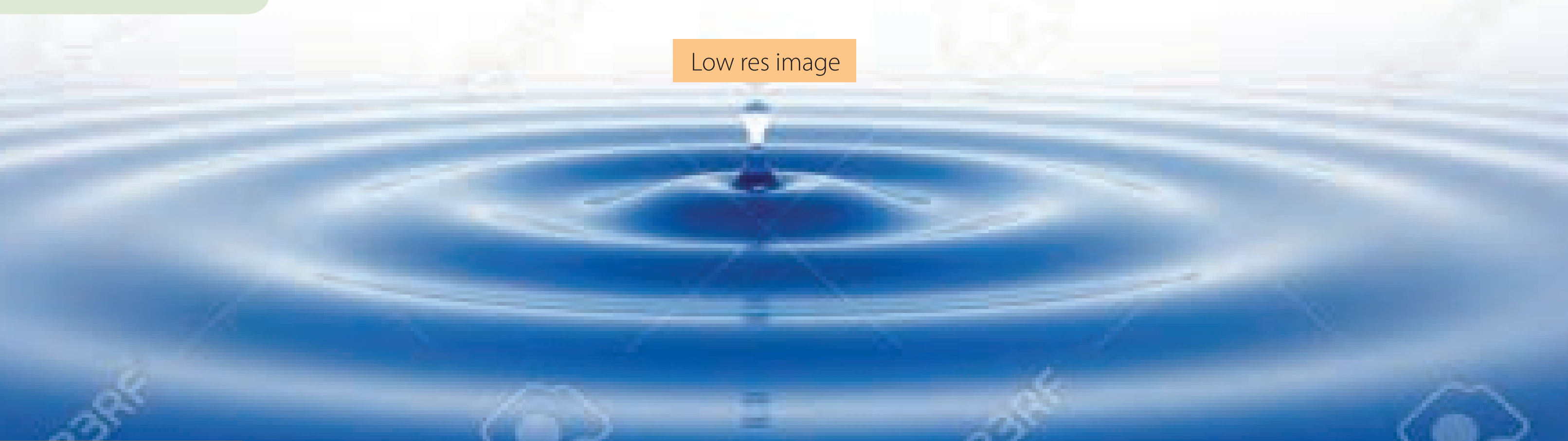
ENRICHMENT *INFO*

Wave Energy

Have you ever experienced being hit by a huge wave while floating at sea? You would find yourself displaced when you are hit. Work is done by the wave in applying force to move you over some distance.

Thus, the energy carried by waves can be used to do useful work such as generating electricity and pumping water. Wave power has not been utilised as much compared to solar power, wind power and hydropower. However, it is able to generate more power per unit area.

Figure 11.2 *As ripples spread outwards, any object on the water surface (e.g. an empty bottle) will only bob up and down. This shows that waves transfer energy without transferring matter.*



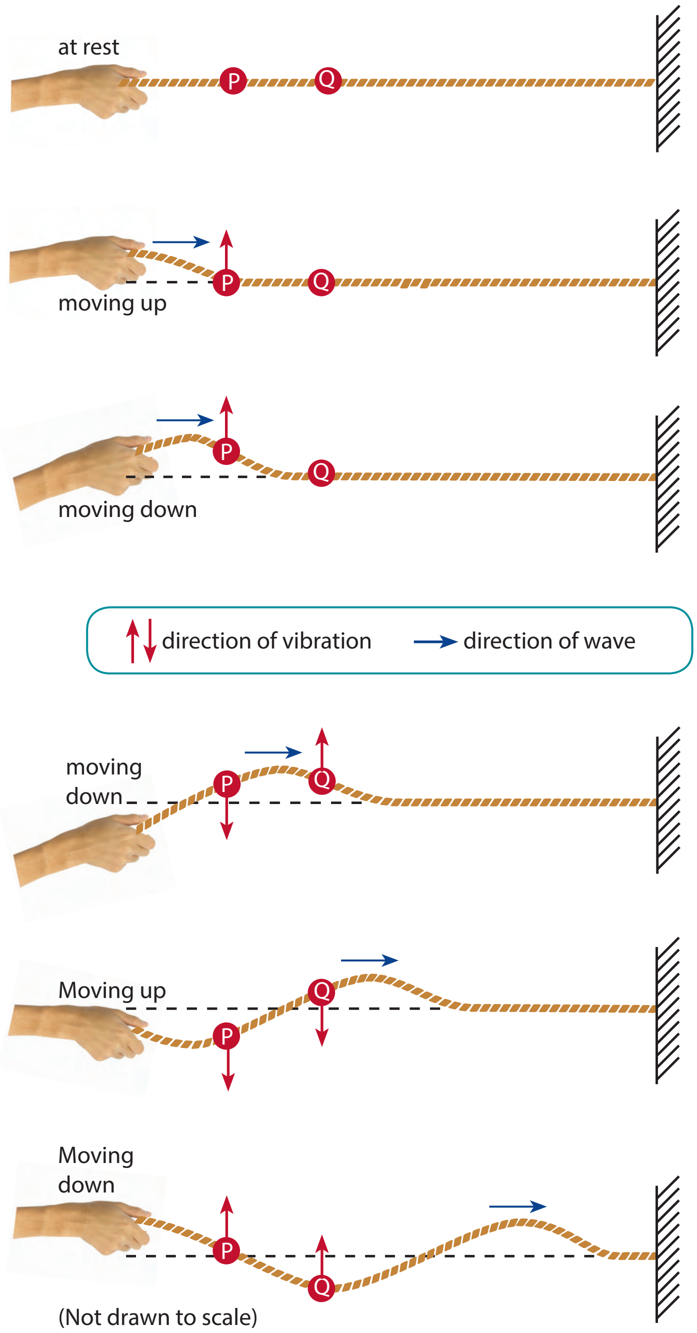
Low res image

How are waves formed?

We can produce waves using a rope, a ripple tank or a Slinky spring. From each of these cases, we can learn how energy is transferred from one point to another.

Waves in a rope

We can produce waves along a rope by fixing one end of the rope to a wall and moving the other end up and down rapidly (Figure 11.3).



① One end of the rope is fixed.

② The kinetic energy (KE) from the moving hand (i.e. source) is transferred to the rope particles (e.g. P) by a rope wave.

③ The rope particles at/near the free end move up and down (i.e. vibrate) as the wave passes through them.

④ The rope wave moves towards the wall.

⑤ The KE of the rope particles near the source is transferred to rope particles further away (e.g. Q) as the wave progresses.

⑥ The rope particles further away vibrate up and down.

⑦ The rope wave continues to move towards the wall.

⑧ Note that the rope particles vibrate up and down about their rest positions.

Figure 11.3 *The rope particles vibrate in a direction perpendicular to the wave motion.*

Note that the rope waves move towards the wall, while the rope particles only vibrate up and down about their rest positions (Figure 11.3). The energy from the hand is transferred by the rope waves towards the wall. The rope is the medium through which the waves move.

WORD ALERT

Medium: substance, matter

Water waves in a ripple tank

We can use a ripple tank to observe waves. In such a tank, there is a small dipper set near the water surface (Figure 11.4).

① The dipper is set near the water surface.

② The kinetic energy (KE) from the vibrating dipper (i.e. source) is transferred to the water particles directly below it by a circular ripple (i.e. wave).

③ The water particles move up and down (i.e. vibrate) as the ripple passes through them.

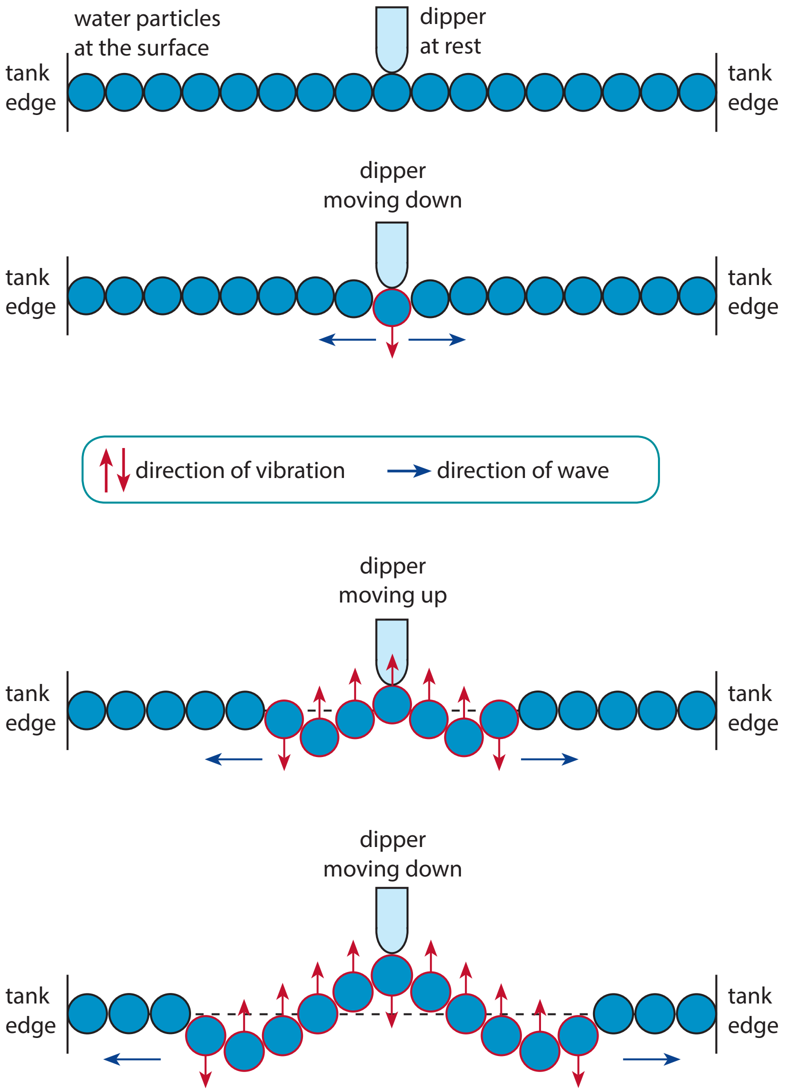
④ The circular ripple spreads outwards towards the tank edges.

⑤ The KE gets transferred to the adjacent water particles and eventually to water particles at the tank edges as the ripple progresses.

⑥ The water particles at other parts also vibrate up and down as the ripple passes through them.

⑦ The circular ripple continues to spread outwards towards the tank edges.

⑧ Note that the water particles vibrate up and down about their rest positions.



(Not drawn to scale)

Figure 11.4 *The water particles vibrate in a direction perpendicular to the wave motion*

Note that the circular ripples (i.e. waves) move towards the tank edges, while the water particles only vibrate up and down (Figure 11.5). The energy from the dipper is transferred by the ripples towards the tank edges.

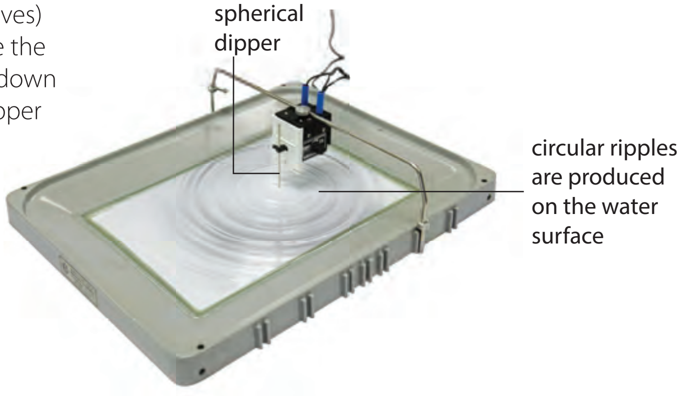


Figure 11.5 *A small dipper in a ripple tank produces circular ripples (waves).*

QUICK CHECK

In Figure 11.5, the medium through which the waves move is air.

True or false?

Waves in a spring

Stretch out a coiled spring or Slinky on the floor and keep one end fixed.

Left-to-right motion

Move the free end of the Slinky left and right (Figure 11.6). Viewing this from the top, we can see the individual coils move perpendicular to the direction of the wave.

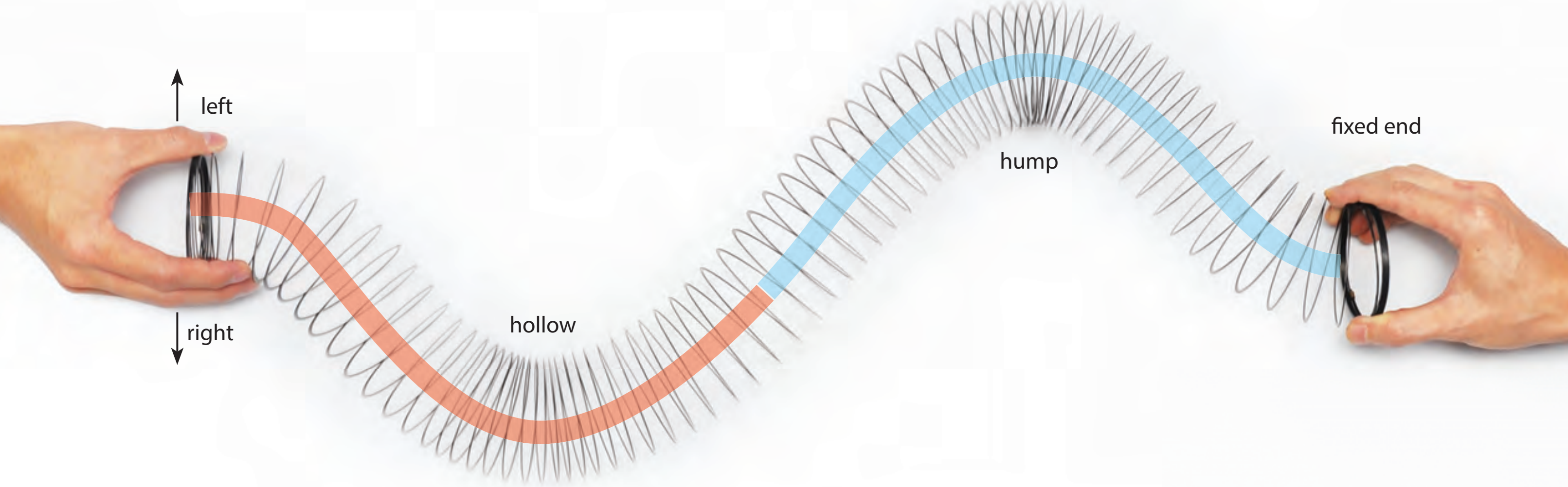


Figure 11.6 *Left-to-right motion of the hand generates waves in a Slinky (top view)*

Push-and-pull motion

Next, push and pull the free end of the Slinky rapidly (Figure 11.7). We can see the individual coils move parallel to the direction of the wave. Dark bands, where the coils are compressed, are seen travelling along the Slinky towards the fixed end.

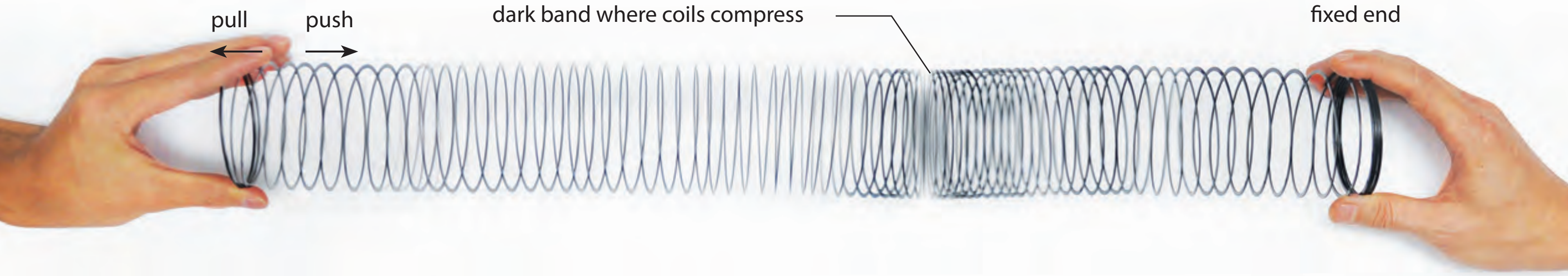


Figure 11.7 *Push-and-pull motion of the hand also generates waves in a Slinky (top view)*

From Figures 11.6 and 11.7, we can observe that the individual coils are restricted to oscillating motion. The individual coils do not move from one end to the other. The waves, however, move from the free end of the Slinky to the fixed end.

As the waves move, energy is transferred from one end of the Slinky to the other. Can you identify the medium in this case?

From our observations of waves produced by the rope, ripple tank and Slinky, we can deduce that waves have the following properties:

- The source of a wave is a vibration or an oscillation.
- Waves transfer energy from one point to another.
- Waves transfer energy without transferring the medium.

How many types of wave motion are there?

There are two types of wave motion: transverse and longitudinal waves. We can produce them using a stretched Slinky that is fixed at one end.

Transverse waves

Move the free end of the Slinky up and down repeatedly (Figure 11.8). Do you notice that the up-and-down movement (i.e. vibration) of the individual coils is perpendicular to the wave motion? We call this type of wave a *transverse wave*. Water waves, electromagnetic waves and seismic S-waves (secondary waves) are transverse waves (Figure 11.9).

Transverse waves are waves that **propagate** perpendicular to the direction of the vibration. We can also say that the direction of the vibration is perpendicular to the direction of propagation.

WORD ALERT

Propagate: to spread, move or travel through something

LINK

Electromagnetic waves include light waves. You will learn more about light waves in Chapter 12 and electromagnetic waves in Chapter 13.

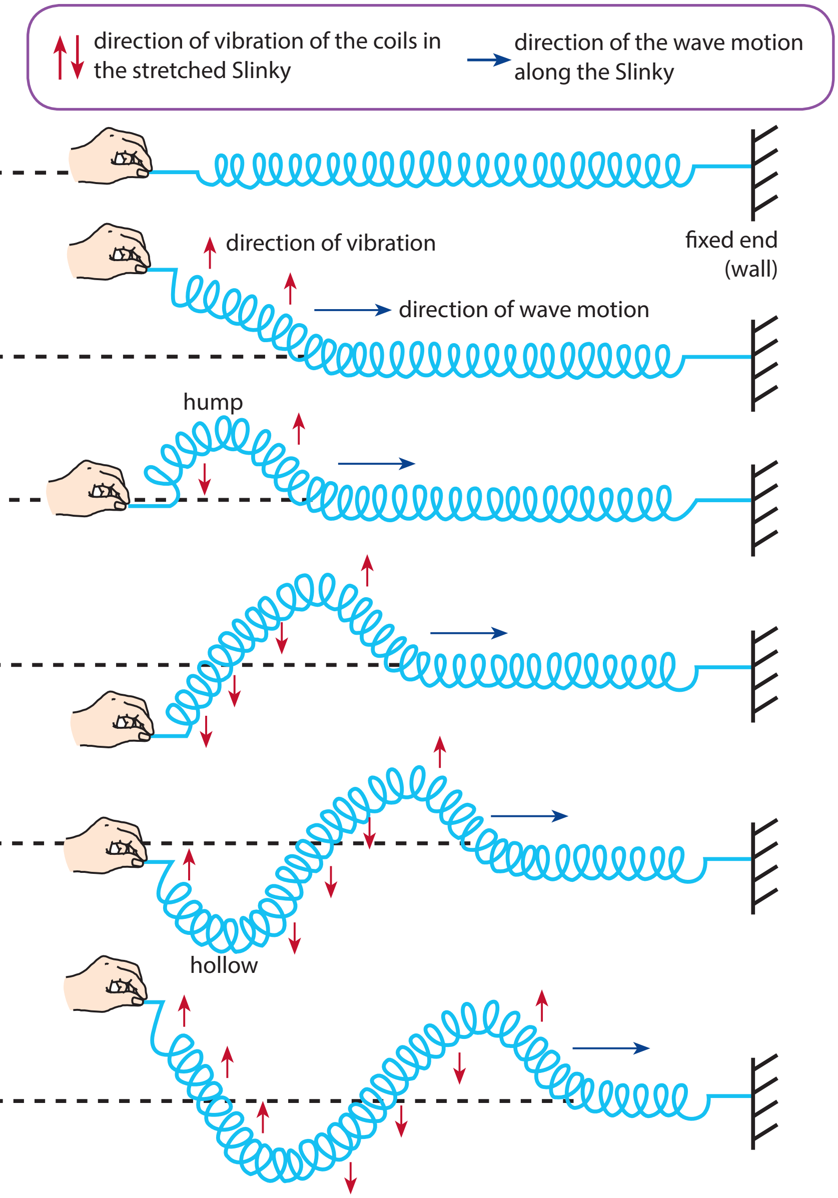
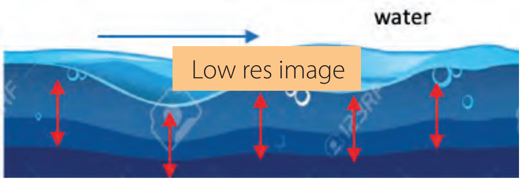
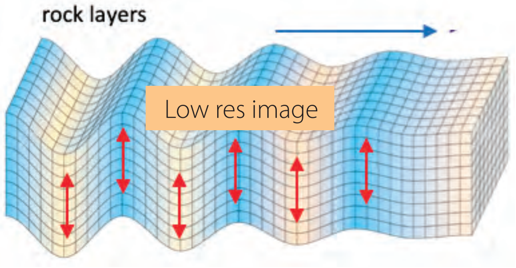


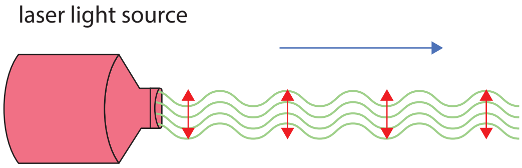
Figure 11.8 For transverse waves, the vibration of the coils (↑↓) is perpendicular to the wave motion (⟶).



Water particles in water waves vibrate up and down as the waves travel horizontally.



An earthquake can cause seismic S-waves to form. The S-waves travel through the Earth as layers of rocks vibrate perpendicularly to the direction of the wave.



Electromagnetic waves such as light waves are produced by charged particles vibrating at right angle to the direction of the wave.

Figure 11.9 *These are examples of transverse waves. The red arrows (↕) show the direction of vibration and the blue arrows (⟶) show the wave motion.*

PHYSICS WATCH

Scan this page to watch a clip on transverse wave.

Longitudinal waves

Push the free end of the Slinky forward to compress it and pull it backwards to stretch it (Figure 11.10). Do you notice that the forward-and-backward movement (i.e. vibration) of the coils is parallel to the wave motion? This type of wave is called a *longitudinal wave*. Sound waves and seismic P-waves (primary waves) are longitudinal waves (Figure 11.11).

Longitudinal waves are waves that propagate parallel to the direction of the vibration. We can also say that the direction of vibration is parallel to the direction of propagation.

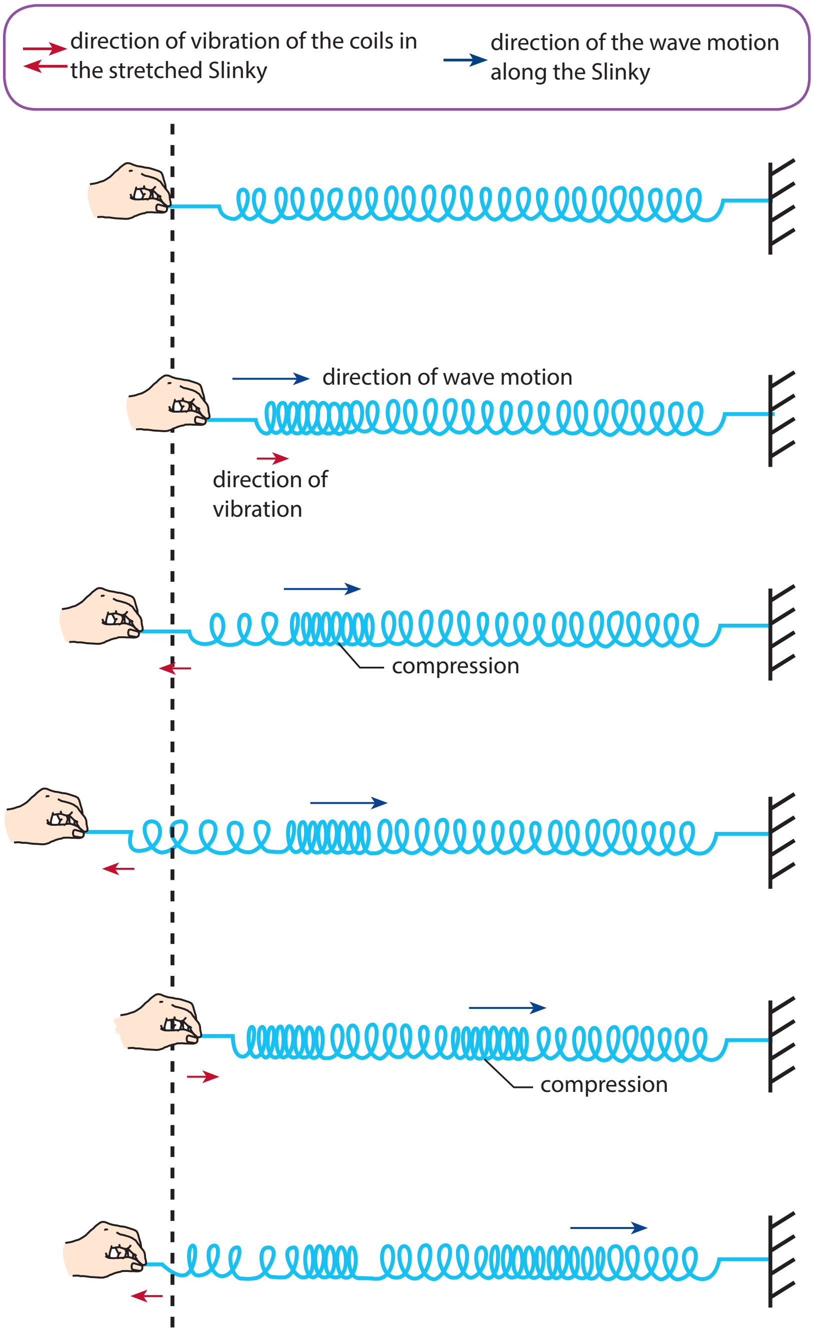
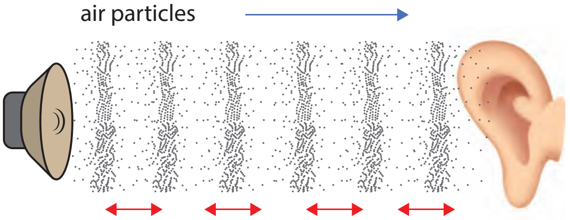


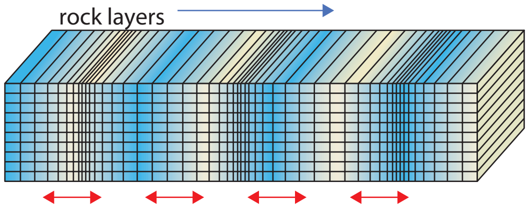
Figure 11.10 *For longitudinal waves, the vibration of the coils (⇄) is parallel to the wave motion (→).*

LINK

You will learn more about sound waves in Chapter 14.



▲ Sound waves are produced by air particles vibrating parallel to the direction of the wave motion.



▲ The seismic P-waves are the first type of waves to be detected during an earthquake. They travel through the Earth as layers of rocks vibrate parallel to the direction of the wave motion.

Figure 11.11 *These are examples of longitudinal waves. The red arrows (↔) show the direction of vibration and the blue arrows (→) show the wave motion.*

QUICK CHECK

For longitudinal waves, the particles do not vibrate along the same direction as the movement of the wave.

True or false?

LINK TWB

Exercise 11A,
pp. X–X

Let's Practise 11.1

1 State whether each of the statements about rope waves is correct or incorrect.
  - **(a)** Rope waves travel up and down, while the rope moves sideways.
  - **(b)** Rope waves provide a mechanism for the transfer of energy from one point to another.
  - **(c)** Rope waves travel sideways, while the rope moves up and down.

2 **(a)** State **one** similarity and **one** difference between transverse waves and longitudinal waves.
  - **(b)** Give an example of each type of wave.

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

11.2 Properties of Wave Motion

In this section, you will learn the following:

- Describe the features of a wave.
- Recall and use the equation for wave speed, $v = f\lambda$.

How can we precisely describe waves?

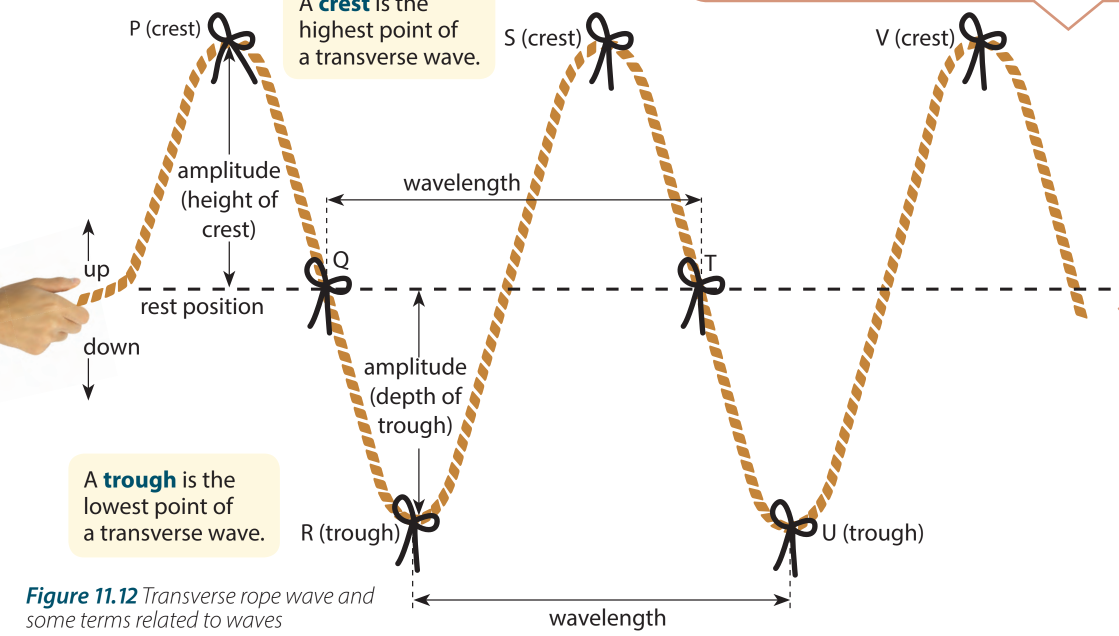
Figure 11.12 shows transverse rope waves that are formed when we move the free end of a rope up and down rapidly. Six ribbons, P, Q, R, S, T and U, are tied at different points along the rope. By observing the movement of these ribbons, we can find out how points along the rope vibrate as the waves move from left to right.

The **amplitude** A of a wave is the maximum displacement of a point from its rest position. Its SI unit is the **metre (m)**.

We can find the amplitude of a transverse wave by measuring the height of its crest or the depth of its trough from the rest position.

Points along a wave are *in phase* if they have the same direction of motion, same speed and same displacement from their rest position. For example,

- P, S and V (i.e. all crests along a wave are in phase);
- R and U (i.e. all troughs along a wave are in phase);
- Q and T (i.e. all alternate points at the rest position along the wave are in phase).



A **crest** is the highest point of a transverse wave.

A **trough** is the lowest point of a transverse wave.

The **wavelength** λ of a wave is the shortest distance between any two points in phase. Its SI unit is the **metre (m)**.

To find the wavelength of a transverse wave, we can measure the distance between

- two successive crests (e.g. P and S, S and V);
- two successive troughs (e.g. R and U);
- any other two nearest points in phase (e.g. Q and T).

Figure 11.12 *Transverse rope wave and some terms related to waves*

Displacement–distance graph

Figure 11.13 shows a displacement–distance graph of the rope wave in Figure 11.12. A photograph of the rope at an instant is equivalent to a displacement–distance graph. A displacement–distance graph describes the displacements of *all particles at a particular point in time*.

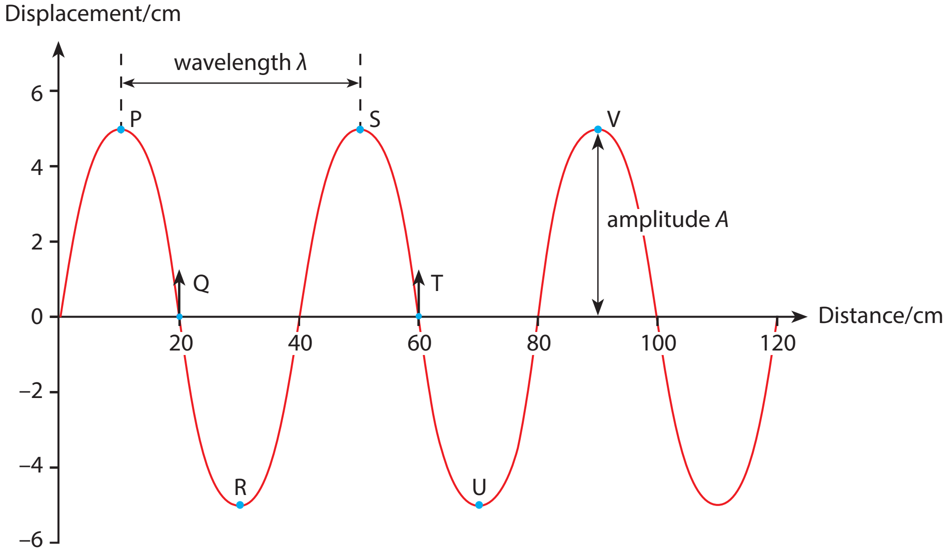


Figure 11.13 *Displacement-distance graph of the rope wave at a certain instant*

Points above the rest position are shown as positive displacements. Points below the rest position are shown as negative displacements.

According to the graph, the amplitude and wavelength of the wave are 5 cm and 40 cm respectively.

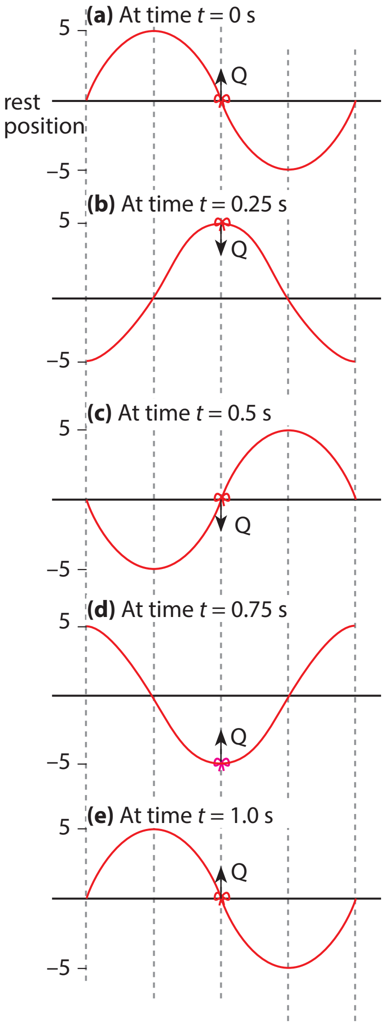


Figure 11.14 *Displacement-distance graphs at different instants over one second*

Displacement–time graph

Figure 11.14 shows the displacement–distance graphs captured at different instants during the flicking of the rope in Figure 11.12.

By tracking the displacements of ribbon Q and plotting them against time, we obtain the displacement–time graph of Q over one second (Figure 11.15). A displacement–time graph describes the displacement of *one particle over a time interval*.

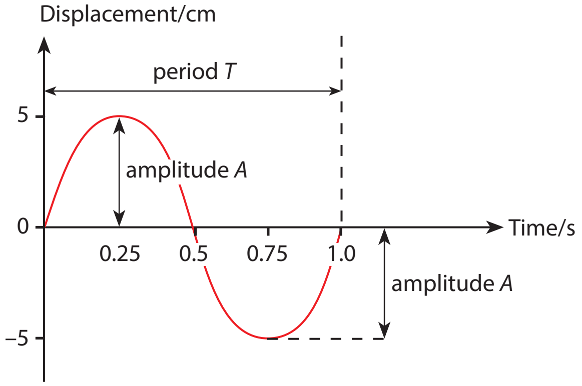


Figure 11.15 *Displacement-time graph of Q over one second*

According to the graph, the amplitude and the period of the wave are 5 cm and 1.0 s respectively.

The **period** T of a wave is the time taken to produce one complete wave. Its SI unit is the **second (s)**.

The period is equivalent to the time taken for the wave to travel through a distance equal to its wavelength.

The **frequency** f of a wave is the number of complete waves produced per second. Its SI unit is the **hertz (Hz)**.

The frequency of a wave is also the number of crests (or troughs) that go past a point per second.

In Figure 11.15 on page 169, one complete wave is produced per second — the frequency of the wave is 1.0 Hz. We can relate frequency to period by the equation $f = \frac{1}{T}$. The higher the frequency, the greater the number of waves produced in one second. A higher frequency also implies that the period is shorter.

Since a crest (or any point on a wave) travels a distance of one wavelength in one period, the wave speed is given by:

$v = \frac{\lambda}{T}$ where v = wave speed (in m/s)

λ = wavelength (in m)

T = period (in s)

Since $f = \frac{1}{T}$,

$$\boldsymbol{v = f\lambda}$$

Wave speed v is the distance travelled by a wave per second. Its SI unit is the **metre per second (m/s)**.

A wavefront can be drawn by joining all the adjacent wave crests. Depending on how the waves are produced, the wavefronts can be straight lines (Figure 11.16), concentric circles (Figure 11.17), or any other shape.

A **wavefront** is an imaginary line on a wave that joins all adjacent points that are in phase.

QUICK CHECK

A dipper is moved up and down to produce waves in water. Increasing the frequency of the dipper will increase the speed of the waves.

True or false?

QUICK CHECK

Refer to pages 168 to 169. The speed of the wave shown in Figures 11.12 to 11.15 is 0.4 cm/s.

True or false?

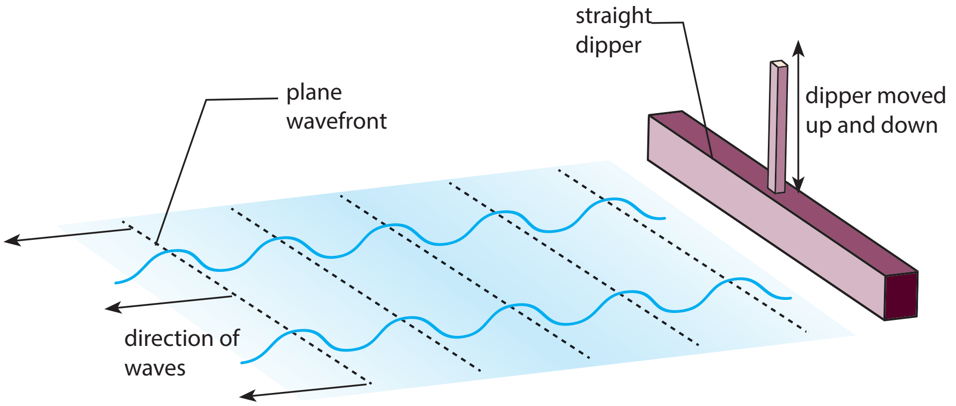


Figure 11.16 A straight dipper produces plane waves that give rise to plane wavefronts.

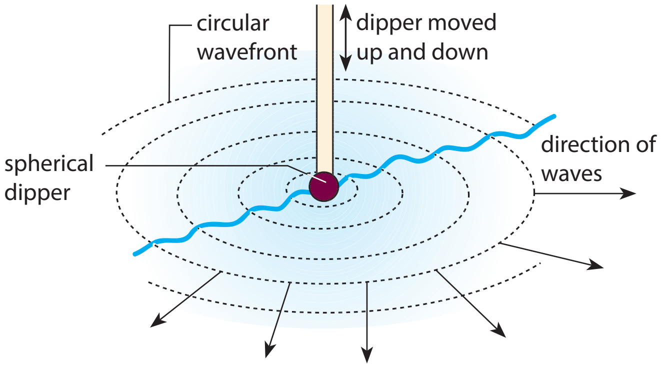


Figure 11.17 A spherical dipper produces circular waves that give rise to circular wavefronts.

Worked Example 11A

Figure 11.18 shows a displacement–distance graph of a wave.

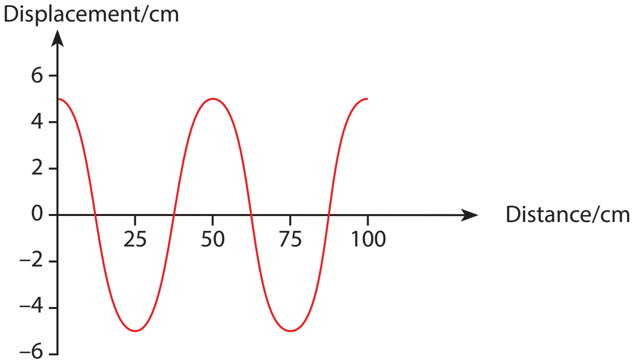


Figure 11.18

(a) What is the wavelength of the wave?

(b) The period of the wave is 1.0 s. What are its frequency and speed?

(c) What will be the wavelength of the wave if its frequency is increased to 5.0 Hz, with no change in speed? Sketch the resulting wave profile with its wavelength marked clearly.

Solution

(a) Wavelength $\lambda = 50$ cm

(b) Given: Period $T = 1.0$ s

Frequency $f = \frac{1}{T}$

$= 1.0$ Hz

Using the wave speed equation,

Wave speed v = frequency $f \times$ wavelength λ

$= 1.0 \text{ Hz} \times 50 \text{ cm}$

$= 50$ cm/s

(c) Given: Wave speed $v = 50$ cm/s

Frequency $f = 5.0$ Hz

Using the wave speed equation,

$v = f\lambda$

$\lambda = \frac{v}{f} = \frac{50 \text{ cm/s}}{50 \text{ Hz}} = 10 \text{ cm}$

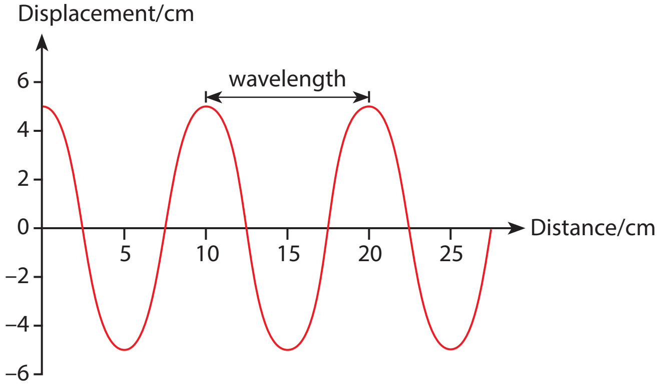


Figure 11.19

Worked Example 11B

(a) Figure 11.20 shows a wave along a Slinky with a frequency of 3 Hz and a wavelength of 0.3 m. What is the wave speed?

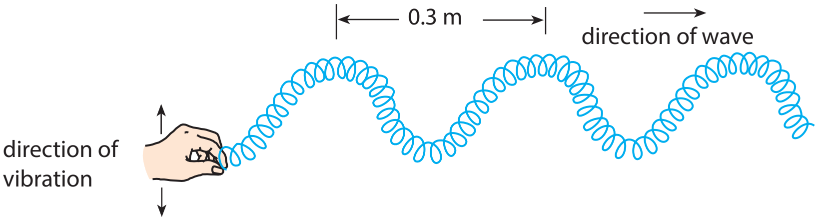


Figure 11.20

(b) Given that in a vacuum, the speed c and wavelength λ of green light are 3.0×10^8 m/s and 0.6 µm respectively, calculate the frequency of the green light.

(c) Compare the waves in **(a)** and **(b)** and comment on them, in terms of speed and frequency.

Solution

(a) Given: Frequency $f = 3$ Hz

Wavelength $\lambda = 0.3$ m

Using $v = f\lambda$,

$v = 3 \text{ Hz} \times 0.3 \text{ m} = 0.9 \text{ m/s}$

(b) Given: Wavelength $\lambda = 0.6 \text{ µm} = 0.6 \times 10^{-6}$ m

Speed $c = 3.0 \times 10^8$ m/s

Using $c = f\lambda$, where f is the unknown frequency of the green light:

$$f = \frac{c}{\lambda}$$

$$= \frac{3.0 \times 10^8 \text{ m/s}}{0.6 \times 10^{-6} \text{ m}} = 5.0 \times 10^{14} \text{ Hz}$$

(c) The speed and frequency of green light are much greater than the speed and frequency of the waves in the Slinky.

LINK PWB

Practical 11A,
pp. XX–XX

Let's Practise 11.2

1 Figure 11.21 shows the displacement–time graph of a periodic motion. Determine the
  (a) period; **(b)** frequency; **(c)** amplitude?

2 State the relationship between the speed, frequency and wavelength of a wave.

3 A wave has an amplitude of 0.4 m and a wavelength of 10.0 m. It is travelling at a speed of 5.0 m/s. Sketch a graph to show how the displacement of a particular point on the wave changes with time. Label the amplitude and period on the graph clearly.

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

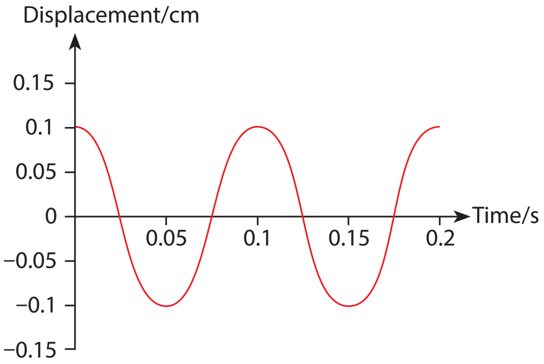


Figure 11.21

LINK TWB

Exercise 11B,
pp. X–X

11.3 Common Features of Wave Behaviour

In this section, you will learn the following:

- Describe how waves can undergo reflection, refraction and diffraction.
- Describe the use of a ripple tank to show reflection, refraction and diffraction of waves.
- S Describe how wavelength and gap size affects diffraction through a gap.
- S Describe how wavelength affects diffraction at an edge.

How do the wavefronts relate to the direction of travel of the waves? The ripple tank can be used to show how water waves behave differently in different situations. Note that in all the wave diagrams in this section, all wavefronts are at 90° to the direction of propagation of the wave. For clarity, the ripple tank itself is not shown.

LINK

Most of these wave behavior are looked at in the context of light in Chapter 12.

What happens when waves hit a straight barrier?

A straight edge is used to create ripples with plane wavefronts. A straight barrier with a plane surface is inserted into the water. When the water waves hit the barrier, they undergo **reflection**. The waves bounce off the plane surface without changing shape.

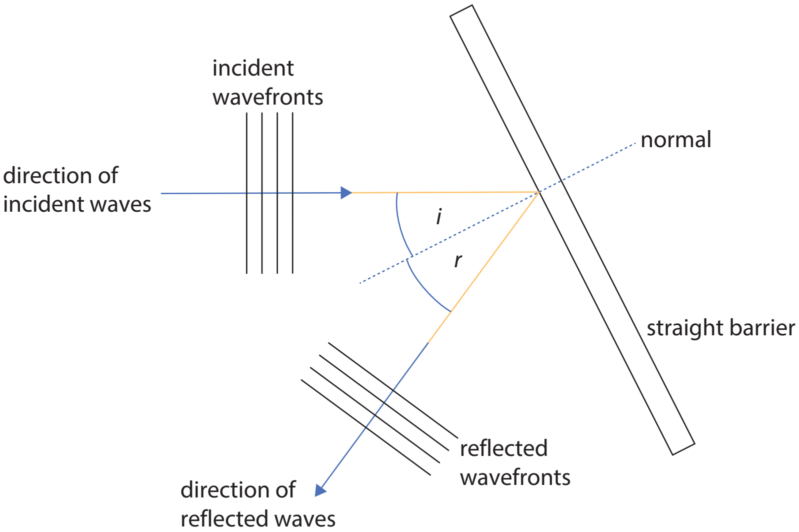


Figure 11.22 *Reflection of water waves in a ripple tank*

HELPFUL NOTES

The distance between two adjacent wavefronts is equivalent to the wavelength. Notice in Figure 11.22 that this distance remains the same before and after reflection. This means that the wavelength does not change.

Figure 11.22 shows how the water waves hit the barrier at an angle *i* and get reflected at an angle *r*. Notice that both angles are equal. This is similar to light waves hitting a plane mirror and sound waves hitting a wall.

LINK

You will learn more about light and sound reflection in Chapters 12 and 14 respectively.

WORD ALERT

Boundary: frontier where two areas meet

What happens when waves pass from one medium to another?

A translucent plate is placed inside a ripple tank so that a portion of the water is deep and another portion is shallow. Figure 11.23 shows plane water waves travelling from the deep water to the shallow water. The wave is said to have crossed the boundary between the deep and shallow water.

Notice the wavefronts in the shallow water are closer together than those in the deep water. This shows that the waves travel faster in the deep water. Given that $v = f\lambda$ and that the frequency is constant, this means that when the waves are in the shallow water, their wavelength must also decrease.

It is also observed that the waves undergo **refraction** when the they pass from one medium to another. In Figure 11.23, we see the waves change direction or bend when they cross the boundary between the deep and shallow waters at an angle. If the angle i is zero, angle r will also be zero, i.e., no refraction occurs.

QUICK CHECK

If the waves are travelling slower in the shallower water, then they must also have a smaller amplitude.

True or false?

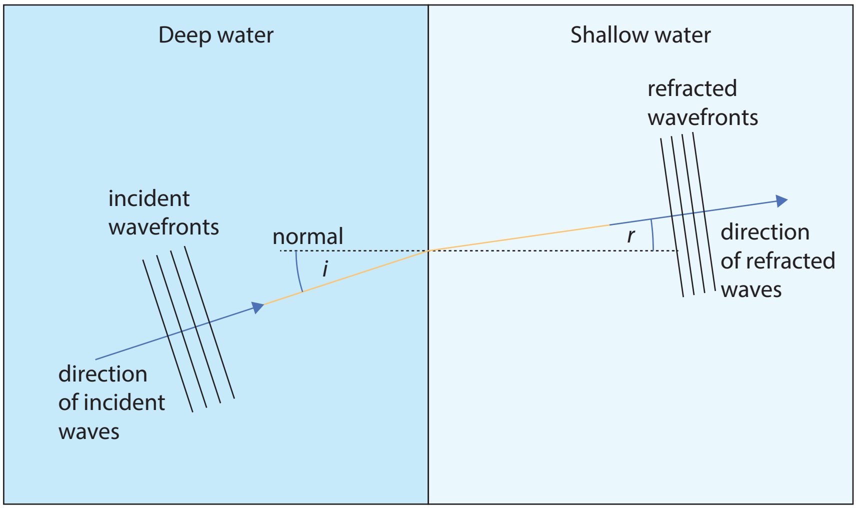
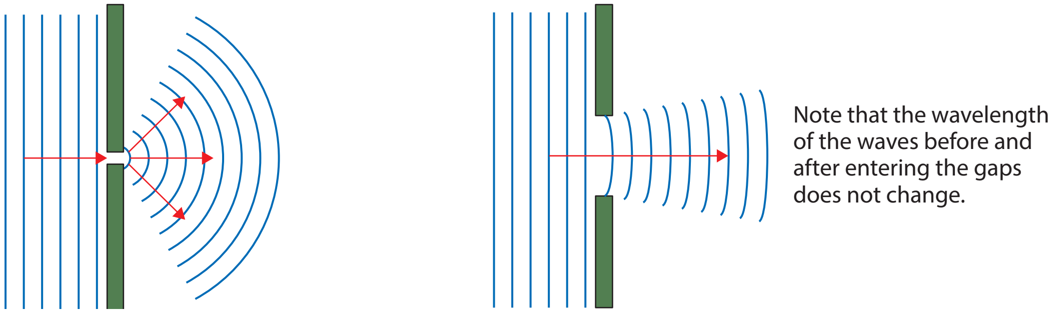


Figure 11.23 Refraction of water waves in a ripple tank

What happens when waves encounter a gap or an edge?

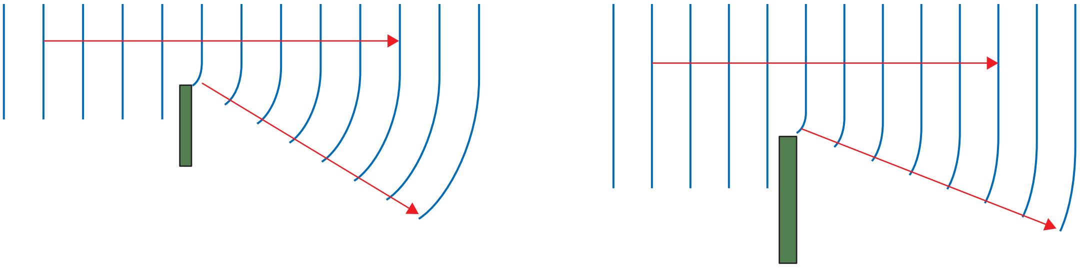
Small barriers are placed inside a ripple tank to create gaps of different widths through which plane water waves can pass. Notice that the wavefronts spread out after passing through the gaps (Figure 11.24). This is called *diffraction*.


Note that the wavelength of the waves before and after entering the gaps does not change.

(a) Waves entering a narrow gap **(b)** Waves entering a wide gap

Figure 11.24 Diffraction of water waves arriving at gaps of different widths

Place a barrier inside a ripple tank to let plane water waves pass over one edge of the barrier. In this case diffraction still occurs. The waves appear to curve around and spread behind the barrier (Figure 11.25).



(a) Long wavelength **(b)** Short wavelength

Figure 11.25 *Diffraction of water waves arriving at a single edge*

In summary, **diffraction** involves the spreading out of waves when they encounter gaps and edges.

S How does gap size and wavelength affect diffraction? As gap size increases relative to the wavelength, the **curvature** at the ends of the wavefronts becomes smaller.

Compare the two diagrams in Figure 11.24. When the wavelength is longer than the gap size, the waves spread out more (Figure 11.24(a)). When the wavelength is shorter than the gap size, the waves spread out less (Figure 11.24(b)). The wavefronts are mostly unchanged and only affected at the ends.

How does wavelength affect diffraction at an edge? This time, the longer the wavelength, the greater the curvature effect. This means a greater proportion of the wave will curve around and spread behind the barrier (Figure 11.25).

WORD ALERT

Curvature: curved or rounded shape

ENRICHMENT
THINK

A house is located at the foot of a hill on the opposite side of a transmitter. The transmitter emits both TV and radio signals.

Explain why it is more difficult to receive TV signals in the house compared to radio signals.

Let's Practise 11.3

1 Figure 11.26 shows some concrete sea barriers and an area of beach at the sea shore.

(a) The water waves have carved out near semi-circular areas from the sand. Suggest how straight plane water waves have done this.

(b) The gaps between the barriers are approximately 20 m wide. Suggest possible values for the wavelength of the waves.

(c) S Explain how the patterns in the sand would be different if

  (i) the wavelength of the water waves was shorter;

  (ii) the gaps were wider.

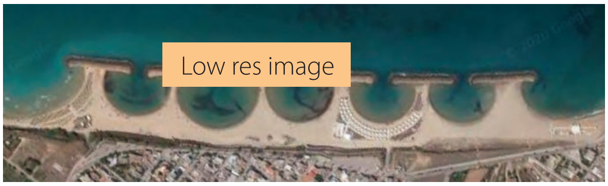


Figure 11.26 *Beach area with sea barriers*

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

LINK

Exercise 11C–11D, pp. XX–XX

Exercise 11E Let's Reflect. p. XX

Let's Map It

WAVES

Transfer energy without transferring matter

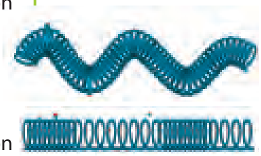
Wave motion is made up of periodic motion or motion repeated at regular intervals.

Transverse wave

- Direction of vibration is perpendicular to direction of propagation

Longitudinal wave

- Direction of vibration is parallel to direction of propagation



Wave behaviour

Reflection

- Waves bounce off the plane surface without changing shape.

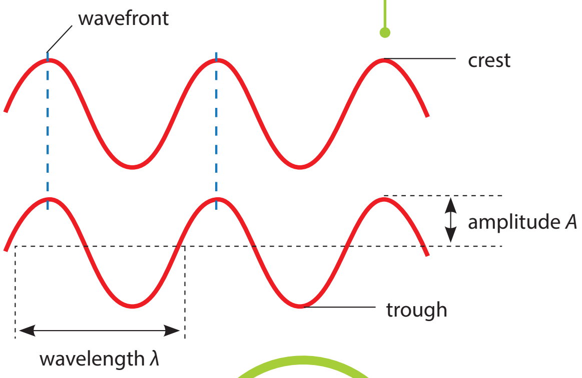
Refraction

- Waves change direction when pass from one medium to another; usually accompanied by a change in speed of the waves.

Diffraction

- Waves spread out when they encounter gaps and edges.

Wave features



Can be plotted on a

- displacement–distance graph
- displacement–time graph

Frequency f is the number of complete waves produced per second.

Period T is the time taken to produce one complete wave.

Wave speed is the distance travelled by a wave per second and given by:

$v = f\lambda$

Let's Review

Section A: Multiple-choice Questions

1 What does a wave transfer?

A Molecules **B** Energy
C Matter **D** Force

2 As a transverse wave passes, the particles of the medium oscillate

A in phase with one another.
B with different frequencies.
C parallel to the direction of the wave travel.
D perpendicular to the direction of travel of wave.

3 Which of the following is an example of longitudinal waves?

A Waves in a ripple tank
B Light waves in air
C A vibrating guitar string
D Sound waves produced by a vibrating guitar string

4 Figure 11.27 shows the displacement–time graph of a particle in a transverse wave. If its speed is 2 cm/s, which of the following pairs of amplitude and wavelength is correct?

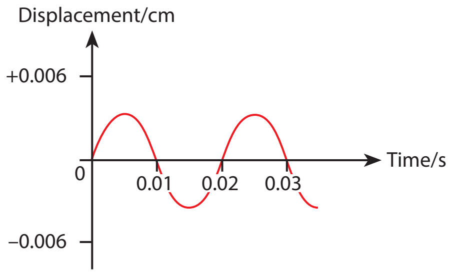


Figure 11.27

	Amplitude/cm	Wavelength/cm
A	0.02	0.006
B	0.003	0.02
C	0.003	0.04
D	0.006	0.04

5 A vibrating dipper of frequency 3 Hz produces water waves in a ripple tank. Which of the following is a possible wavelength and speed of the waves?

	Wavelength/cm	Speed/cm/s
A	3	1
B	3	6
C	4	12
D	15	5

6 From the sea to the shore, the depth of the water decreases. Which of these statements describes waves coming in from the sea to the shore?

A Speed increases and amplitude decreases.
B Speed increases and amplitude increases.
C Speed decreases and amplitude increases.
D Speed decreases and amplitude decreases.

7 Ⓢ A beam of light was shone through a gap. Diffraction of light was not observed. What does this suggest about the wave nature of light?

A Light is not a wave.
B The speed of light is very large.
C The wavelength of visible light is much larger than the width of the gap.
D The wavelength of visible light is much smaller than the width of the gap.

Section B: Short-answer and Structured Questions

1 **(a)** What is meant by *a frequency of 2 Hz*?

(b) **(i)** Draw a labelled diagram to show the waveform in a rope with a wavelength of 5 cm and an amplitude of 3 cm.

(ii) Assuming the rope wave is travelling from left to right at a speed of 0.50 m/s, calculate the frequency of the wave.

2 Water waves enter a dock at a rate of 120 crests per minute. At the dock are two poles 12 m apart. A worker watches a particular wave crest pass from one pole to another in 4 s. Calculate the

(a) frequency of the wave motion;
(b) wavelength of the waves.

Let's Review

3 Draw the displacement–distance graphs for the following waveforms:

- **(a)** Two waves that have the same amplitude and speed, but one has a frequency that is twice that of the other
- **(b)** Two waves that have the same speed and frequency, but one has an amplitude that is twice that of the other

4 Figure 11.28 shows the instantaneous position of some particles in a medium through which waves are passing continuously in the direction indicated by the arrow.

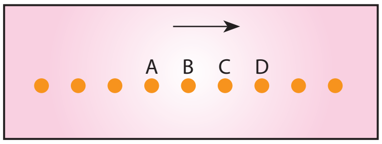


Figure 11.28

Describe the motion of the particles A, B, C and D if the wave is

- **(a)** longitudinal;
- **(b)** transverse.

5 Figure 11.29 shows a displacement–distance graph and a displacement–time graph of a wave.

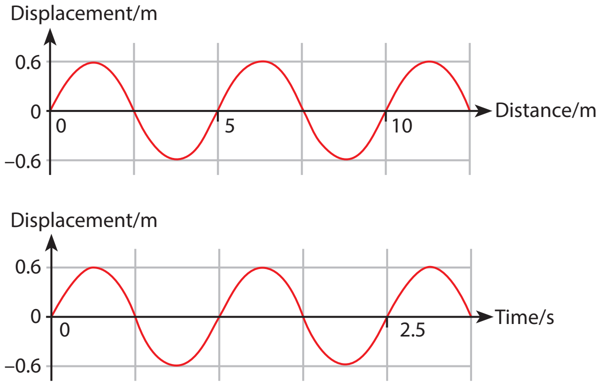


Figure 11.29

- **(a)** State the amplitude of the wave.
- **(b)** State the wavelength of the wave.
  - **(i)** State the time taken for one complete oscillation.
  - **(ii)** Calculate the frequency of the wave.
  - **(iii)** Calculate the speed of the wave.

6 Figure 11.30 shows water waves about to encounter deeper water. Complete the diagram to show qualitatively the path and wavelength of the waves in the deeper water.

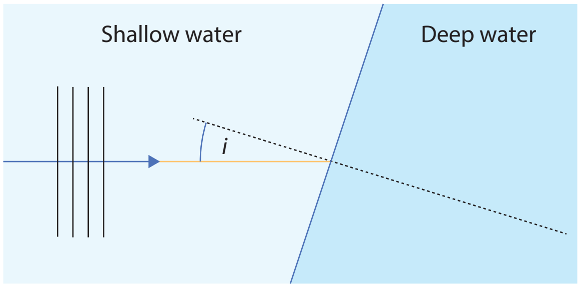
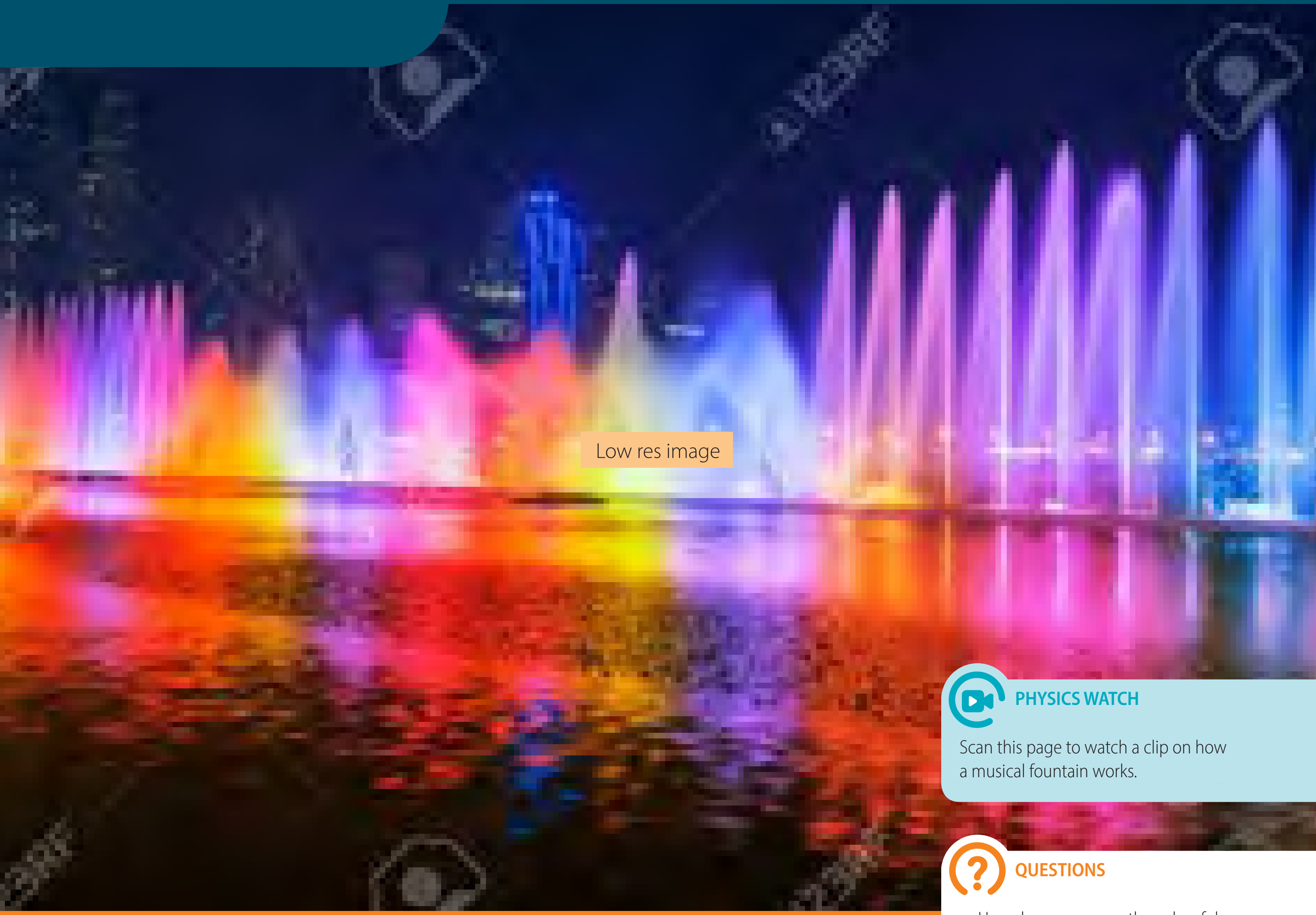


Figure 11.30

7 S Explain how a conversation in a corridor can be heard around a corner in the corridor.

CHAPTER

12 Light



PHYSICS WATCH

Scan this page to watch a clip on how a musical fountain works.

QUESTIONS

- How do our eyes see the colourful musical fountain?
- How do the colours get into the water?
- How does the light and water interact?

Have you ever seen a musical fountain?

There is one in Sharjah, in the United Arabs Emirates. The Sharjah Musical Fountain, as shown in the photo, is one of the biggest and most spectacular in the region. Many people enjoy watching how the fountain dances with the music. What is more interesting is the colourful jets of water. The elegant and complex fountain uses the interaction between light and water to create the stunning effects.

Don't just enjoy the show — get to know the science behind it!

12.1 Reflection of Light

In this section, you will learn the following:

- Define and use the terms *normal*, *angle of incidence* and *angle of reflection*.
- Describe the formation of an optical image by a plane mirror, and give the characteristics of the image.
- State that for reflection, the angle of incidence is equal to the angle of reflection; recall and use this relationship.
- Ⓢ Use simple constructions, measurements and calculations for reflection by plane mirrors.

How do we represent light?

You have learnt that light is a form of electromagnetic wave. The wave nature of light enables it to undergo reflection. This explains how we see things. We can see objects around us only if light from them enters our eyes. Luminous objects, such as a lamp or a fire, can be seen because they give out their own light. Non-luminous objects, such as a wall picture, are visible to us because they reflect light from a light source into our eyes (Figure 12.1).

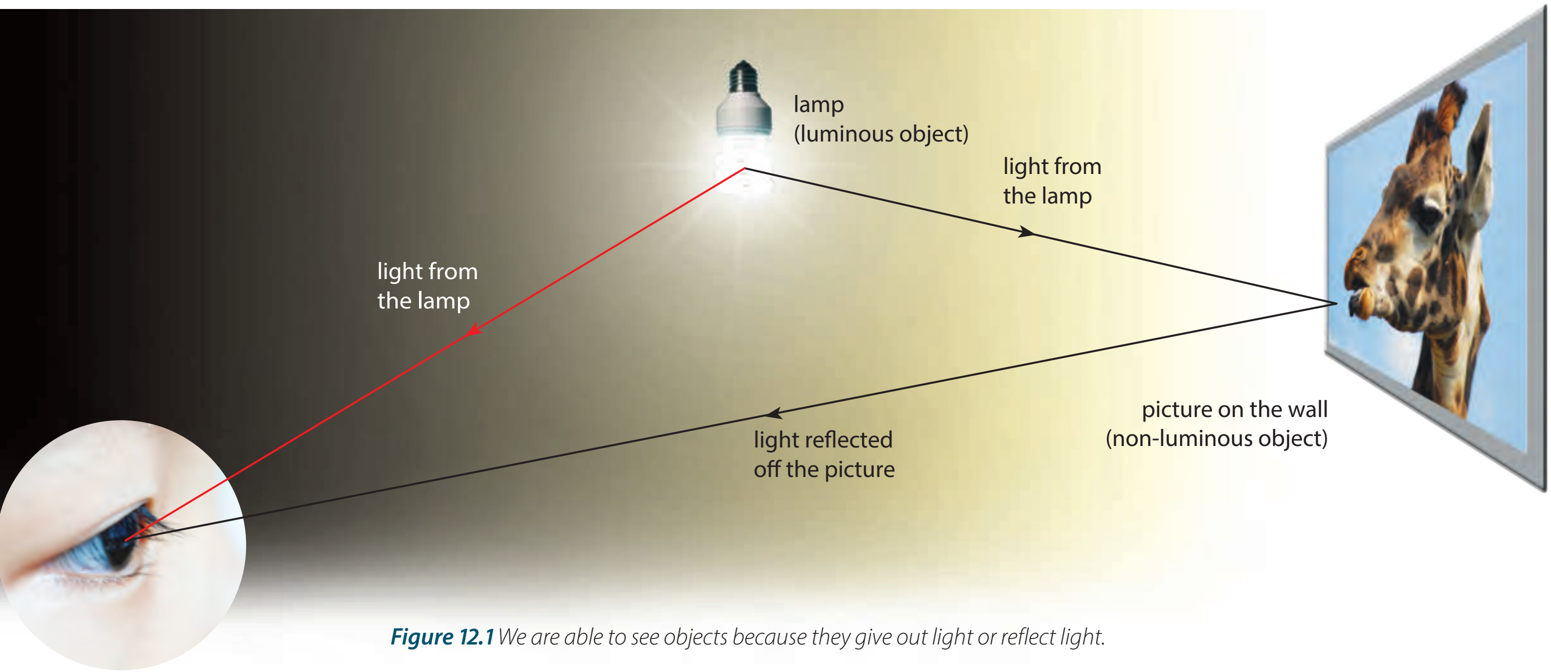
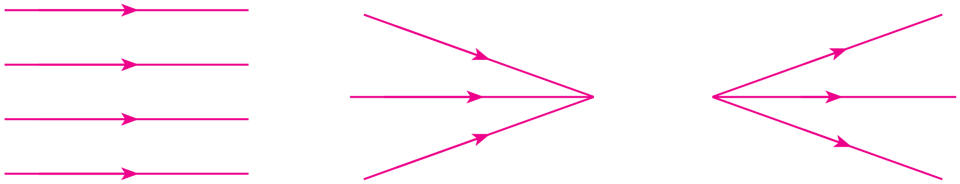


Figure 12.1 *We are able to see objects because they give out light or reflect light.*

In physics, we use straight lines with arrows to represent paths of light. The arrows indicate the direction in which the light travels. Such lines are called light rays. A beam of light is actually a bundle of light rays.

A light beam can be a bundle of parallel rays, convergent rays or divergent rays (Figure 12.2). We use parallel lines to represent light rays from a distant object (e.g. the Sun), and divergent lines to represent light rays from a nearby object.



Parallel light rays

Convergent light rays

Divergent light rays

Figure 12.2 *Different types of light rays*

Below are some terms that are used to describe the reflection of light:

- **Reflection** is the rebounding of light at a surface.
- **Incident ray** is light ray that hits the reflecting surface.
- **Point of incidence** is the point at which the incident ray hits the reflecting surface.
- **Reflected ray** is light ray that bounces off the reflecting surface.

Can you identify the incident ray, point of incidence and reflected ray in Figure 12.1?

What is the law of reflection?

We can carry out Let's Investigate 12A to learn about the law that governs the reflection of light.

Let's Investigate 12A

Objective

To investigate the law of reflection

Apparatus

Plane mirror, ray box and power supply, paper

Precautions

A ray box with a filament lamp may get hot.

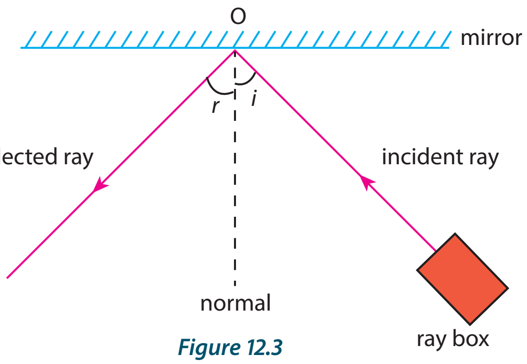


Figure 12.3

Procedure

1. Figure 12.3 shows the reflection of light by a plane mirror. Note that the mirror needs to be placed vertically upright (i.e. at right angle to the sheet of paper).
2. Mark out a dotted line perpendicular to the mirror on the paper. This line is the called the *normal*.
3. Label the intersection of the mirror and the normal, 'O'.
4. Switch on the ray box and direct a ray of light at point O.
5. Measure and record the angle of incidence *i* and the corresponding angle of reflection *r*.
6. Repeat steps 4 and 5 for different angles of incidence *i*.

Results and discussion

1. Every angle of incidence *i* is equal to its corresponding angle of reflection *r*.
2. The incident ray, reflected ray and the normal at the point of incidence all lie in the same plane (i.e. a flat surface).

Our finding from Let's Investigate 12A is consistent with the **law of reflection**:

- the angle of incidence *i* is equal to the angle of reflection *r* (i.e. $i = r$).

Below is a summary of a few more terms you need to know for reflection of light:

- **Normal** is the imaginary line perpendicular to the reflecting surface at the point of incidence.
- **Angle of incidence** *i* is the angle between the incident ray and the normal.
- **Angle of reflection** *r* is the angle between the reflected ray and the normal.

LINK

Recall the reflection of waves that you have learnt in Chapter 11.

LINK

Practical 12A, pp. XX–XX

ENRICHMENT ***THINK***

Explain why the shoes (Figure 12.4) shine after they have been polished.

Figure 12.4 *Polished shoes*

Worked Example 12A

Figure 12.5 shows a ray of light incident on a mirror.

(a) State the relationship between the angle of incidence and the angle of reflection.

(b) Complete the diagram to show the reflected ray.

(c) What is the angle of incidence?

(d) What is the angle of reflection?

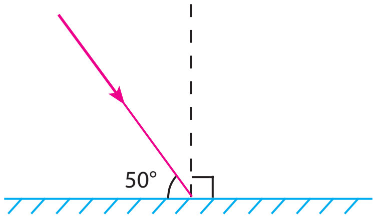


Figure 12.5

Solution

(a) The angle of incidence is equal to the angle of reflection.

(b) Refer to Figure 12.6.

(c) Angle of incidence $i = 90° - 50° = 40°$

(d) Based on the law of reflection, angle of reflection $r = i = 40°$.

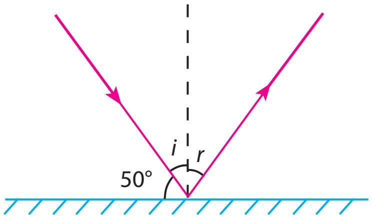


Figure 12.6

What are the properties of a mirror image?

We can carry out Let's Investigate 12B to learn the characteristics of an image formed in a plane mirror.

Let's Investigate 12B

Objective

To investigate the characteristics of an image formed in a plane mirror

Apparatus

Plane mirror, three pins, graph paper, wooden holder, softboard

Precautions

The pins are sharp.

Procedure

1 Set up the apparatus shown in Figure 12.7.

2 Observe the images formed.

3 Find the distances d_1 and d_2 by counting the number of squares between one of the pins and the mirror surface, and between its image and the mirror surface. Compare these two distances.

4 Repeat step 3 for the two other pins and their images.

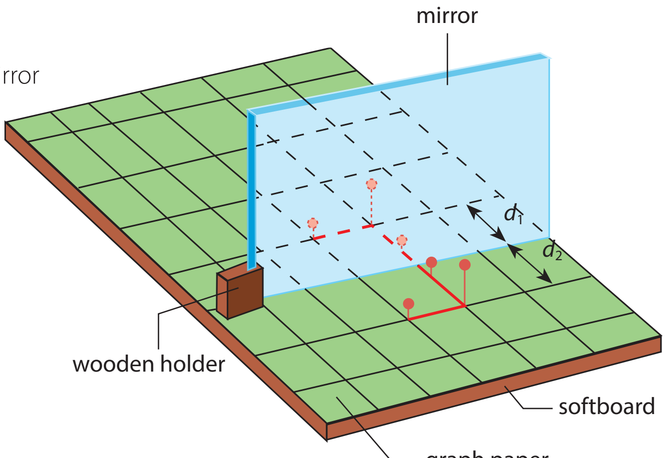


Figure 12.7

Observations

The following observations were made regarding the mirror images.

1 The image of each pin is the same size as the pin, upright and virtual.

2 The distances of the image from the plane mirror, d_1, is equal to the distance of the object form the plane mirror, d_2.

3 Taking the figure formed by the pins as an object, its image is laterally inverted.

LINK PWB

Practical 12B,
pp. XX–XX

Characteristics of a plane mirror image

From Let's Investigate 12B, we can conclude the following characteristics of a plane mirror image:

- The image is of the **same size** as the object.
- The image is **laterally inverted**. The left-hand side of the image appears as the right-hand side of the object and vice versa.
- The image is **upright**.
- The image is **virtual**. It cannot be captured on a screen and the light rays do not meet at the image position. This is opposite to a real image.
- The image has the **same distance** from the mirror as the object.

Note: A **real** image can be captured on a screen and the light rays meet at the image position.

Worked Example 12B

(a) There are seven letters in the word PHYSICS.

(i) Hold the word up in front of a plane mirror as shown in Figure 12.8. Write down how these letters appear in the mirror.

(ii) How many of these letters appear to be different when the word is reflected?

(iii) Write down the letters that appear to be the same.

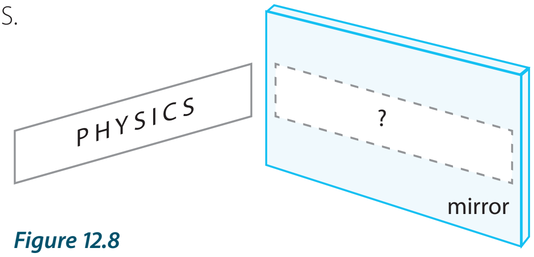


Figure 12.8

(b) The driver of car A saw car B behind him from his rear-view mirror. If the registration number of car B is SDE 789H, write down the number, as seen by the driver of car A in his rear-view mirror.

Solution

(a) (i) Ƨ Ɔ I Ƨ Y H ꟼ

(ii) 4 **(iii)** H, Y, I

(b) H98٦ ƎᗡƧ

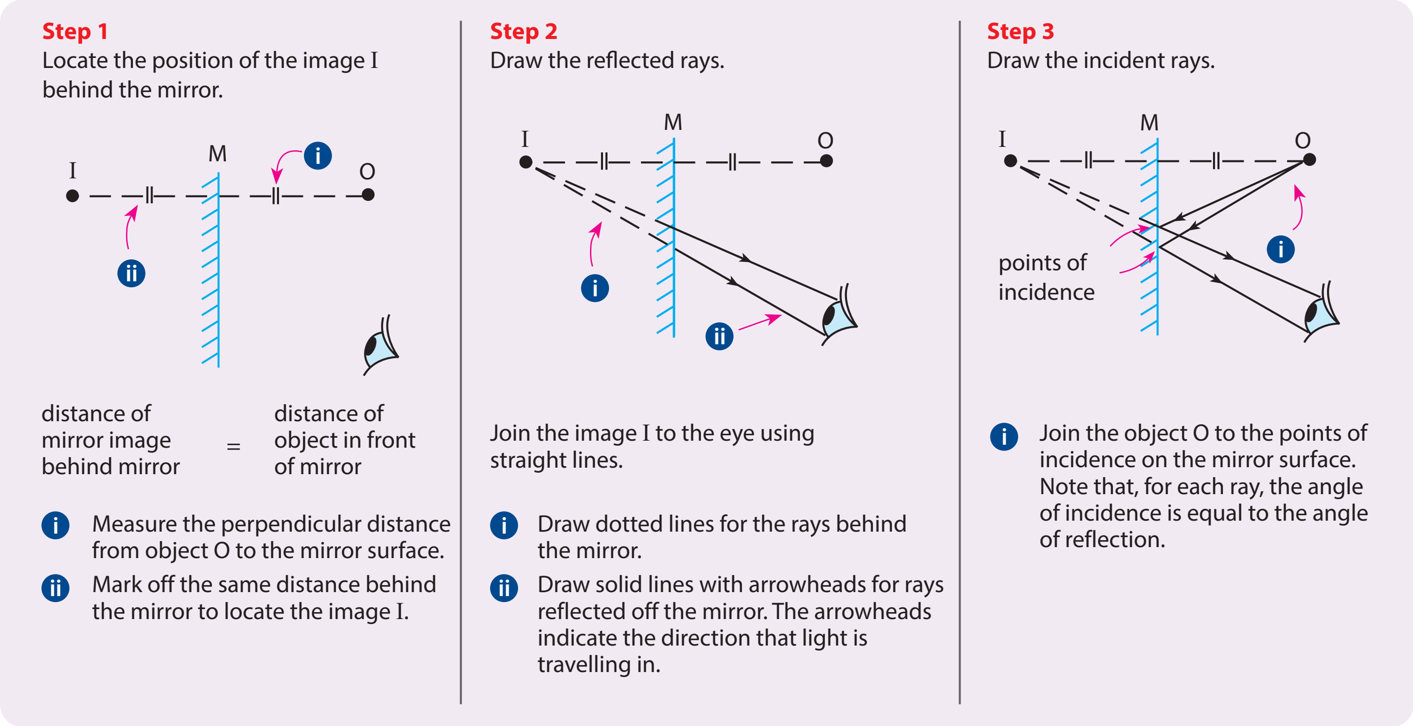
Ray diagrams for plane mirrors

We cannot capture a mirror image on a screen because it is a virtual image. However, we can locate its position by drawing ray diagrams. Figure 12.9 shows a point object O in front of a plane mirror M. The point object O is represented by a dot. The mirror is represented by a straight line, with shading to show its silvered back.

Figure 12.9

Ray diagram for a point object

Figure 12.10 shows how a ray diagram for a point object is drawn.



Step 1
Locate the position of the image I behind the mirror.

distance of mirror image behind mirror = distance of object in front of mirror

- (i) Measure the perpendicular distance from object O to the mirror surface.
- (ii) Mark off the same distance behind the mirror to locate the image I.

Step 2
Draw the reflected rays.

Join the image I to the eye using straight lines.

- (i) Draw dotted lines for the rays behind the mirror.
- (ii) Draw solid lines with arrowheads for rays reflected off the mirror. The arrowheads indicate the direction that light is travelling in.

Step 3
Draw the incident rays.

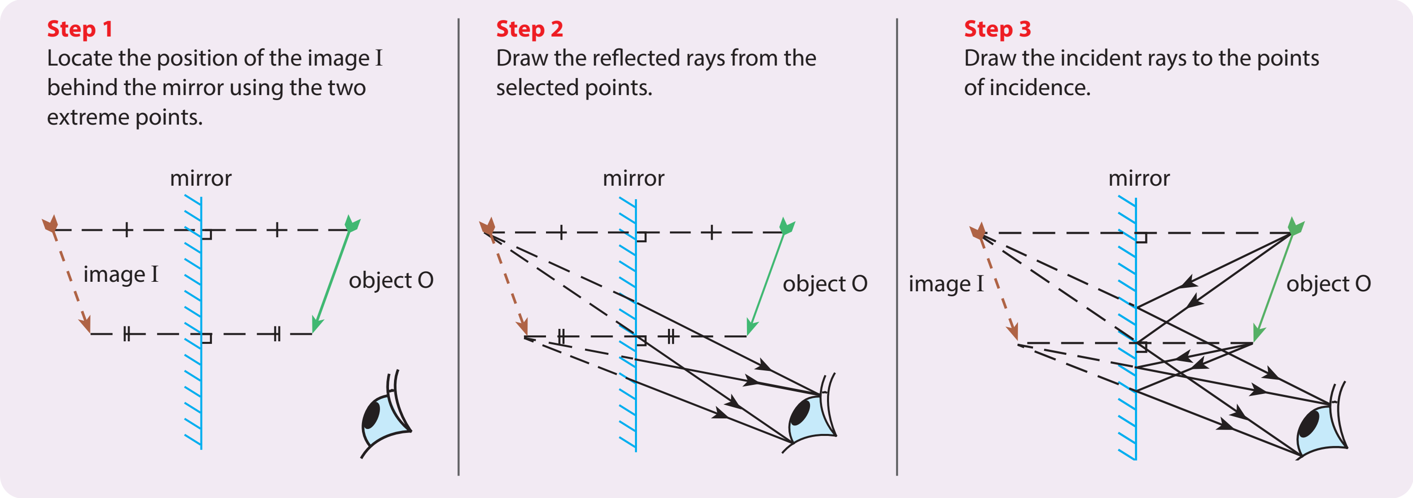
- (i) Join the object O to the points of incidence on the mirror surface. Note that, for each ray, the angle of incidence is equal to the angle of reflection.

Figure 12.10 *Drawing a ray diagram for a point object*

By measuring the distances IM and OM, it can be seen that the distance from the object to the mirror and the mirror to the image are the same.

Ray diagram for an extended object

An extended object can be seen as many points. To draw the ray diagram for the extended object (Figure 12.11), we need to select several of these points and apply the same steps in Figure 12.10 to them.



Step 1
Locate the position of the image I behind the mirror using the two extreme points.

Step 2
Draw the reflected rays from the selected points.

Step 3
Draw the incident rays to the points of incidence.

Figure 12.11 *Drawing a ray diagram for an extended object*

By measuring the length of the image and the length of the object, it can be seen that the size of the image and the size of the object are the same.

Worked Example 12C

Two point objects P and Q are placed at different positions in front of a plane mirror, as shown in Figure 12.12.

(a) Draw a single ray to locate the position of the image of P as seen by the eye at E.

(b) The eye at E is also able to see the image of Q. Draw a single ray to show how this is possible.

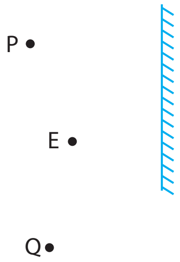


Figure 12.12

Solution

Refer to Figure 12.13.

(a) P' is the image of P.

(b) Q' is the image of Q.

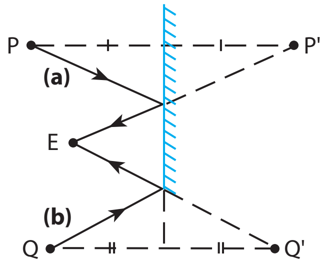


Figure 12.13

WORD ALERT

Optical: relating to sight or the ability to see

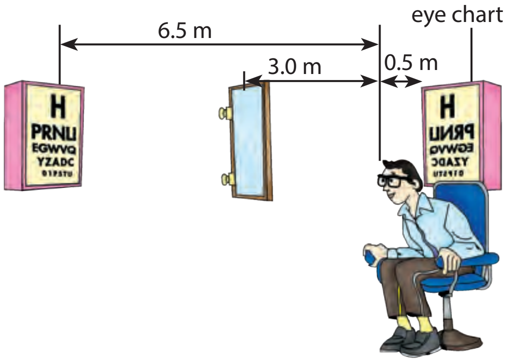
Some applications of mirrors

Figure 12.14 shows some applications of mirrors.

Applications of mirrors

Vision testing

Before you can get a pair of spectacles at an optical shop, you have to go through a vision test. You need to read letters and numbers off an eye chart from a standard distance during the test. To allow a vision test to be carried out in a small room, mirrors are used to make the numbers on the eye chart appear further away.



Periscope

A periscope comes with two plane mirrors inclined at 45°. It helps a person look over obstacles such as a high wall or other spectators in a game or an event!

Blind corner mirror

Fitting curved mirrors at the corners of shops allows shopkeepers to keep a lookout for shoplifters. Such mirrors are also used to help drivers see around blind corners before making a turn.

Instrument scale

A mirror placed below the pointer of a scale can help us avoid parallax error when taking readings. To avoid parallax error, we need to make sure that the pointer is aligned with its mirror image.

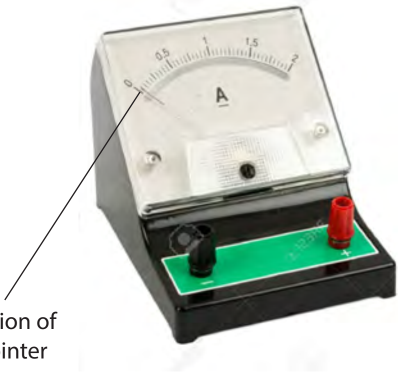


Figure 12.14 *Applications of mirrors*

Let's Practise 12.1

1 With the help of a diagram, state the law of reflection.

2 What are the characteristics of an image formed in a plane mirror?

3 S Figure 12.15 shows an arrow placed above a mirror.

(a) On the diagram,

(i) draw its image formed by the mirror;

(ii) show how light rays from the object are reflected at the mirror to form the image for the eye.

(b) Describe the image.

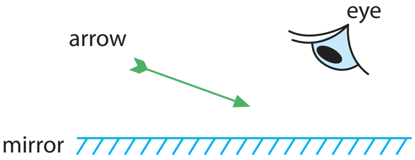


Figure 12.15

4 S A person is looking at the image of an eye chart in a mirror placed 3.0 m in front of him. Given that the actual eye chart is positioned 0.5 m behind his eyes, find the distance between the image of the chart and his eyes.

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

LINK TWB

Exercise 12A, pp. XX–XX

12.2 Refraction of Light

In this section, you will learn the following:

- Define and use the terms *normal*, *angle of incidence* and *angle of refraction*.
- Describe an experiment to show refraction of light.
- Describe the passage of light from one medium to another through a transparent material.
- S Define *refractive index*, *n*.
- S Recall and use the equation $n = \frac{\sin i}{\sin r}$.

LINK

Recall the refraction of waves that you have learnt in Chapter 11.

Light can travel through transparent materials such as glass and water. This is why we can see a pencil in a glass of water. But why does the pencil appear bent at the water surface (Figure 12.16)?

Light travels at different speeds in different transparent materials (i.e. optical **media**). For example, its speed is 3.0×10^8 m/s in air and 2.0×10^8 m/s in glass. When light travels from air to glass, it undergoes a change in speed at the **boundary** of the two optical media. The change in speed causes light to bend (i.e. change its direction). This called *refraction*.

WORD ALERT A-Z

Media: (plural of medium), matter, substances

Boundary: interface where two areas meet

Figure 12.16 *We can see the pencil in a glass of water because it reflects light through the water and glass into our eyes. But why does the pencil appear bent?*

Light travels the fastest in vacuum. It slows down in an optically denser medium (e.g. glass, water). Figure 12.17 shows a ray of light striking and refracting at a surface, PQ.

Below are some terms that are used to describe the refraction of light:

- **Refraction** is the bending of light as it passes from one optical medium to another.
- **Incident ray** is light ray that hits the refracting surface.
- **Point of incidence** is the point at which the incident ray hits the refracting surface.
- **Normal** is the imaginary line perpendicular to the refracting surface at the point of incidence.
- **Angle of incidence** i is the angle between the incident ray and the normal.
- **Angle of refraction** r is the angle between the refracted ray and the normal.

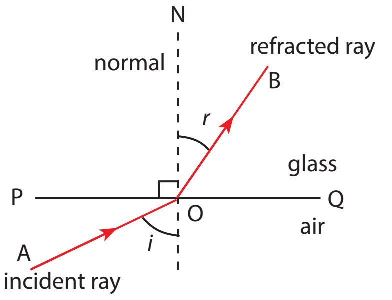


Figure 12.17 *Refraction of light at a surface*

What is the law of refraction?

We can carry out Let's Investigate 12C to learn the law that governs the refraction of light.

Let's Investigate 12C

Objective
To investigate the law of refraction

Apparatus
Translucent rectangular block, ray box and power supply, paper

Precautions
A ray box with a filament lamp may get hot.

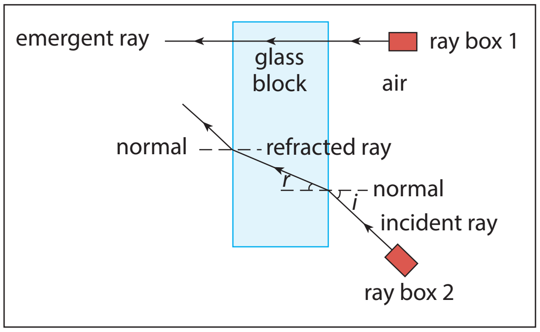


Figure 12.18 *a piece of paper*

Procedure

1. Place the glass block on a piece of paper.
2. Using ray box 1, shine a light ray through the glass block along the normal (Figure 12.18), and observe the path of the light ray.
3. Using ray box 2, shine a light ray through the glass block at an angle (Figure 12.18), and observe the path of the light ray.
4. Vary the angle of incidence i and measure the corresponding angles of refraction r. Tabulate the results as shown in Table 12.1 and plot the graph of sin i against sin r as shown in Figure 12.19.

Table 12.1 *Recorded data and calculated values*

i / °	r / °	$\sin i$	$\sin r$	$\frac{\sin i}{\sin r}$
20.0	13.0	0.342	0.225	1.52
30.0	20.0	0.500	0.342	1.46
40.0	25.0	0.643	0.423	1.52
50.0	31.0	0.766	0.515	1.49
60.0	35.0	0.866	0.574	1.51
70.0	39.0	0.940	0.629	1.49

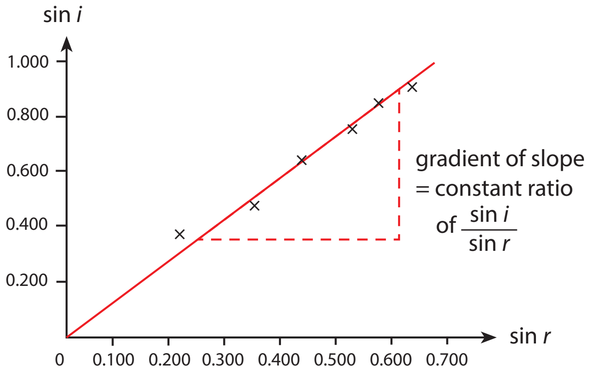


Figure 12.19

LINK PWB

Practicals 12C–12D, pp. XX–XX

WORD ALERT A-Z

Conversely: on the other hand, in the opposite way

HELPFUL NOTES

Although a light ray travelling from one medium to another along the normal is not refracted, it still undergoes a change in speed.

Observations and results

1 For ray box 1, the light ray passes through the glass block in a straight line. There is no change in its direction.

2 For ray box 2,
  - the light ray bends towards the normal as it enters the block;
  - the light ray bends away from the normal as exits the block. The emergent ray is parallel to the incident ray;
  - Ⓢ the graph of sin *i* against sin *r* is a straight line the goes through the origin with a constant gradient (Figure 12.19).

Discussion and conclusion

1 A light ray that travels from one medium to another along the normal is not refracted.

2 A light ray bends towards the normal when it enters an optically denser medium at an angle (e.g. air to glass).

3 Conversely, a light ray bends away from the normal when it enters an optically less dense medium at an angle (e.g. glass to air).

4 The incident ray, the normal and the refracted ray all lie in the same plane.

5 Ⓢ From Figure 12.19, we can deduce that the ratio of sin *i* to sin *r* for a particular medium (or gradient of its straight-line graph) gives us a constant.

Ⓢ The conclusion in Let's Investigate 12C is consistent with the **law of refraction** discovered by the Dutch scientist, Willebrord Snell:

- For two given media, the ratio of the sine of the angle of incidence, *i*, to the sine of the angle of refraction, *r* is a constant.

$$\frac{\sin i}{\sin r} = \text{constant}$$

This is also known as **Snell's Law**.

Refractive index and speed of light

The **refractive index** *n* is the ratio of the speeds of a wave in two different regions.

Consider light travelling through a medium. The refractive index *n* of a medium is the ratio of the speed of light in vacuum to the speed of light in the medium.

$n = \frac{c}{v}$ where c = speed of light in vacuum

v = speed of light in the medium

The higher the value of the refractive index of a medium, the slower light travels in the medium.

For light travelling from vacuum to an optical medium, the constant ratio $\frac{\sin i}{\sin r}$ is also known as the refractive index *n* of that medium.

$\boldsymbol{n = \frac{\sin i}{\sin r}}$ where i = angle of incidence in vacuum

r = angle of refraction in the medium

The higher the value of the refractive index of a medium, the smaller the angle of refraction *r* (i.e. the more the light bends towards the normal). This is can be seen when we compare refraction in diamond to refraction in water (Figure 12.21).

QUICK CHECK

In Figure 12.20, medium P is optically more dense than medium Q.

True or false?

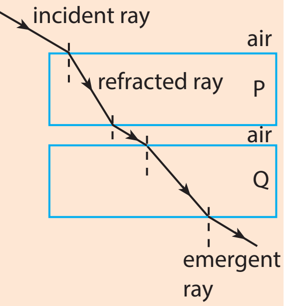


Figure 12.20

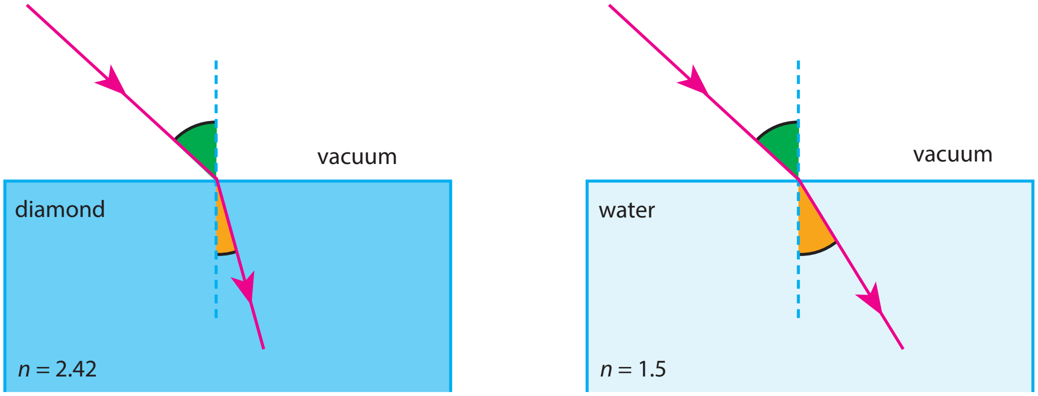


Figure 12.21 *The angle of refraction is smaller in diamond than in water*

Table 12.2 *Refractive* **indices** *of and speed of light in some materials*

Medium	Refractive index *n*	Speed of light (× 10^8 m/s)
Diamond	2.40	1.25
Glass	1.50*	2.00
Perspex	1.50	2.00
Water	1.33	2.25
Ice	1.30	2.30
Air	1.000 293	2.999

* For glass, the refractive index varies between 1.48 and 1.96, depending on the composition of the glass.

From Table 12.2, we can see that the speed of light in air is very close to that in vacuum. Hence, for most practical purposes, we can find the approximate value of the refractive index even though we use the speed of light in air instead of vacuum.

$$n = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}} \approx \frac{\text{speed of light in air}}{\text{speed of light in medium}}$$

Worked Example 12D

Given that the speed of light in vacuum is 3.0×10^8 m/s, calculate the speed of light in crown glass of refractive index 1.52.

Solution

Given: Speed of light in vacuum $c = 3.0 \times 10^8$ m/s
Refractive index of crown glass $n = 1.52$

Using $n = \frac{c}{v}$ where v = speed of light in crown glass,

$$v = \frac{c}{n}$$
$$= \frac{3.0 \times 10^8 \ m/s}{1.52}$$
$$= 1.97 \times 10^8 \text{ m/s}$$

WORD ALERT

Indices: plural of *index*

HELPFUL NOTES

A transparent material of higher refractive index is an optically denser medium.

However, optical density is different from mass density. For example, liquid paraffin is optically denser than water, but its mass density is lower.

Worked Example 12E

Figure 12.22 shows a ray of light passing through a rectangular glass block of refractive index 1.5.

If the ray strikes the surface PQ at an angle of incidence *i* of 60°, calculate the

(a) angle of refraction *r* at the air-to-glass boundary (PQ);

(b) angle of incidence *x* in the glass block;

(c) angle of refraction *y* at the glass-to-air boundary (RS).

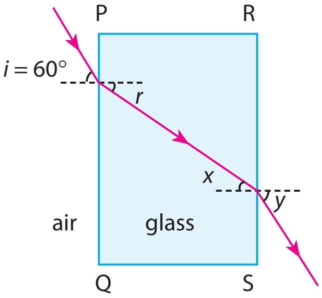


Figure 12.22

Solution

Given: Refractive index of the glass $n = 1.5$

(a) At the air-to-glass boundary (PQ):

$$n = \frac{\sin i}{\sin r} \text{ (Snell's law)}$$

$$\sin r = \frac{\sin i}{n} = \frac{\sin 60°}{1.5}$$

$$r = 35.3°$$

(b) Since x and r are alternate angles, $x = r = 35.3°$

(c) At the glass-to-air boundary (RS):

In this case, we cannot write $n = \frac{\sin x}{\sin y}$ as the angle of incidence x is not in air. However, since a light ray travels along the same path if its direction is reversed, we can solve for angle of refraction y by reversing the direction of the light ray.

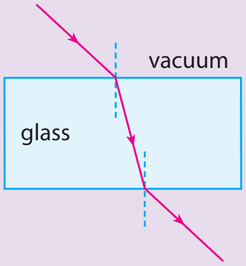
$$n = \frac{\sin x}{\sin y} \text{ (Snell's law)}$$

$$\sin y = n \sin x = 1.5 \sin 35.3°$$

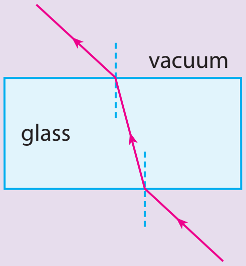
$$y = 60°$$

HELPFUL NOTES

A light ray will travel along the same path if its direction of travel is reversed (Figure 12.23). This is the *principle of reversibility* and it applies to the reflection and refraction of light.



(a) When light shines from top to bottom



(b) When the direction of light is reversed, the angles it makes with the normal are the same as in (a).

Figure 12.23

Worked Example 12F

Figure 12.24 shows a ray of light being partially reflected and refracted at the surface of a glass block of refractive index 1.6.

Determine the value of

(a) *x*; **(b)** *y*.

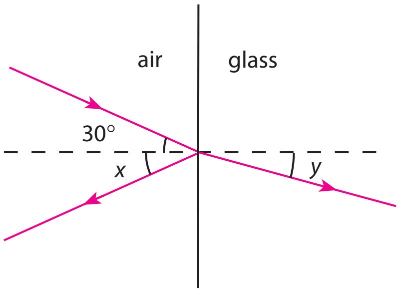


Figure 12.24

Solution

Given: Angle of incidence = 30°

Refractive index of glass block = 1.6

Angle of reflection = *x*

Angle of refraction = *y*

(a) By the law of reflection, angle of incidence *i* = angle of reflection *r*

$\therefore x = 30°$

(b) Using Snell's law,

$$n = \frac{\sin i}{\sin r}$$

$$1.6 = \frac{\sin 30°}{\sin y}$$

$$y = 18.2°$$

Daily phenomena and applications of refraction

'Bent' objects

Objects in water or other optically denser media appear bent because of refraction. In Figure 12.25, we can see the rod because it reflects light to our eyes. It appears to be bent because the reflected light from the immersed part of the rod refracts when it travels from water to air.

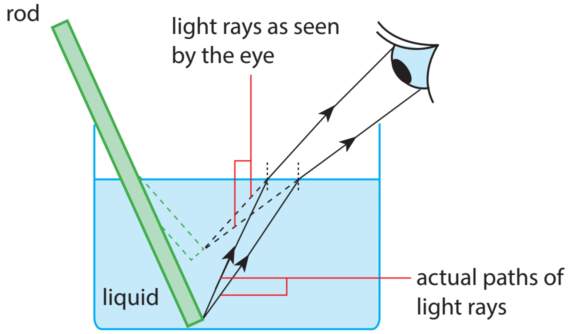


Figure 12.25 *A partially immersed rod appears bent because light bends away from the normal when it travels from water to air.*

Misperception of depth

Swimming pools appear shallower than they actually are because of refraction (Figure 12.26).

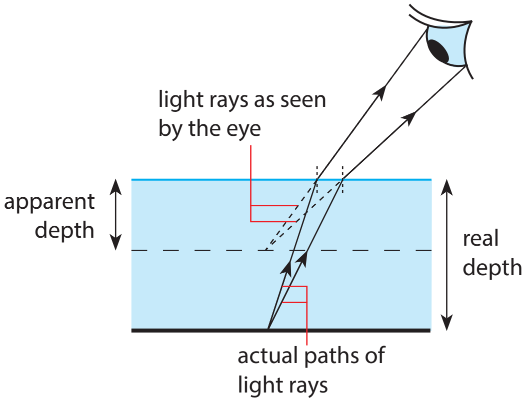


Figure 12.26 *A swimming pool is deeper than it seems.*

Worked Example 12G

Figure 12.27 shows a thin rod partially immersed in a beaker of water. Given that the refractive index of water is 1.33, determine the value of

(a) θ; **(b)** x.

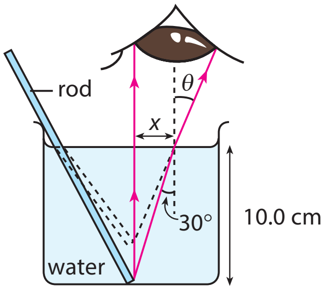


Figure 12.27

Solution

(a) We can solve for θ by reversing the direction of the light ray.

$$n = \frac{\sin\theta}{\sin 30°} \text{ (Snell's law)}$$

$$1.33 = \frac{\sin\theta}{\sin 30°}$$

$$\theta = 41.7°$$

(b) Since angle AOB and the angle of incidence are alternate angles, angle AOB is 30°.

$$\therefore \tan 30° = \frac{x}{10 \text{ cm}}$$

$$x = 5.77 \text{ cm}$$

HELPFUL NOTES

The refractive index n of a medium is also given by the ratio of the real depth of an object in a medium to its apparent depth in the same medium.

i.e. $n = \frac{\text{real depth}}{\text{apparent depth}}$

ENRICHMENT INFO

The Archer's Fish Secret

The archer fish uses a unique way to catch its prey. It shoots a jet of water with pinpoint accuracy, knocking its prey off a branch or a leaf. How is it able to hit its target with such high accuracy despite the visual distortion caused by refraction?

Biologists are still trying to establish an answer to this question. If you were an archer fish, how would you overcome distorted vision due to refraction so that you could always hit your target?

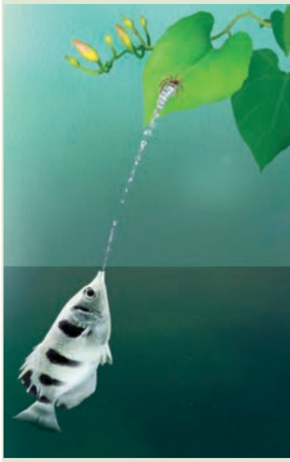


Figure 12.28 *An archer fish spitting a jet of water at its prey resting on a leaf*

Let's Practise 12.2

1 Draw a clearly labelled diagram to show the refraction of light when it travels from air to water.

2 S How is the speed of light in glass related to the angle of incidence and angle of refraction of light?

3 At what angle of incidence will light pass from air to another transparent material without being refracted?

4 Draw a diagram to show how a coin at the bottom of a bucket of water appears to a viewer.

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

LINK TWB

Exercise 12B, pp. XX–XX

12.3 Total Internal Reflection

In this section, you will learn the following:

- State the meaning of *critical angle*.
- Describe *internal reflection* and *total internal reflection* using both experimental and everyday examples.
- S Recall and use the equation $n = \frac{1}{\sin c}$.
- S Describe the use of optical fibres, particularly in telecommunications.

Figure 12.29 shows the reflection of a turtle under water. This reflection is at the water–air boundary and occurs due to the *total internal reflection* of light.

Total internal reflection can only occur when light passes from an optically denser to a less dense medium. To understand this unique behaviour of light, we need to first understand what *critical angle* is.

Figure 12.29 The reflection of the turtle can be clearly seen underwater at the water–air boundary.

What is a critical angle? How can we find it for a material?

We can carry out Let's Investigate 12D to demonstrate critical angle.

Let's Investigate 12D

Objective
To investigate the critical angle in total internal reflection

Apparatus
Transparent semi-circular block, ray box and power supply, paper

Precautions
A ray box with a filament lamp may get very hot.

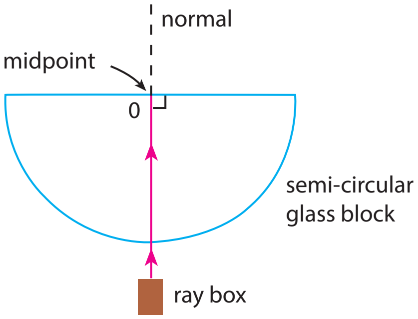


Figure 12.30

LINK PWB

Practical 12E, pp. XX–XX

Procedure

1. Set up the apparatus as shown in Figure 12.30.
2. Direct a light ray through the semi-circular block at the midpoint O such that it is perpendicular to the flat surface of the glass block. Observe the path of the light.
3. Direct the light ray at an angle *i* at O. Vary angle *i* and observe the corresponding change in the path of the light ray.

Observation, discussion and conclusion

1. When the light ray was directed through the midpoint O such that it was perpendicular to the flat surface of the block, the light ray passed straight through, without any deviation (Figure 12.31).

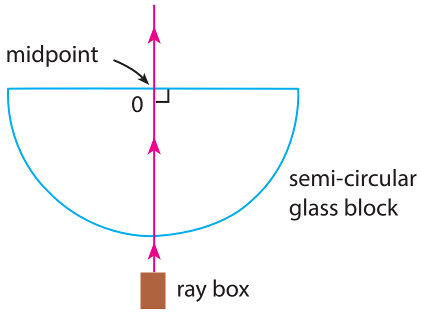


Figure 12.31

2. When the light ray was directed at a point O at an angle *i*, it refracted away from the normal upon emerging from the glass (Figure 12.32). This is because it was travelling from an optically denser medium (e.g. glass) to an optically less dense medium (e.g. air). A small amount of light is reflected off the flat surface of the glass block.

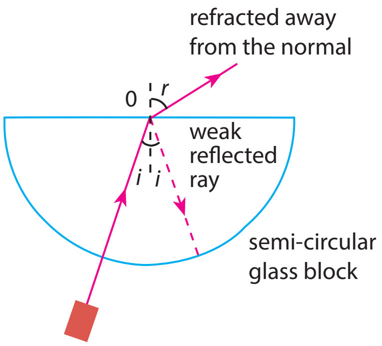


Figure 12.32

3. As the incident angle is increased, the refracted ray bends further away from the normal until the angle of refraction *r* becomes 90° (Figure 12.33). When the angle of refraction is 90°, the corresponding angle of incidence is known as the *critical angle c*.

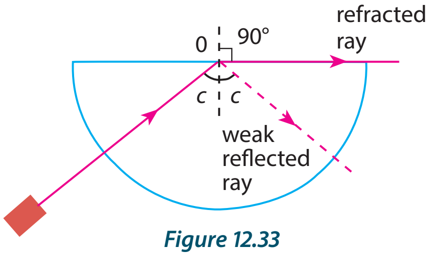


Figure 12.33

The **critical angle** *c* is defined as the angle of incidence (in an optically denser medium) for which the angle of refraction (in the optically less dense medium) is 90°.

HELPFUL NOTES

In Investigation 12D, a semi-circular glass block is used, and the light ray is always directed towards the midpoint O of the diameter of the block.

Recall that a tangent to a circle is perpendicular to the radius at the point of contact (Figure 12.34).

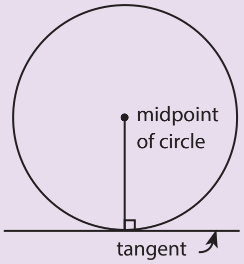


Figure 12.34

Therefore, a light ray directed towards the midpoint O will always enter the curved surface of the glass block at an angle of incidence of 0° (i.e. it passes through the surface without bending). This makes the study of critical angle at the flat surface of the glass block more convenient.

Critical angle and total internal reflection

When the angle of incidence in the glass block is larger than the critical angle *c*, the light ray reflects off the flat surface of the glass block. There is no refraction at the flat surface (i.e. glass–air boundary) (Figure 12.35). This phenomenon is known as *total internal reflection*. This explains why we can see the reflection of the turtle underwater in Figure 12.29 on page 192.

Total internal reflection is the complete reflection of a light ray inside an optically denser medium at its boundary with an optically less dense medium.

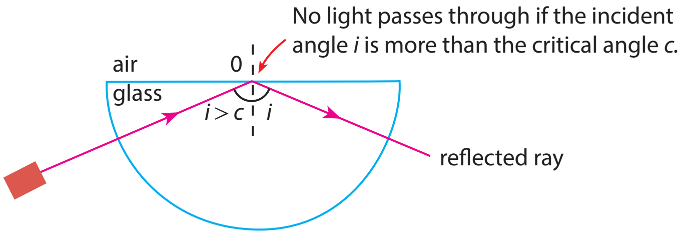


Figure 12.35

ENRICHMENT
THINK

Radio waves transmitted from the ground can undergo total internal reflection from the sky. The waves are reflected off the ionosphere, an upper layer of the Earth's atmosphere, and can be received many hundreds of kilometres away. Explain how the ionosphere causes the total internal reflection of the waves.

PHYSICS WATCH

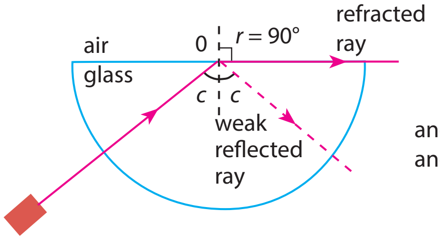
Scan this page to watch a clip of an experiment on total internal reflection.

In summary, two conditions that must be satisfied in order for a light ray to undergo total internal reflection are:

1. The light ray in an optically denser medium strikes its boundary with an optically less dense medium.
2. The angle of incidence is greater than the critical angle of the optically denser medium.

S Determining critical angle

Given the refractive index *n* of a transparent material, we can find its critical angle *c*. Consider a light ray travelling from air into a semi-circular glass block before exiting into air at O (Figure 12.36).



angle of incidence i = critical angle c
angle of refraction $r = 90°$

Figure 12.36

With reference to page 188, when the light is travelling from vacuum to the medium, the refractive index of the medium is given by the ratio $\frac{\text{sin (angle of incidence)}}{\text{sin (angle of refraction)}}$. However, in Figure 12.36, the light is travelling from glass to air. We can visualise the same path of light in Figure 12.36 but with the directions reversed (refer to Figure 12.23 on page 190). This will give the following:

$$n = \frac{\sin 90°}{\sin c} = \frac{1}{\sin c}$$

$$\therefore \boldsymbol{\sin c = \frac{1}{n}}$$

Worked Example 12H

Figure 12.37 shows a light ray entering a right-angled glass prism of refractive index 1.5.

(a) Calculate the critical angle of the prism.

(b) Complete the path of the light ray until it emerges into the air.

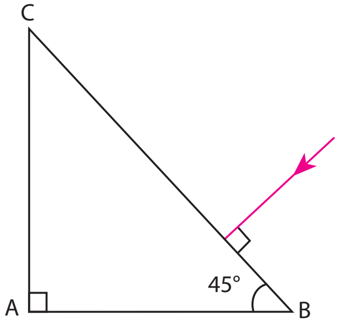


Figure 12.37

Solution

(a) Given: Refractive index $n = 1.5$

$$\sin c = \frac{1}{n} = \frac{1}{15}$$

$$c = 41.8°$$

(b) Since the ray enters the prism at a right angle, it does not bend and hits surface AB at 45° (i.e. angle of incidence *i*).

Since the angle of incidence (45°) is greater than the critical angle of 41.8°, total internal reflection occurs. Similarly, total internal reflection also occurs at surface AC. The light ray exits at a right angle to surface BC.

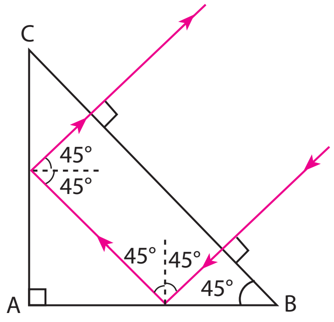


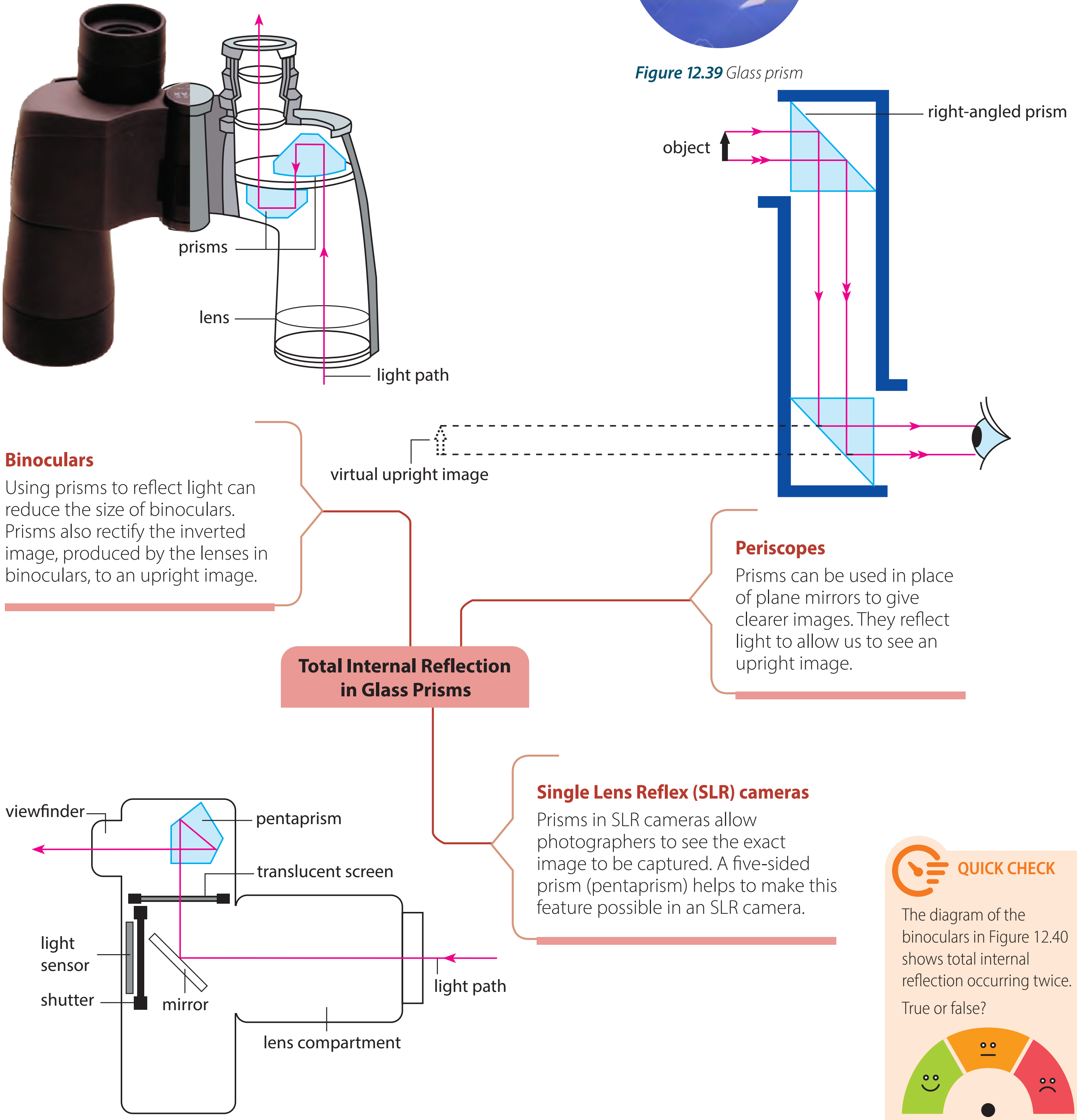
Figure 12.38

What are the applications of total internal reflection?

Glass prisms

Glass prisms (Figure 12.39) are used to reflect light in some optical instruments such as binoculars and periscopes. They reflect light by total internal reflection.

Figure 12.39 *Glass prism*



Total Internal Reflection in Glass Prisms

Binoculars

Using prisms to reflect light can reduce the size of binoculars. Prisms also rectify the inverted image, produced by the lenses in binoculars, to an upright image.

Periscopes

Prisms can be used in place of plane mirrors to give clearer images. They reflect light to allow us to see an upright image.

Single Lens Reflex (SLR) cameras

Prisms in SLR cameras allow photographers to see the exact image to be captured. A five-sided prism (pentaprism) helps to make this feature possible in an SLR camera.

Figure 12.40 *Use of total internal reflection in glass prisms*

QUICK CHECK

The diagram of the binoculars in Figure 12.40 shows total internal reflection occurring twice.

True or false?

Optical fibres

The transmission of data using optical fibres is an important application of total internal reflection. Optical fibres are long, thin and flexible. They are made of glass or plastic and can transmit light over long distances through total internal reflection (Figure 12.41).

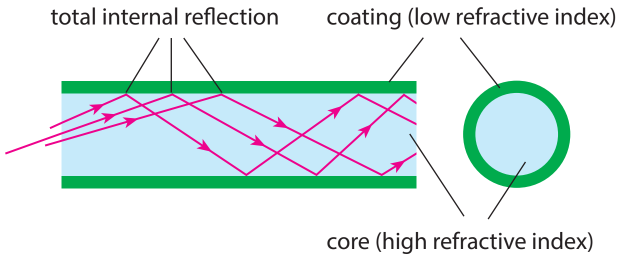


Figure 12.41 An optical fibre has a core of a high refractive index. The core is coated with another material of a lower refractive index.

Even when the fibre is bent, light rays entering it will still be internally reflected at the boundary between the two refractive materials. These flexible fibres have innovative uses in many industries such as telecommunications and medicine (Figure 12.42).

Total Internal Reflection in Optical Fibres

Telecommunications industry

Today, telephone conversations and Internet data are transmitted across continents using optical fibres, and not copper wires. Advantages of optical fibres over copper wires in telecommunications are as follows:

- *Higher carrying capacity:* An optical fibre can carry much more information over long distances than a copper wire.
- *Less signal degradation:* A signal transmitted via optical fibres experiences much less signal loss as compared to copper wires.
- *Lightweight:* Optical fibres are lighter than copper wires.
- *Lower cost:* Optical fibres are becoming cheaper to manufacture as compared to copper wires of equivalent lengths.

Medical industry

The high flexibility of optical fibres makes them ideal for medical applications such as endoscopes. Doctors use endoscopes to see inside hollow organs, such as the intestines.

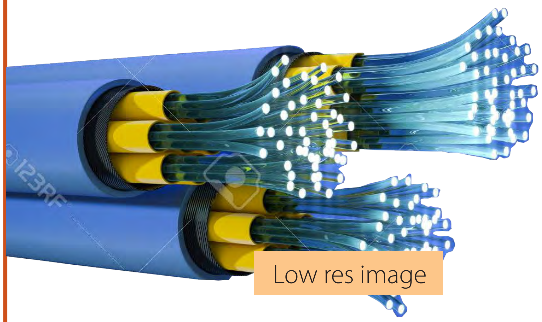


Figure 12.42 Use of total internal reflection in optical fibres

Let's Practise 12.3

1 Explain what is meant by term *critical angle*.
2 Draw a clearly labelled diagram to show total internal reflection.
3 S The refractive index of a glass prism is 1.9. Calculate its critical angle.
4 State **two** applications of total internal reflection.
5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

TWB LINK

Exercise 12C,
pp. XX–XX

12.4 Refraction by Thin Lenses

In this section, you will learn the following:

- Describe the action of thin converging and thin diverging lenses on a parallel beam of light.
- Define and use the terms *focal length*, *principal axis* and *principal focus (focal point)*.

A lens is a piece of clear plastic or glass with curved surfaces. Lenses are widely used in cameras, spectacles, projectors and many other optical instruments.

Figure 12.43 *Camera with interchangeable lenses*

Figure 12.44 *How are spectacles for long-sightedness different from those for short-sightedness?*

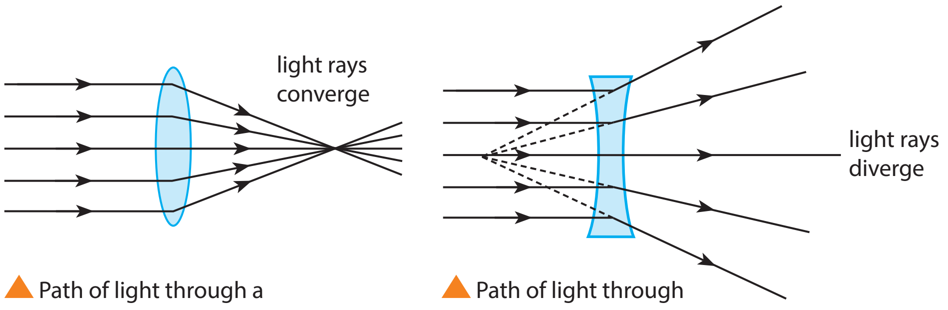
A-Z WORD ALERT

Converge: heading towards a point

Diverge: spread out

What determines the path of light through a lens?

A typical lens can be thought of as a set of small prisms (Figures 12.45). As the surface of a lens is curved, parallel light rays hitting different parts of its surface have different incident angles. This causes the individual rays to refract by different angles. The angle of refraction is the largest at the outermost part of the lens, while no refraction occurs in the middle. As a result, depending on the curvature of the lens, light rays either converge or diverge after passing through the lens (Figure 12.44).



▲ Path of light through a converging lens

▲ Path of light through a diverging lens

Figure 12.45 *A typical lens can be thought of as a set of small prisms.*

A **converging lens** causes light rays to converge to a point. It is *thicker in the centre*.

A **diverging lens** causes light rays to diverge from a point. It is *thinner in the centre*.

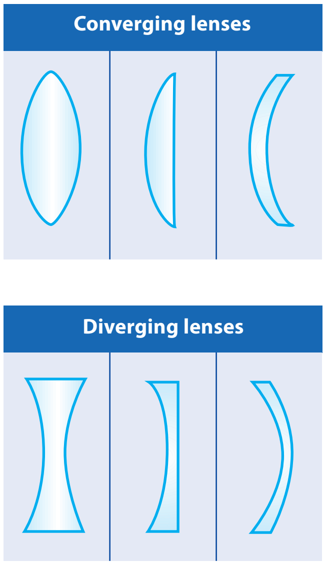
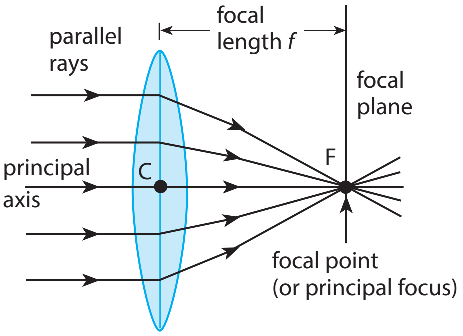


Figure 12.46 *Different types of converging and diverging lenses*

Thin converging lens

We will learn what focal length is and other terms that are used to describe a thin converging lens (Figure 12.47).



The **principal axis** is the horizontal line passing through the optical centre of the lens. It is perpendicular to the vertical plane of the lens.

Focal length *f* is the distance between the optical centre C and the focal point F.

The *optical centre* C is the midpoint between the surfaces of the lens on its principal axis. Rays passing through the optical centre are not refracted.

The **principal focus (or focal point)** is the point at which all rays parallel to the principal axis converge after refraction by the lens. A lens has two focal points, one on each side of the lens.

The *focal plane* is the plane that passes through the focal point F and perpendicular to the principal axis.

Figure 12.47 *Parallel beam of rays parallel to the principal axis*

When the parallel beam of rays incident on a thin converging lens is not parallel to the principal axis, the rays are refracted to a point (not the focal point F) on the focal plane (Figure 12.48).

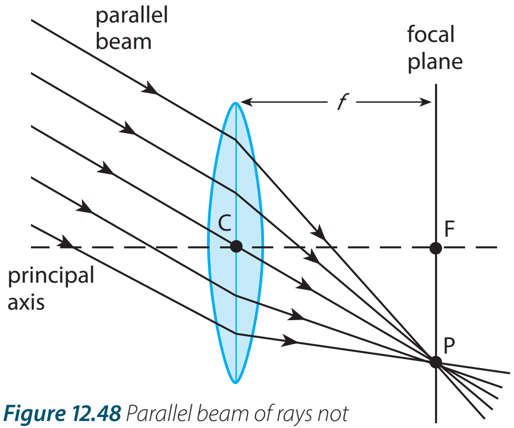


Figure 12.48 *Parallel beam of rays not parallel to the principal axis*

Let's Practise 12.4

1 With the help of a diagram, describe how a converging lens is different from a diverging lens in terms of their structure and their effect on light.

2 Figure 12.50 shows a diagram of light rays passing through a thin converging lens. Explain whether the diagram is correct?

3 With the help of a diagram, define the focal length of a thin converging lens.

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

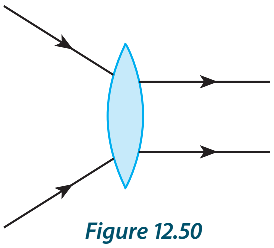


Figure 12.50

ENRICHMENT *ACTIVITY*

In this activity, you will use the rays of the Sun to find the focal length of a magnifying glass.

Precaution

Be careful! The bright spot may cause the paper (or anything else) to burn.

1 Hold a magnifying glass above a piece of paper under the Sun.

2 Adjust the distance between the lens and the paper until you can observe a small bright spot. This distance is its focal length.

At its focal length, a magnifying glass focuses the Sun's rays onto one small spot on its focal plane (Figure 12.49).

Figure 12.49

Can you think of other ways to find the focal length of a magnifying glass?

LINK TWB

Exercise 12D, pp. XX–XX

12.5 Ray Diagrams for Thin Converging Lenses

In this section, you will learn the following:

- Describe the characteristics of an image.
- Know how a virtual image is formed.
- Draw and use ray diagrams to show how a real image is formed.
- Ⓢ Draw and use ray diagrams to show how a virtual image is formed.
- Ⓢ Describe the use of a single lens as a magnifying glass.
- Ⓢ Describe the use of converging and diverging lenses to correct long-sightedness and short-sightedness.

From Section 12.4, we know that

- any light ray passing through the optical centre C of a lens is not refracted;
- any light ray parallel to the principal axis of a lens will converge at the focal point F (Figure 12.51).

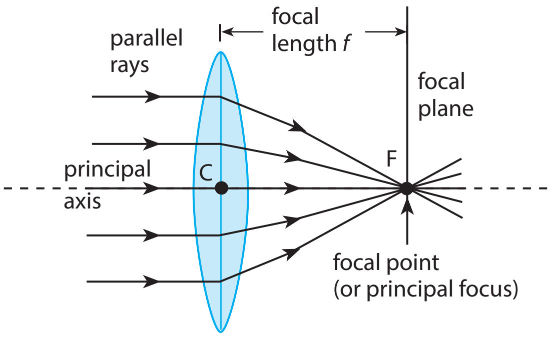
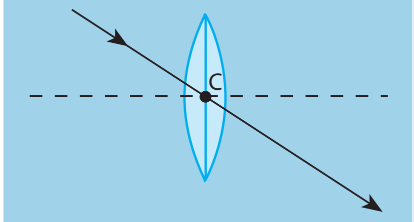
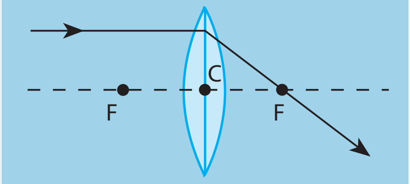
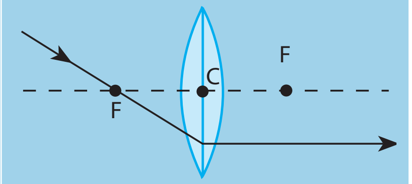


Figure 12.51

With this, we can identify three particular light rays that behave in a predictable way whenever they pass through any thin converging lens (Table 12.3).

Table 12.3 *Behaviour of three particular light rays when passing through a thin converging lens*

Ray 1 passes through optical centre C	Ray 2 parallel to principal axis	Ray 3 passing through focal point F
		
An incident ray through the optical centre C passes without bending.	An incident ray parallel to the principal axis is refracted to pass through F.	An incident ray passing through the focal point F is refracted parallel to the principal axis.

Where is the image made by a thin converging lens?

The image of a lens is determined by the relative positions of the focal point and the object distance. Using any two of the three rays mentioned in Table 12.3, we can draw a ray diagram to locate the position of an image produced by a thin converging lens.

Object distance longer than the focal length (i.e. $f < u < 2f$)

Figure 12.52 shows how a real image is formed when the distance of the object is longer than the focal length.

Step 1: Set up the ray diagram

i Draw a horizontal line to represent the principal axis.

ii Draw a double-headed arrow perpendicular to the horizontal line to represent the converging lens.

iii The intersection point of the principal axis in **(i)** and the lens in **(ii)** is the optical centre of the converging lens. Label the point C.

iv Label the focal point F of the lens on the principal axis. The distance CF is the focal length *f* of the lens.

Step 2: Place the object on the left of the lens

i Draw a vertical arrow on the left of the lens to represent an object. Label the object O.

ii Label the distance OC *u*. Note that $f < u < 2f$.

Step 3: Trace the rays and locate the image

i Select and draw any two of the three rays, e.g. ray 1 and ray 2, from the tip of the object.

ii The intersection point of the two rays represents the real image of the tip of the object. Complete the real image by drawing an arrow and labelling it I.

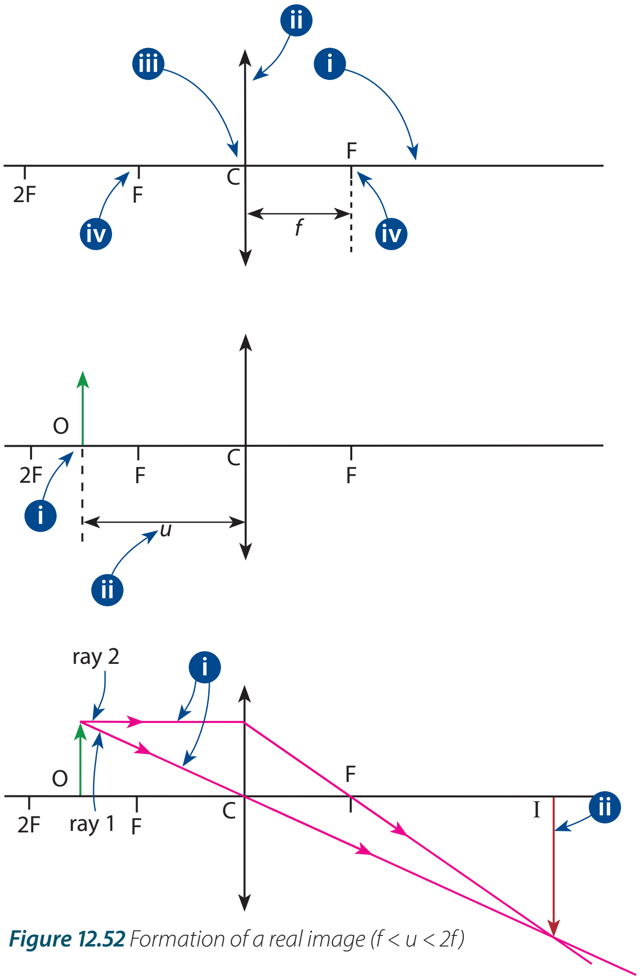


Figure 12.52 Formation of a real image ($f < u < 2f$)

Object distance shorter than the focal length (i.e. $u < f$)

Place the same object at a distance less than the focal length and draw the ray diagram (Figure 12.53). We can see that the light rays diverge and the intersection point of ray 1 and ray 2 can be found only if the rays are extended backwards.

When the diverging rays enter our eyes, they appear to come from a point on the same side as the object. The point represents the virtual image of the tip of the object and the broken arrow represents the virtual image of the object.

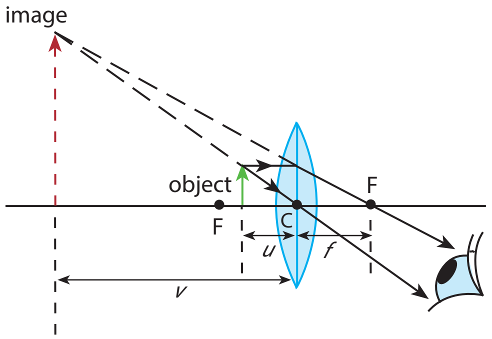
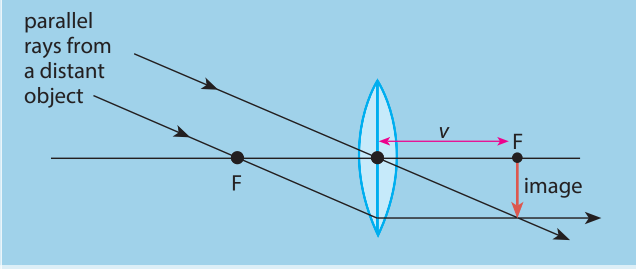
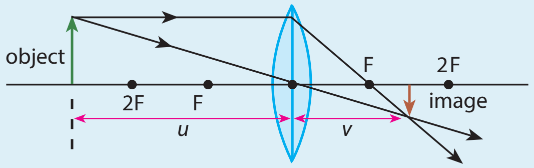
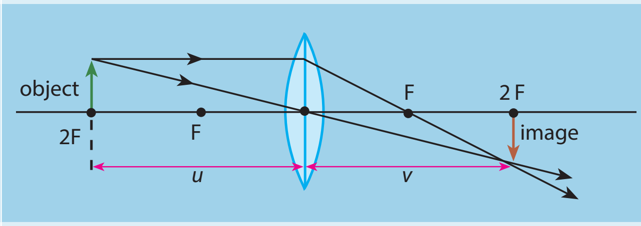
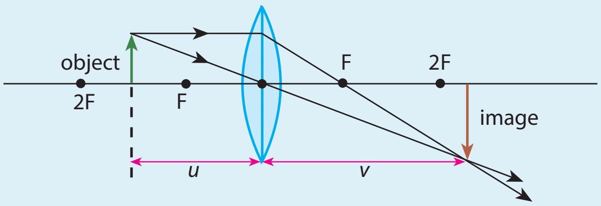
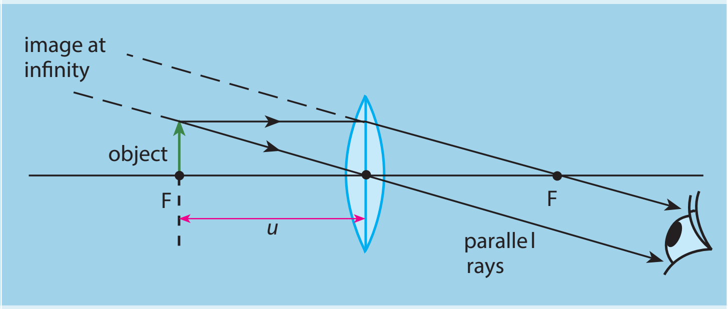
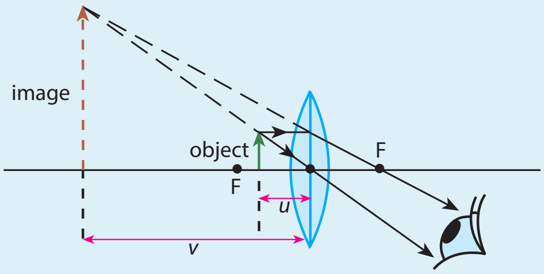


Figure 12.53 Formation of a virtual image ($u < 2f$)

The distance of an object from a thin converging lens determines the type of image that is formed. Table 12.4 shows the types of images formed when an object is placed at different distances from the lens.

Table 12.4*Types of images formed by a thin converging lens with different range of values of u*

Object distance (u)	Ray diagram	Type of image	Image distance (v)	Uses
$u = \infty$		• inverted • real • diminished	$v = f$ • opposite side of the lens	• object lens of a telescope
$u > 2f$		• inverted • real • diminished	$f < v < 2f$ • opposite side of the lens	• camera • eye
$u = 2f$		• inverted • real • same size	$v = 2f$ • opposite side of the lens	• photocopier making same-sized copy
$f < u < 2f$		• inverted • real • magnified	$v > 2f$ • opposite side of the lens	• projector • photograph enlarger
$u = f$		• upright • virtual • magnified	• image at infinity • same side of the lens	• eyepiece lens of a telescope
$u < f$		• upright • virtual • magnified	• image is behind the object • same side of the lens	• magnifying glass

PHYSICS WATCH

Scan this page to explore a simulation on formation of images by lenses.

From Table 12.4, we can see that

- when $u > f$, the image formed is real, inverted and on the opposite side of the lens as the object;
- when $u \leq f$, the image formed is virtual, upright and on the same side of the lens as the object.

Worked Example 12I

An object 2 cm high is placed 7.5 cm from a thin converging lens. The focal length of the lens is 5 cm.

(a) Find, by scale drawing, the position of the image formed.

(b) State the characteristics of the image.

Solution

(a) Horizontal scale: 1 unit square represents 1 cm

Vertical scale: 1 unit square represents 1 cm

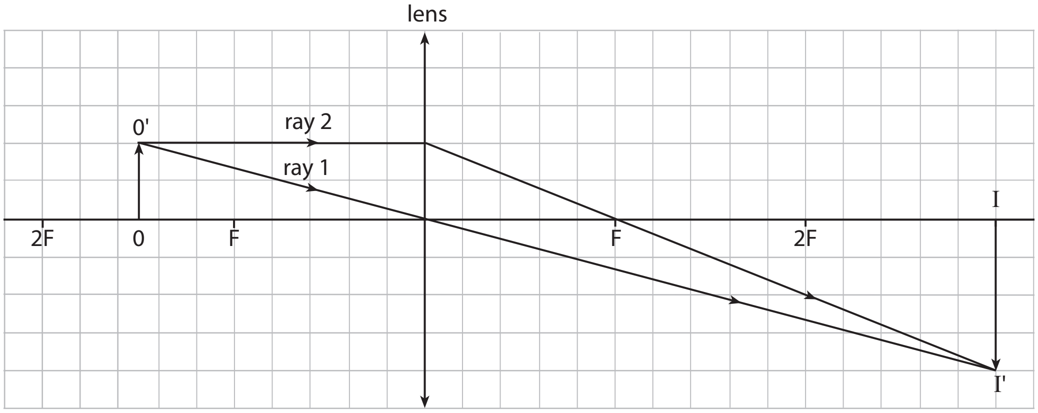


Figure 12.54

From Figure 12.54, the image distance is 15 cm from the lens.

(b) The image formed is real, inverted and magnified. It is on the opposite side of the lens.

LINK PWB

Practical 12F,
pp. XX–XX

What can lenses be used for?

Magnifying glass

A magnifying glass is a thin converging lens. It is used to make objects look bigger (Figure 12.55). In order to get a magnified image, the lens should be positioned at a distance less than a focal length f from the object (i.e. $u < f$).

Figure 12.55 *In comparison to the rest of the textbook cover, the letters under the magnifying glass are magnified.*

Visual correction for long-sightedness

People who are long-sighted are unable to see objects close to their eyes clearly. The lenses in their eyes are unable to focus a clear image of a close object on the retina (Figure 12.56).

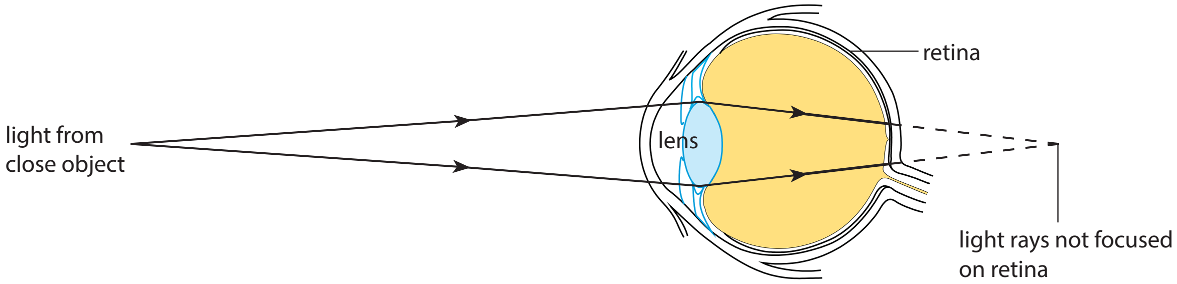


Figure 12.56 *Long-sightedness — the eye lens is unable to focus the light rays onto the retina*

Spectacles with converging lenses can be used to partially converge the light rays before they enter the eyes (Figure 12.57). This way, the light rays coming from the object can be focused on the retina to produce a sharp image.

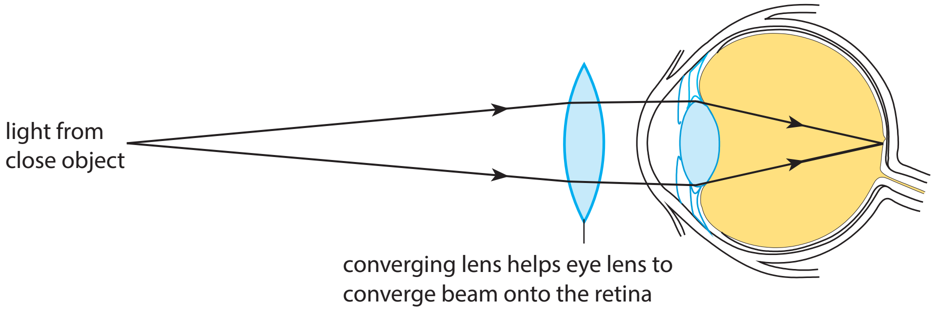


Figure 12.57 *Correcting long-sightedness using a converging lens*

Visual correction for short-sightedness

A person is short-sighted when his or her eyeball is longer than normal along the horizontal axis from the lens to the retina. The eye can still focus on near objects. However, parallel light rays from distant objects are focused in front of the retina, forming a blurred image (Figure 12.58).

Short-sightedness can be corrected by wearing spectacles with concave lenses. The concave lenses diverge the rays from distant objects before they reach the eye. The diverged rays can then be focused onto the retina and this will enable the person to see distant objects clearly (Figure 12.59).

PHYSICS WATCH

Scan this page to explore a simulation on short-sightedness and long-sightedness.

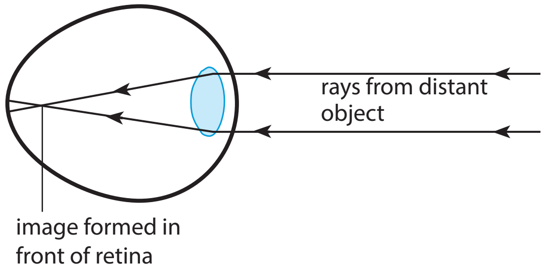


Figure 12.58 *Short-sightedness — image forms in front of the retina*

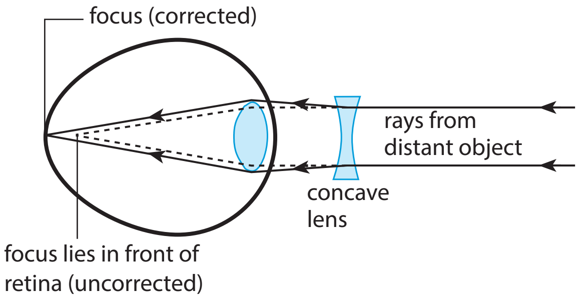


Figure 12.59 *Correcting short-sightedness with a concave lens*

Worked Example 12J

Figure 12.60 shows a small object of height 1.0 cm placed 1.4 cm away from a thin converging lens L of focal length 1.9 cm.

By drawing a suitable ray diagram,

(a) find the position and height of the image;

(b) describe the characteristics of the image formed.

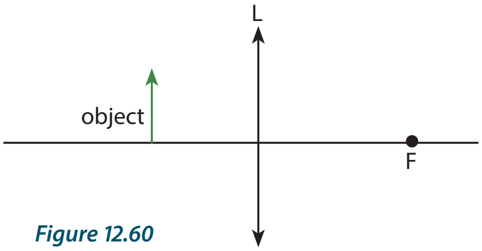


Figure 12.60

Solution

Given: Size of object OO′ = 1.0 cm, object distance u = 1.4 cm, focal length f = 1.9 cm

(a) By scale drawing, the image distance v is 5.8 cm and the height of image I′ is 3.9 cm.

(b) The image formed is upright, magnified, virtual and on the same side of the lens as the object.

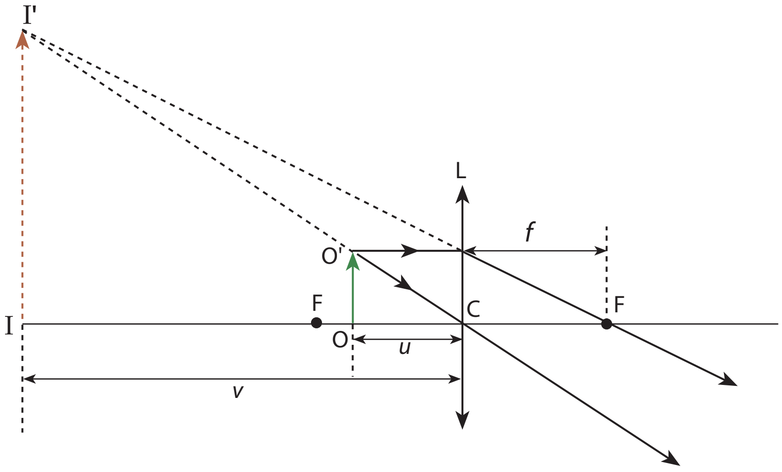


Figure 12.61

Let's Practise 12.5

1 Describe how far an object should be placed from a thin converging lens to produce

  (a) a magnified real image;

  (b) S a magnified virtual image.

2 S State **two** applications of converging lenses.

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

LINK TWB

Exercise 12E, pp. XX–XX

12.6 Dispersion of Light

In this section, you will learn the following:

- Describe the dispersion of light as illustrated by the refraction of white light by a glass prism.
- Know the traditional seven colours of the visible spectrum in order of frequency and in order of wavelength.
- S Recall that visible light of a single frequency is described as monochromatic.

We have seen in this chapter that light can be refracted when it travels from one medium to another. So far, we have assumed that all wavelengths of light travel at the same speed. This is true in the vacuum of space, yet it is merely an approximation in all other media.

Isaac Newton performed a famous experiment where he placed a glass prism in the path of a thin beam of white light from the Sun (Figure 12.62).

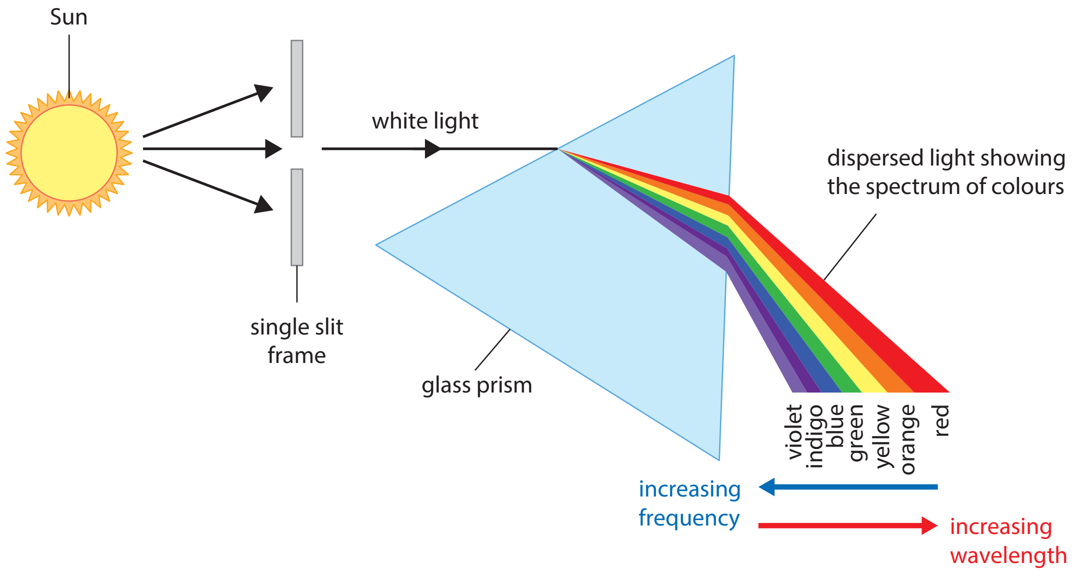


Figure 12.62 *Newton's dispersion experiment to show the spectrum of visible light*

The different colours that Newton observed is called a **spectrum**. The spectrum is shown in Figure 12.62 from red to violet in order of increasing frequency and decreasing wavelength. Red light has the lowest frequency and violet light has the highest.

It arises because the refractive index for each of the colours in the spectrum have a slightly different refractive index. The refractive index for red light is the lowest of all the visible colours, whereas violet light has the highest of the visible colours. This change in refractive index across the spectrum is known as **dispersion**.

S Although there are traditionally seven colours in the visible spectrum, there are an infinite number of different frequencies between red light and violet light. Any single frequency of light is described as **monochromatic**.

Let's Practise 12.6

1 State the order of colours of the visible spectrum, starting with the shortest wavelength.

2 Explain which of the colours of the visible spectrum travels fastest in glass.

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

HELPFUL NOTES

To help you remember the seven colours of the visible spectrum, remember this acronym: **ROYGBIV**

QUICK CHECK

Red light has the longest wavelength in the visible spectrum.

True or false?

LINK

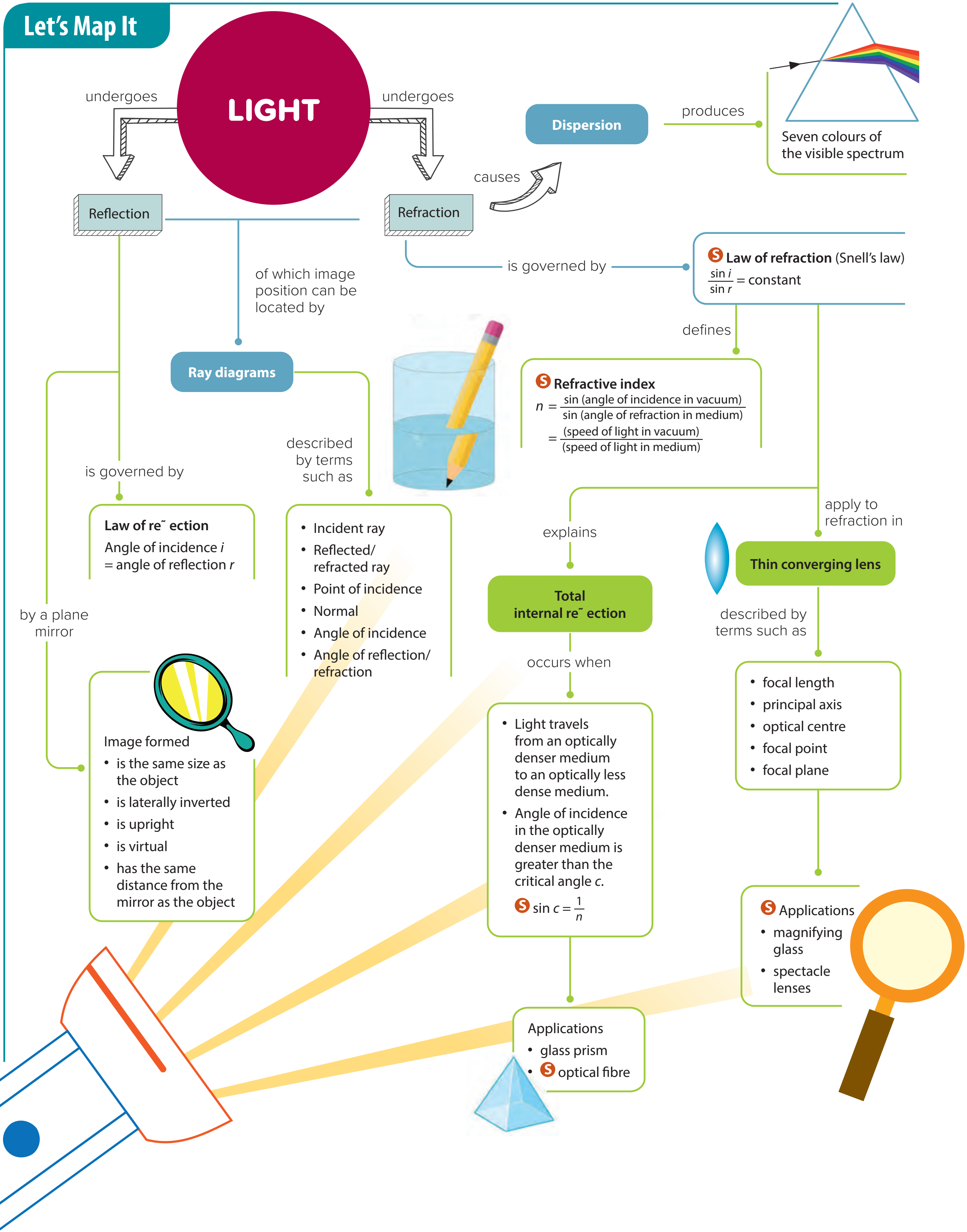
The spectrum of visible light is part of the electromagnetic spectrum. Find out more in Chapter 13.

LINK

Exercise, 12 F–12G, pp. XX–XX

Exercise 12H Let's Reflect, p. X

Let's Map It



LIGHT

undergoes

Reflection

undergoes

Refraction

causes

Dispersion

produces

Seven colours of the visible spectrum

Reflection … of which image position can be located by

Ray diagrams

described by terms such as

- Incident ray
- Reflected/ refracted ray
- Point of incidence
- Normal
- Angle of incidence
- Angle of reflection/ refraction

Reflection is governed by

Law of reflection

Angle of incidence i = angle of reflection r

by a plane mirror

Image formed

- is the same size as the object
- is laterally inverted
- is upright
- is virtual
- has the same distance from the mirror as the object

Refraction is governed by

S **Law of refraction** (Snell's law)

$$\frac{\sin i}{\sin r} = \text{constant}$$

defines

S **Refractive index**

$$n = \frac{\sin\text{ (angle of incidence in vacuum)}}{\sin\text{ (angle of refraction in medium)}}$$

$$= \frac{\text{(speed of light in vacuum)}}{\text{(speed of light in medium)}}$$

explains

Total internal reflection

occurs when

- Light travels from an optically denser medium to an optically less dense medium.
- Angle of incidence in the optically denser medium is greater than the critical angle c.

S $\sin c = \frac{1}{n}$

Applications

- glass prism
- S optical fibre

apply to refraction in

Thin converging lens

described by terms such as

- focal length
- principal axis
- optical centre
- focal point
- focal plane

S Applications

- magnifying glass
- spectacle lenses

Let's Review

Section A: Multiple-choice Questions

1 Which characteristics best describe an image formed in a plane mirror?

A Diminished and virtual
B Same size and virtual
C Same size and real
D Magnified and virtual

2 Which statement about the size of an image formed in a plane mirror image is false?

A The image can be taller than the mirror.
B The image height depends on the object distance.
C The image height depends on the object height.
D The width of the image is the same as that of the object.

3 Ⓢ A girl stands at point P as shown in Figure 12.63. A wall separates her from four other persons standing at points W, X, Y and Z. It blocks her direct line of sight to them. If a mirror is placed as shown in the diagram, how many persons can she see reflected in the mirror?

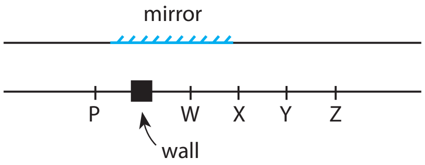


Figure 12.63

A 1 **B** 2
C 3 **D** 4

4 Ⓢ Figure 12.64 shows the complete path of a light ray travelling from air to a liquid.

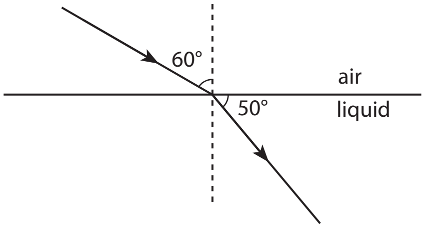


Figure 12.64

The refractive index of the liquid is given by

A $\frac{\sin 60°}{\sin 50°}$ **B** $\frac{\sin 30°}{\sin 50°}$
C $\frac{\sin 60°}{\sin 40°}$ **D** $\frac{\sin 40°}{\sin 50°}$

5 A light ray in air is incident at an angle on one side of a rectangular glass block (Figure 12.65).

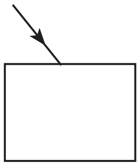
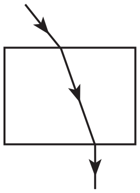
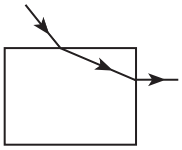
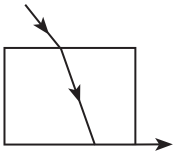


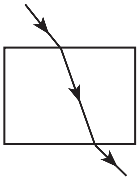
Figure 12.65

Which ray diagram correctly describes the complete path of the light ray?

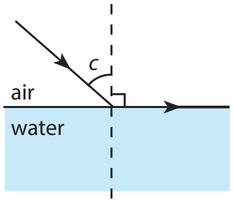
A


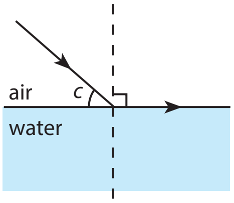
B


C


D


6 Which diagram correctly describes the critical angle *c* for an air–water surface?

A


B


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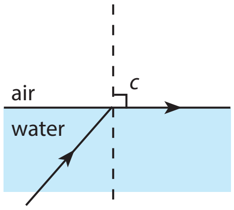

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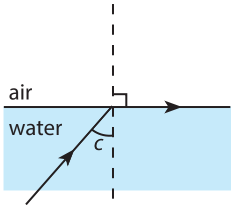


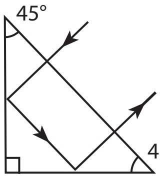
7 The fish in a pond appears to be

A deeper in the water than it really is because light reflected from the fish will refract towards the normal.
B deeper in the water than it really is because light reflected from the fish will refract away from the normal.
C nearer to the surface than it really is because light reflected from the fish will refract towards the normal.
D nearer to the surface than it really is because light reflected from the fish will refract away from the normal.

Let's Review

8 The critical angle for an air–glass interface is 42°. Which diagram shows the incorrect path of a light ray passing through a glass prism?

A



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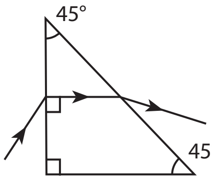

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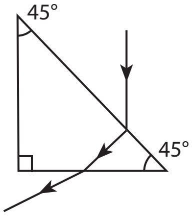

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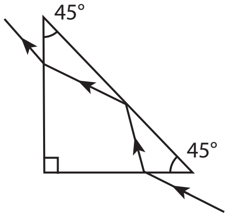


9 A thin converging lens is used to focus the rays from the Sun onto a piece of paper. When the rays burn a hole in the paper, the distance between the lens and the paper is ____________ the focal length of the lens.

A less than half **B** equal to half

C equal to **D** equal to twice

10 Figure 12.66 shows the position of an object relative to a lens. At which position should a viewer's eyes be to see a magnified and clear image of the object?

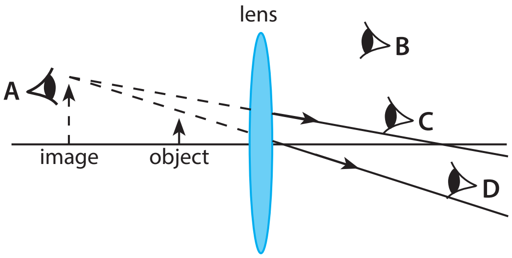


Figure 12.66

11 A person attempts to measure the focal length of a lens, as shown in Figure 12.67.

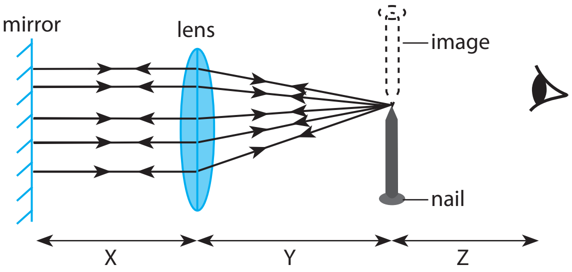


Figure 12.67

Which distance is the focal length of the lens?

A X **B** Y

C Z **D** X + Y

12 An object is placed in front of a converging lens of focal length *f*, as shown in Figure 12.68.

At which position will the image be formed?

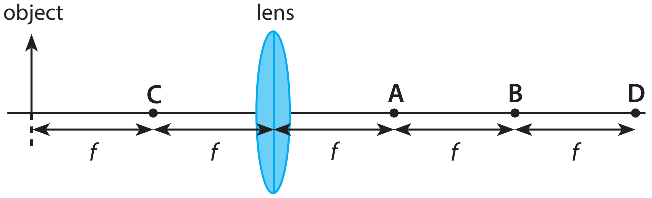


Figure 12.68

13 Ⓢ The image formed by a slide projector on the screen is

A real, inverted and diminished.

B real, inverted and magnified.

C virtual, upright and diminished.

D virtual, upright and magnified.

14 Which of the following is the correct term for the splitting up of light when it passes through a medium?

A Diffraction **B** Dispersion

C Interference **D** Reflection

15 Ⓢ Which of the following is the correct term for light of a single colour?

A Achromatic **B** Dichromatic

C Monochromatic **D** Polychromatic

Section B: Short-answer and Structured Questions

1 **(a)** Figure 12.69 shows a large letter F placed in front of a plane mirror with two incident rays.

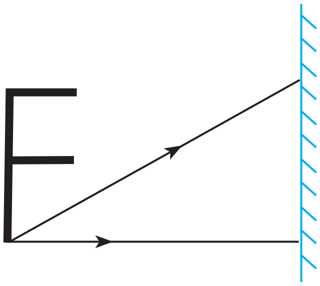


Figure 12.69

- **(i)** Using the law of reflection, locate the position and draw the image of F.
- **(ii)** State the characteristics of the image of F.

(b) Figure 12.70 shows a person looking at the image of a test card in a plane mirror. Find the distance from his eyes to the image of the card.

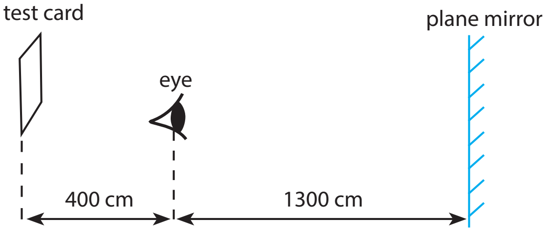


Figure 12.70

2 **(a)** What is refraction?

(b) Ⓢ Figure 12.71 shows the path of a light ray from air through a glass block and into air again.

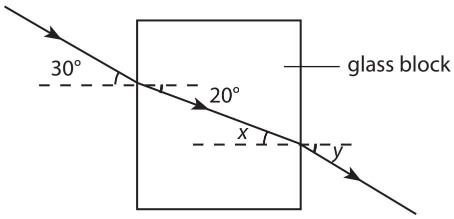


Figure 12.71

- **(i)** Determine the refractive index of the glass.
- **(ii)** State the angles *x* and *y*.

3 Ⓢ The refractive indices of some transparent materials are shown in Table 12.5.

Table 12.5

Medium	Refractive index *n*
Diamond	2.4
Perspex	1.5
Water	1.33
Air	1.000 293

(a) For the same angle of incidence,

- **(i)** which medium will cause light to bend the most?
- **(ii)** which medium will cause light to bend the least? Explain your choice in each case.

(b) Given that the refractive index of flint glass is 1.7 and the speed of light in air is 300 000 km/s, what is the speed of light in flint glass?

(c) Given that the speed of light in crown glass is 200 000 km/s and the speed of light in air is 300 000 km/s, what is the refractive index of crown glass?

4 Ⓢ

(a) Given that the refractive index of water is 1.33, find the angle of refraction of a light ray at the water–air boundary in Figure 12.72.

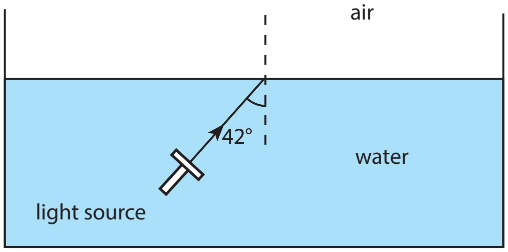


Figure 12.72

(b) Calculate the critical angle of water. Then draw, in Figure 12.72, the refracted ray and the reflected ray when the critical angle is reached.

5 Ⓢ

(a) Figure 12.73 shows a light ray incident on a right-angled prism of refractive index 1.5. Using Snell's law, calculate the angle of refraction of the ray within the prism.

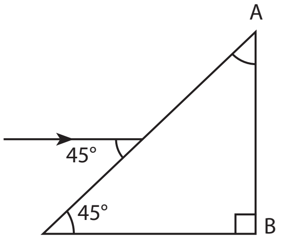


Figure 12.73

(b) Determine whether this ray within the prism will undergo total internal reflection when it hits the face AB of the prism.

6 A converging lens is used to project a 250-mm image of a square slide onto a screen 1000 mm away. The focal length of the lens is 200 mm. By means of a scale drawing, determine

(a) the distance of the slide from the lens;

(b) the size of the slide.

Let's Review

7 Ⓢ Figure 12.74 shows a lady of height 1.5 m looking into a vertical plane mirror GH. Her eyes are 10 cm below the top of her head.

Figure 12.74

(a) By drawing a ray diagram, determine
  (i) the minimum length of the mirror that allows the lady to see a full-length image of herself;
  (ii) the height of the bottom of this mirror above the floor.

(b) Suppose that the mirror is moved away from the person at a speed of 1 m/s. Determine the speed at which the image appears to move and state the direction of its movement.

8 **(a)** A sheet of white paper and a polished metal surface each reflects a parallel beam of light. With the help of diagrams, explain how the reflections by the paper and the metal differ.

(b) Ⓢ A bus driver has placed the centre of a 20-cm-wide plane mirror 50 cm in front of him. The rear of the bus is 500 cm directly behind the plane mirror. How wide is the driver's rear field of vision whenever he looks into the mirror while driving?

9 Figure 12.75 shows the behaviour of a light ray passing through an optical fibre from one end A to the other end B.

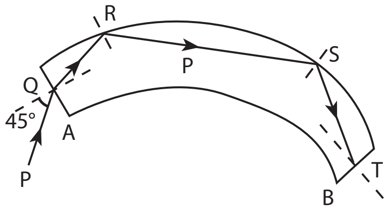


Figure 12.75

(a) **(i)** Explain why the light ray changes direction at Q.
  (ii) Explain why the light ray undergoes total internal reflection at R and S.

(b) Ⓢ If the refractive index of the glass that is used to make the optical fibre is 1.5, calculate the angle of refraction at Q.

(c) On Figure 12.75, draw the path of the light ray after refraction at T.

(d) Ⓢ State **two** advantages of using optical fibres instead of copper wires in telecommunications.

10 Explain, with the aid of a diagram, how a rainbow is formed in the sky.

CHAPTER

13

Electromagnetic Spectrum

PHYSICS WATCH

Scan this page to watch a clip about electromagnetic waves around us.

QUESTIONS

- Name a few examples of wireless electronic gadgets.
- Where does the information come from?
- How does information travel through air?

We live in a technologically advanced world, where more and more electronic gadgets are going wireless. It seems like these gadgets are able to detect and receive information out of thin air!

More people around the world are accessing the information in the Internet using their mobile phones. Asia has the highest population growth in the world. In just a few years' time, it is expected that countries such as China, Indonesia, India, and Pakistan will see the highest growth rate in mobile phone usage.

13.1 Electromagnetic Spectrum

In this section, you will learn the following:

- Know the main regions of the electromagnetic spectrum in order of frequency and wavelength.
- Know that all electromagnetic waves travel at the same high speed in a vacuum.

LINK

Recall the traditional seven colours of visible light that you have learnt in Chapter 12.

PHYSICS WATCH

Scan this page to watch a clip of an experiment on searching for invisible electromagnetic waves.

What light is invisible?

You have learnt in Chapter 12 that sunlight produces a spectrum of colours when passed through a prism. These colours are part of visible light that can be seen by the human eye.

Suppose you place thermometers to measure the temperature of different parts of the visible spectrum and beyond (Figure 13.1). What do you think you will observe?

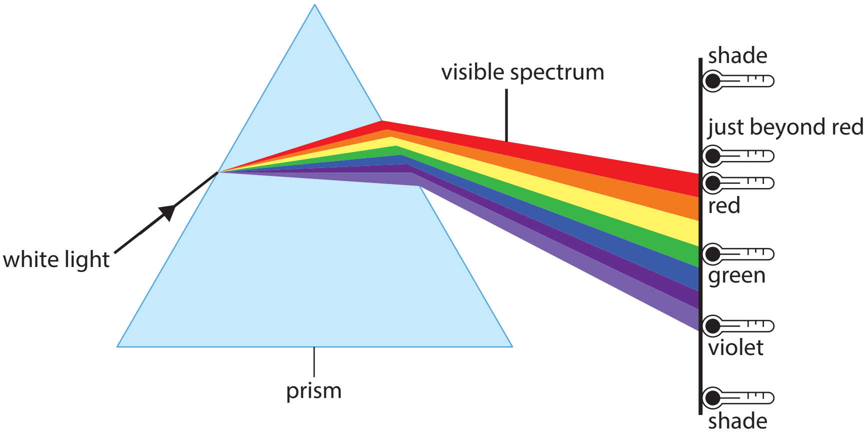


Figure 13.1 *Will the temperature just beyond the red be the same as in the shade?*

WORD ALERT

Invisible: cannot be seen

The astronomer Sir Frederick William Herschel did the above experiment. His experiment showed that there are some parts of the spectrum just beyond the red that are invisible to our eyes (Figure 13.2).

As it turns out, later scientists learnt that the spectrum of light from the Sun consists of more than the colours of light that we can see. There are invisible parts that can only be detected by instruments.

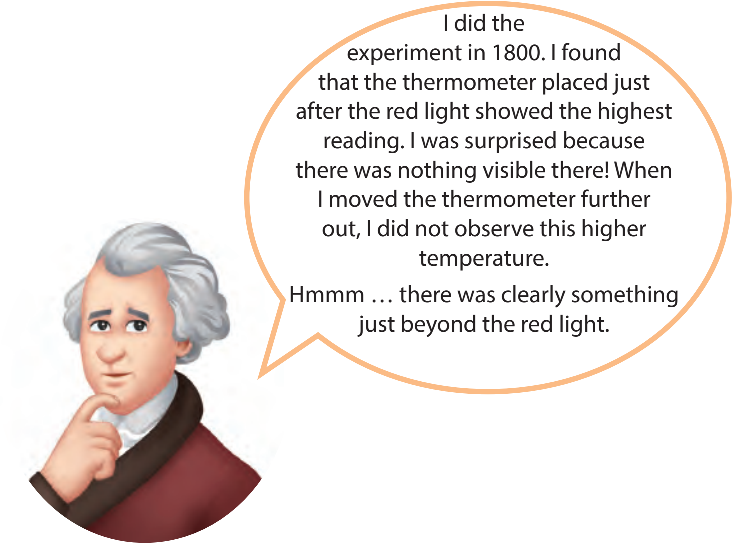


Figure 13.2 *Sir Frederick William Herschel*

What are the main regions of an electromagnetic spectrum?

Light from the Sun travels as electromagnetic waves. These waves are of different types and they make up the **electromagnetic spectrum**. Our eyes can only detect the visible light waves which is only a small part of the spectrum. Other waves include radio waves, microwaves, infrared radiation, ultraviolet radiation, X-rays and gamma rays. Some of these waves can be generated using electricity.

Figure 13.3 shows the main regions of the electromagnetic waves.

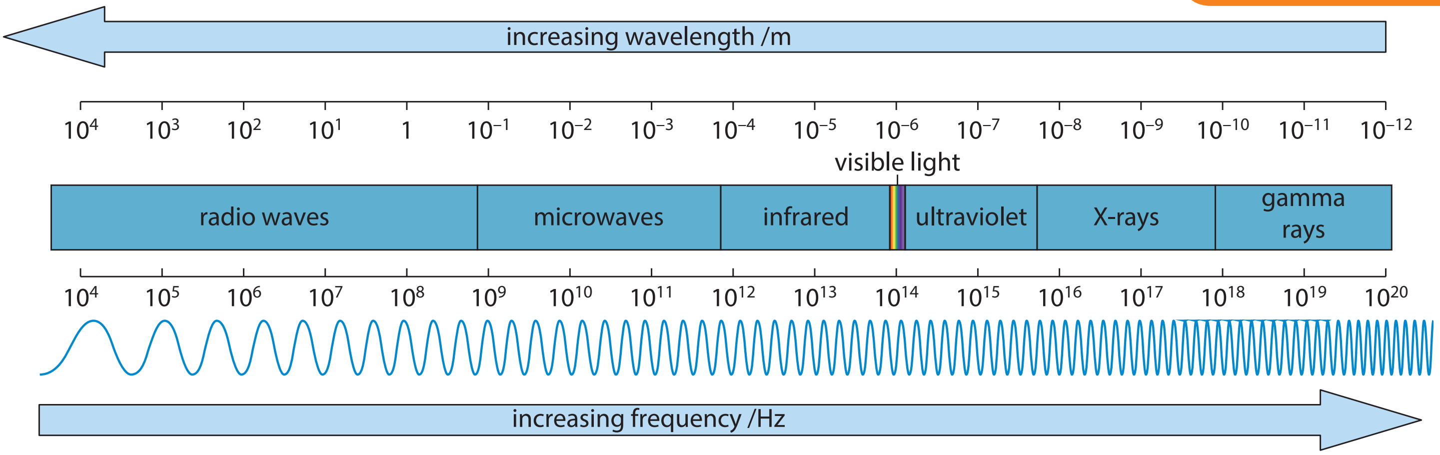


Figure 13.3 *Main regions of the electromagnetic spectrum in order of frequency (increasing from left to right) and wavelength (increasing from right to left)*

Each type of electromagnetic wave has different ranges of wavelengths and frequencies. For example, visible light ranges from violet with the shortest wavelength to red with the longest wavelength.

Electromagnetic waves travel at high speed in a vacuum

Look at Figure 13.3. What do you notice about the wavelength and frequency?

Waves with higher wavelength have lower frequencies. Recall the equation for wave speed and see the **inverse** relationship between wavelength λ and frequency f:

$$v = f \times \lambda$$

$$\therefore \lambda = \frac{v}{f}$$

All electromagnetic waves travel at the **same high speed** in a vacuum.

Infrared, visible light, ultraviolet and all the other electromagnetic waves travel from the Sun to the Earth with the same high speed. This is also true for electromagnetic waves coming from faraway stars and galaxies, i.e., they travel with the same high speed.

Let's Practise 13.1

1 Which region of the electromagnetic spectrum has
(a) the shortest wavelengths; **(b)** the longest wavelengths?

2 Which region of the electromagnetic spectrum has
(a) the lowest frequencies; **(b)** the highest frequencies?

3 Arrange regions of the electromagnetic spectrum according to wavelengths from the highest to the lowest.
visible light, microwaves, infrared, gamma rays, ultraviolet, X-rays, radio waves

4 The speed of radio waves from far away stars is smaller than the speed of visible light from the Sun. True of false? Explain your answer.

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

HELPFUL NOTES

To recall electromagnetic waves in order of frequency (or wavelength), remember this line:

Rugby (Radio waves)
Match (Microwaves)
Is (Infrared)
Very (Visible light)
Unlike (Ultraviolet)
Xylophone (X-rays)
Game (Gamma rays)

WORD ALERT

Inverse: opposite effect (in this case, when one variable increases, the other decreases)

LINK

Exercise 13A, pp. XX–XX

13.2 Electromagnetic Radiation

In this section, you will learn to:

- Describe some uses of the different regions of the electromagnetic spectrum.
- Describe some harmful effects of electromagnetic radiation.
- Know that communication with artificial satellites is mainly by microwaves.

What is electromagnetic radiation?

Electromagnetic waves transfer energy as they move. The term *radiation* is usually used to refer to the energy being transferred. The energy carried by electromagnetic radiation depends on the frequencies. Higher frequency radiation has more energy for the same intensity of radiation. The different types of electromagnetic radiation have different uses and harmful effects.

What are some uses of electromagnetic radiation?

Figure 13.4 shows some uses of electromagnetic radiation.

Uses of Electromagnetic Radiation

Gamma rays

- They are produced when radioactive nuclei decay. (You will learn more about radioactivity and gamma rays in Chapter 20.)
- They can kill living organisms such as bacteria, and are therefore used to *sterilise food and medical equipment*.
- They can be used to *treat cancer* by destroying cancer cells. Gamma rays can penetrate body tissues. Very small amount of radioactive chemicals that emit gamma rays can be placed inside specific body parts. A gamma camera outside the body captures images that show the inside of the human body. Such images can be used to *detect cancer*.

X-rays

- They can penetrate soft tissues in the human body but are blocked by bones and tumours. They are useful for *medical scanning*.
- Their ability to pass through most materials make them useful as *security scanners* to locate hidden weapons. The metal in guns and knives absorbs the X-rays. Baggage scanners at airports use X-rays.

Ultraviolet light

- It has frequencies just above the higher end of visible light. Although we cannot see ultraviolet light, what we see is the violet-blue end of the visible spectrum. However, some animals such as birds can detect ultraviolet light.
- It can damage the cells of microorganisms. So, it can be used *to sterilise water and other objects* such as a mobile phone.
- Some chemicals that appear transparent can be made to glow under ultraviolet light. This fact is used to make invisible *security marking* and *for detecting fake banknotes*.

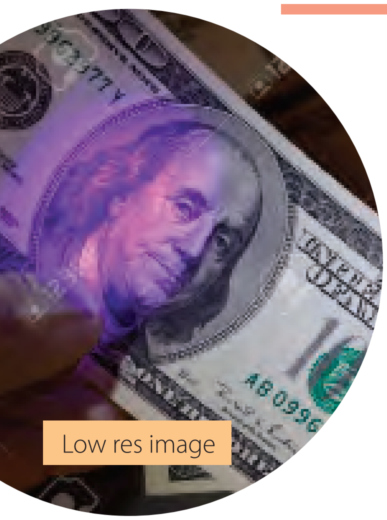


Figure 13.4 Some uses of electromagnetic radiation

Visible light

- It consists of wavelengths that can be detected by our eyes.
- We rely on this light for *vision* and *illumination*.
- In *photography*, sensors that are sensitive to visible light are used in cameras for taking photographs.

Microwaves

- They have wavelengths that are longer than infrared.
- They cause water molecules in food to vibrate and heat up quickly. This effect is used in *microwave ovens* for cooking.
- Some microwaves can penetrate clouds. Artificial satellites high above the Earth receive and retransmit microwave signals. These signals from the satellites carry image and sound data which can be received by the antenna of a satellite television. Direct broadcast television, on the other hand, uses geostationary satellites to beam the television signals directly to homes.
- *Satellite phones* can receive microwave signals from geostationary satellites, which are about 36 000 km above the equator. Due to the great distance, the signals are not very strong. So some satellite phones use signals from low Earth orbit (LEO) satellites, which are at about 1500 km above the Earth.
- A *mobile (cell) phone* convert sound energy to microwave signals. The microwaves are sent out to the nearest cell tower. The receiver on the mobile phone converts the microwaves back to sound.

Infrared light

- It has wavelengths longer than red light.
- It causes heating and is used to generate heat. Some people use infrared lamps for *warmth* or for *pain relief*.
- An *electric grill* converts electrical energy to infrared, which is used to heat and cook food.
- In *thermal imaging*, thermal scanners have detectors that convert infrared to electrical signals. These electrical signals are in turn converted into thermal images. Thermal images use colours to display the temperatures of objects.
- Infrared can be easily generated and detected. This is used in *short-range communications*. For example, a simple LED (light emitting diode) is the infrared source for the television remote controller.
- An infrared transmitter and detector can be used to *detect intruders*. The alarm will sound when the direct path between the transmitter and detector is blocked.
- Like visible light, some infrared can pass through glass. When used in *optical fibres*, infrared signals can transmit data over long distances with minimal loss in signal strength.

Radio waves

- They have the lowest frequencies and the lowest energies.
- They are used in *radio and television transmissions*. Tall broadcast towers send radio waves out into the air. The radio waves are converted to sound in radios, and to sound and images in televisions. Having long wavelengths (as long as 1 km and longer), radio waves can diffract around most objects such as buildings and hills, and can pass through walls. In order for radio waves to travel very far (e.g. across oceans), the broadcast signals have to be very strong.
- In *astronomy*, large radio telescopes detect radio waves emitted by astronomical objects far out in space. This enables astronomers to learn about stars, comets and galaxies.
- In radio frequency identification (RFID), radio waves are used to transfer data for tracking. Items are given RFID tags that contain data. The data can be read by an RFID reader to track and identify the items.

What are some harmful effects of electromagnetic radiation?

Figure 13.5 shows some harmful effects of electromagnetic radiation.

Harmful Effects of Electromagnetic Radiation

Infrared radiation

- Excessive exposure to infrared radiation can cause *skin burns*.

Microwaves

- Excessive exposure to microwaves can cause *internal heating of body cells*.

X-rays

- They can damage body cells.
- Excessive exposure to X-rays can cause *cancer*.

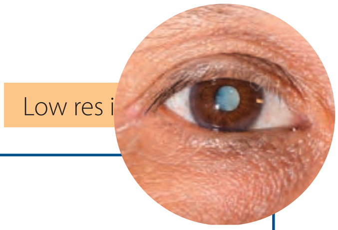
Ultraviolet radiation

- It is the invisible part of sunlight that cause *damage to the surface cells in our skin and eyes*.
- Excessive exposure to ultraviolet radiation can cause skin cancer and eye conditions such as cataracts and macular degeneration. Remember not to stare at the UV sterilising lamp to avoid damaging your eyes.

Gamma rays

- They can harm living cells.
- The human body must be shielded from gamma rays to protect against *damage to body cells*.

Figure 13.5 *Some harmful effects of electromagnetic radiation*



Let's Practise 13.2

1 **(a)** Complete Table 13.1 by filling in one typical use and one harmful effect due to excessive exposure for each electromagnetic radiation.

Table 13.1

Electromagnetic radiation	Typical use	Harmful effect to our body from over exposure
Infrared		
Ultraviolet		
Microwaves		
X-rays		
Gamma rays		

(b) What regions of the electromagnetic spectrum are missing from the table? What are their typical uses?

2 Which part of the electromagnetic spectrum is usually used to communicate with artificial satellites?

3 For each of the following, state **one** use in communication:

(a) Geostationary satellites

(b) Low Earth orbit satellites

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

LINK TWB

Exercise 13B,
pp. XX–XX

13.3 Electromagnetic Radiation in Communication

In this section, you will learn the following:

- Know how fast electromagnetic waves travel in a vacuum/air.
- Know that many important systems of communications, such as mobile phones, wireless Internet, Bluetooth and optical fibres, rely on electromagnetic radiation.
- Know the difference between a digital signal and an analogue signal.
- Know that a sound can be transmitted as a digital or an analogue signal.
- Explain the benefits of digital signaling.

What do remote controllers, optical fibres, mobile phones, wireless Internet and Bluetooth have in common? They are important parts of the communication systems that we have today. They all rely on electromagnetic radiation, which enables fast communication.

How fast do electromagnetic waves travel?

All electromagnetic waves travel at the same high speed of **3×10^8 m/s** in a vacuum. They also travel at approximately this same speed in air.

You use a television remote controller to change your television channel. The channel changes immediately when you click the remote controller. The infrared signal (or wave) travels from the remote controller to the receiver on the television at approximately 3×10^8 m/s. It is so fast that we feel the change happening in an instance.

Microwave signals travel to and from our mobile phones at approximately 3×10^8 m/s.
See Worked Example 13A below to find out how long a microwave signal takes to travel over a very long distance.

Worked Example 13A

How long does it take a microwave signal to travel from Earth to a geostationary satellite 36 000 km away and back?

Solution

Total distance = 36 000 km + 36 000 km = 72 000 km or 72×10^6 m

Speed of microwaves in air/vacuum = 3.0×10^8 m/s.

So, time taken for microwave signal to travel $= \dfrac{72 \times 10^6 \text{ m}}{3 \times 10^8 \text{ m/s}} = 0.24$ s

Figure 13.6 A satellite dish transmits microwave signals to a geostationary satellite in outer space.

ENRICHMENT INFO

Looking Back in Time

A supernova is a violent explosion that occurs when a star is dying.

In 1987, astronomers spotted a supernova named SN1987A. The light emitted travelled 1.66 × 1021 m before reaching the Earth.

Using the formula speed $= \dfrac{\text{distance}}{\text{time}}$, we know that the light took about 175 000 years to reach us!

No wonder astronomers say that viewing a supernova is like looking back in time!

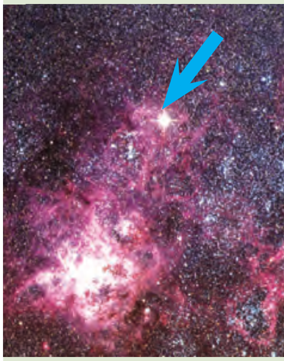


Figure 13.7 Blue arrow pointing to Supernova SN1987A

How do communication systems rely on electromagnetic radiation?

Wireless communication made possible

The invisible radio waves and microwaves allow us to communicate wirelessly — there is no need to use a physical cable to link the transmitter and the receiver.

QUICK CHECK

In wireless communication, information is transported without the need of free space.

True or false?

Microwaves for mobile phones and wireless Internet can pass through some walls. You can use your mobile phone in different rooms of your house. You can use your computer in the bedroom even though your wireless router is in the living room (Figure 13.8).

Figure 13.8 A wireless router in the living room can connect to a computer in the bedroom using microwaves.

You may have seen aerials such as the one shown in Figure 13.9 on the roofs of houses. The rods on the aerial transmit and receive electromagnetic signals of a certain wavelength. To ensure a good reception, the length of the rods needs to be approximately the same size as the wavelength of the signals. The wavelengths of microwaves used in mobile phones are much shorter than radio waves used for television and radio broadcasts. So, by using suitable microwaves, a mobile phone only requires a short aerial for transmission and reception. From the calculation below, we can compare the wavelengths.

Figure 13.9 Different length of rods on this aerial allows it to receive signals of different wavelengths.

To calculate wavelength, use the wave equation $c = f\lambda$. The speed of electromagnetic waves in air c is approximately 3×10^8 m/s.

Radio waves at 90 MHz,

$$\lambda = \frac{3 \times 10^8 \text{ m/s}}{9 \times 10^6 \text{ 1/s}}$$
$$= 3.3 \text{ m}$$

Mobile phone microwaves at 1800 MHz,

$$\lambda = \frac{3 \times 10^8 \text{ m/s}}{1800 \times 10^6 \text{ 1/s}}$$
$$= 0.17 \text{ m or } 17 \text{ cm}$$

Bluetooth technology uses radio waves to allow for wireless connection between two devices. For example, you may connect your mobile phone to a speaker using Bluetooth (Figure 13.10).

Figure 13.10 Two devices can be connected wirelessly over short distances using Bluetooth.

Radio waves and microwaves can be weakened as they travel and pass through walls. As a result, you may encounter poor connection when your Bluetooth devices are in different rooms in your house.

QUICK CHECK

Wireless connection is strongest when the transmitter and the receiver are in view of each other.

True or false?

Optical fibres for long distances and high data rates

Optical fibres are more often being used for cable television and high-speed broadband Internet access. What makes them more advantageous compared to copper wires? Optical fibres are long thin glass fibres that can carry and transmit light over long distances. Visible light undergoes total internal reflection and travels from one end to the other with little loss in energy.

Infrared waves with wavelengths slightly longer than red light can also pass through glass. These infrared waves have shorter wavelengths than other infrared waves. *Optical fibres can transmit both visible light and invisible short wavelength infrared pulses.*

The wavelengths of visible light and infrared used in optical fibres are very short (between 650 nm to 1600 nm). The frequencies of the waves are very high. Many pulses can be transmitted in short time intervals. So, *optical fibres can carry high rates of data.*

What are digital and analogue signals?

Electromagnetic radiation can be used to communicate in two ways: analogue signaling (using analogue signals) and digital signaling (using digital signals).

An **analogue signal** has continuous values in time. The information is transmitted using waves with varying frequencies and amplitudes.

A **digital signal** has fixed values. For example, it can have two values of 1 and 0. The information is transmitted as 'on' and 'off' pulses. The 'on' pulses have a value of 1 and the 'off' pulses have a value of 0.

Figure 13.11 shows graphs of analogue and digital signals.

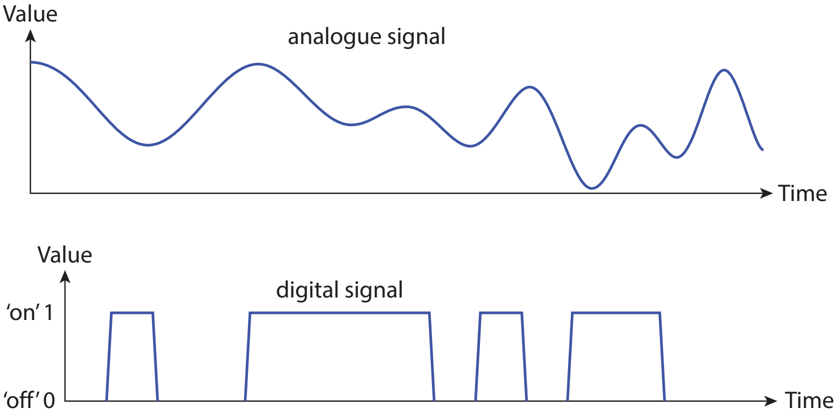


Figure 13.11 *Graphs showing an analogue signal and a digital signal*

Sound can be converted into electrical signals by a microphone. The converted signals are analogue signals. These analogue signals can be encoded and transmitted by radio waves or through a telephone line. However, the analogue sound signals can also be further converted into digital signals before transmission. This is the preferred method of transmission.

When you speak into a mobile phone, your continuous sound signals are converted into digital signals. The phone encodes these digital signals and transmits the signals as microwaves.

Low res image

LINK

Recall how data is transmitted through optical fibres by total internal reflection. You have learnt this in Chapter 12.

HELPFUL NOTES

Within the electromagnetic spectrum, short wavelength infrared occurs just beyond the red light.

ENRICHMENT
THINK

Figure 13.12 shows an analogue clock. Explain how the clock is similar to analogue signals?

Low res image

Figure 13.12 *Analogue clock*

WORD ALERT

Encoded: convert into another form using symbols

What are the benefits of digital signals?

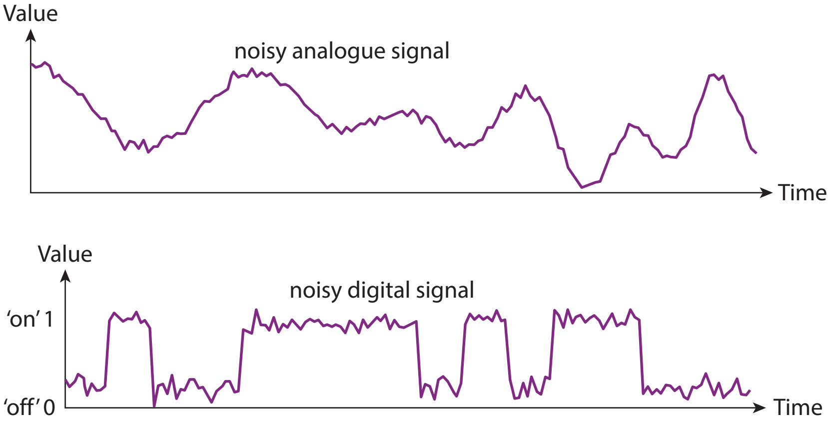
Digital signals can be represented as numbers, which can be added and multiplied. Using mathematics, these numbers can be transformed and later recovered by processors.

The transformed data take less numbers to encode the same information. This means more data can be transmitted and the rate of data transmission is increased. Since more information can be carried, video and sound transmitted digitally have higher quality compared to when they are transmitted using analogue signals.

When signals are transmitted, two unwanted effects take place: *noise* and *loss in power*. Noisy signals are not very smooth as shown by the graphs (Figure 13.13).

WORD ALERT

Regenerated: created again, reproduce



Compare the graph of this noisy digital signal to the graph of the digital signal in Figure 13.11. The 'on' and 'off' values of a noisy digital signal can still be distinguished.

Figure 13.13 *Graphs showing a noisy analogue signal and a noisy digital signal*

For digital signals, only 'on' and 'off' (e.g. 1's and 0's) values are expected. So, if the noise is not too big, the signals can be regenerated accurately. This is especially important when signals are transmitted over long distances because signals lose power. Amplifiers are used to increase the strength of analogue signals. However, in the process, noise is also increased. The result is poor quality signals. For digital signals, repeaters are used along the transmission path. Repeaters recover the digital signal and retransmit it. In this way, digital signals can be accurately regenerated and transmitted over very long distances.

ENRICHMENT *ACTIVITY*

Do a survey on electronic devices in your home. Make a list of devices that use analogue signals and those that use digital signals.

Share your list with the class.

Let's Practise 13.3

1 For each of the following, state its speed of travel in air:
(a) radio waves; **(b)** gamma rays; **(c)** ultraviolet; **(d)** infrared.

2 State **two** properties of microwaves that are important for their use in mobile phones.

3 Which regions of the electromagnetic spectrum are used in optical fibres? Why?

4 Compare a digital signal and an analogue signal. How are they different?

5 State **two** benefits of digital signaling.

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

LINK

Exercises 13C–13D, pp. XX–XX

Exercise 13E Let's Reflect, p. XX

Let's Map It

ELECTROMAGNETIC SPECTRUM

consists of the following main regions

- Radio waves
- Microwaves
- Infrared radiation
- Visible light
- Ultraviolet radiation
- X-rays
- Gamma rays

Increasing *f*

Increasing λ

with the following common property

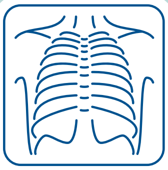
All electromagnetic waves travel at the same high speed in a vacuum.

S The speed of electromagnetic waves in a vacuum is 3.0×10^8 m/s and is approximately the same in air.

has

Uses

- In medical field: sterilisation, medical diagnosis, scanning, treatment
- In communications: radio and TV transmissions, remote controllers, optical fibres, mobile phones
- In security: security marking, baggage scanners, detection of fake notes
- In other applications: heating, cooking, thermal imaging, photography



has

Harmful effects

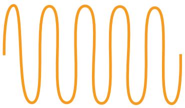
- Damage to body cells leading to cancer
- Damage to eyes
- Skin burns

relied upon by

S Communication systems

- Involve the use of mobile phones, wireless Internet, Bluetooth and optical fibres

transmit signals in two forms



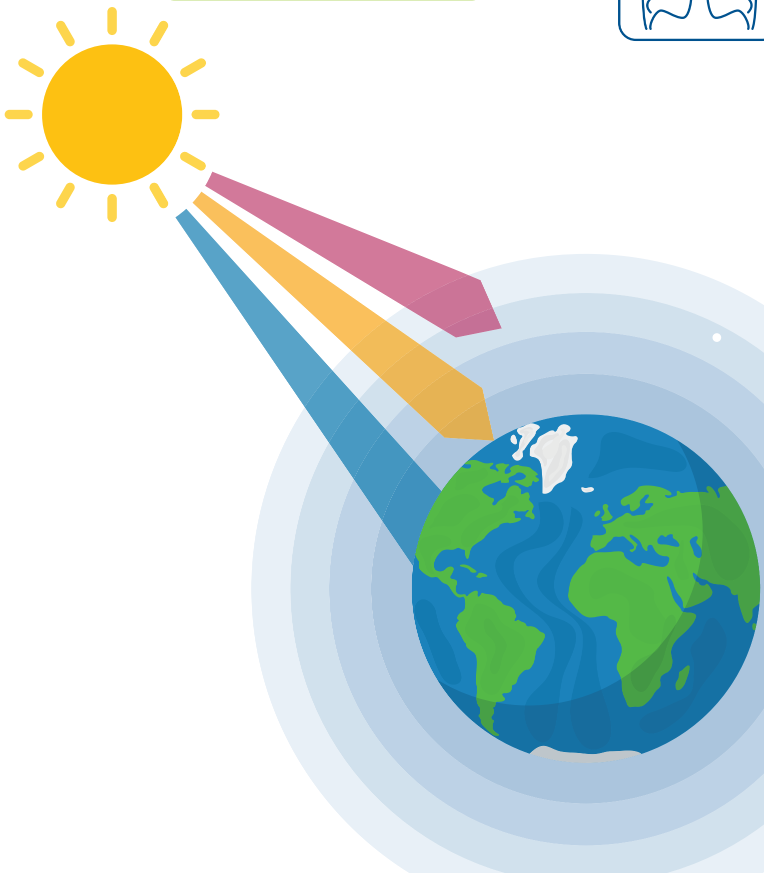
S Analogue signals

- Have continuous values

S Digital signals

- Have fixed values

- S Increased rate of transmission of data
- S Increased range of transmission



Let's Review

Section A: Multiple-choice Questions

1 Which statement about electromagnetic waves is correct?
- **A** All electromagnetic waves are harmful to people.
- **B** All electromagnetic waves have the same wavelengths.
- **C** In vacuum, all electromagnetic waves travel at the same high speed.
- **D** In vacuum, visible light travels faster than all the other electromagnetic waves.

2 Which of the following regions of electromagnetic spectrum can be used to cook food?
- **A** Infrared only
- **B** Microwave only
- **C** Infrared and microwave only
- **D** No region can be used

3 Which region of the electromagnetic spectrum is used to communicate with artificial satellites?
- **A** Radio waves
- **B** Microwaves
- **C** Infrared
- **D** Visible light

4 A lamp is used to sterilise water in an aquarium. What light is used?
- **A** Infrared
- **B** Red light
- **C** Green light
- **D** Ultraviolet

5 Ⓢ Which statement about microwaves is correct?
- **A** Microwaves travel at approximately 3×10^8 m/s in air.
- **B** Microwaves are not used to communicate with satellites because they are blocked by clouds.
- **C** The wavelengths of microwaves are shorter than visible light.
- **D** The frequencies of microwaves are lower than radio waves.

6 Ⓢ Which statement about optical fibres is correct?
- **A** Optical fibres carry microwave signals.
- **B** Optical fibres cannot be used to transmit television signals.
- **C** Only visible light is used in optical fibres because only visible light can undergo total internal reflection.
- **D** Visible light and infrared are used because glass is transparent to these waves.

Section B: Short-answer and Structured Questions

1 Figure 13.14 shows the regions in the electromagnetic spectrum.

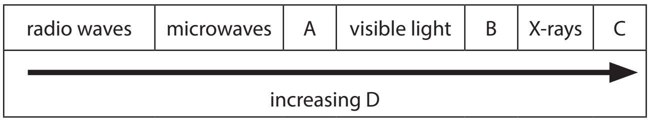


Figure 13.14

(a) State what each of the labels A, B, C and D represents.

(b) What could happen to someone who is excessively exposed to B?

(c) Describe one use for the waves in region C.

2 To determine the distance of the Moon from the Earth, the time taken for a radio wave signal to travel from the Earth to the Moon and back is 2.5 s.

Given that the speed and frequency of the radio waves are 3.0×10^8 m/s and 10 MHz respectively, calculate the

(a) distance of the Moon from the Earth;

(b) wavelength of the radio waves used.

3 Ⓢ Figure 13.15 shows two signals corrupted by noise.

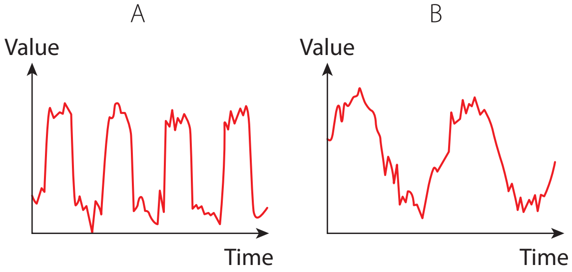


Figure 13.15

(a) Which signal, A or B, is a digital signal?

(b) Explain the benefits of digital signaling.

CHAPTER 14 Sound

PHYSICS WATCH

Scan this page to watch a clip about how sound travels.

QUESTIONS

- Imagine a battle scene taking place on Earth. What sounds would you expect to hear and why would you be able to hear these sounds?
- What misconception about sound in space do people have?
- Why do you think we cannot hear sound in space?

Have you watched any of the Star Wars movies or one that is similar to it? If you have, you would probably find the battle scenes in space most thrilling. The scenes are made exciting with dazzling sights and sounds. But, can we hear sound in outer space? The answer is 'No'. Movie producers ignore this law of physics and go for 'effects'.

Often, there is a misconception about sound in space. This is mostly due to the sound effects used in sci-fi movies.

14.1 What Is Sound?

In this section, you will learn the following:

- Describe the production of sound by vibrating sources.
- Describe the longitudinal nature of sound waves.
- S Describe *compression* and *rarefaction*.
- State the approximate range of frequencies audible to humans.

LINK

Recall the characteristics of longitudinal waves that you have learnt in Chapter 11.

Sound is a form of energy that is transferred from one point to another.

Since sound is a type of wave. It has amplitude, frequency and wavelength. *Sound waves travel parallel to the direction of vibration of a medium*. Therefore, sound waves are *longitudinal waves*.

How is sound produced?

PHYSICS WATCH

Scan this page to watch an experiment on producing sound.

How do guitar players produce sounds from their guitars? They strike the guitar strings causing the strings to vibrate. Sometimes, guitar players place their palms on the strings. This mutes the guitar because it stops the guitar strings from vibrating.

Sound is produced by **vibrating sources** placed in a medium. The medium is usually air, but it can be any gas, liquid or solid.

How does a sound wave propagate?

An object vibrating in air causes the layers of air particles around it to be displaced. This displacement of particles causes sound waves to propagate. We cannot see the displacement of air particles. However, if we dip a vibrating tuning fork in water, we will see that the water is displaced (Figure 14.1).

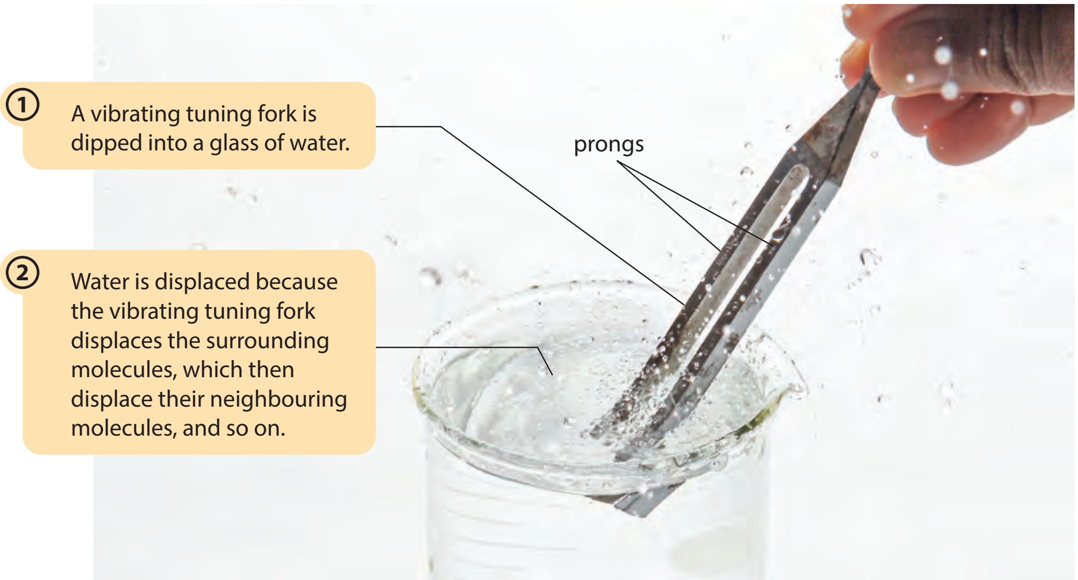


Figure 14.1 *A vibrating object displaces the particles in a medium.*

As sound is a longitudinal wave, the direction of vibration of air molecules is parallel to the direction in which the wave travels. This is similar to the longitudinal waves produced when a Slinky spring is made to vibrate parallel to its length (Figure 14.2).

ENRICHMENT *ACTIVITY*

Use your mouth and try to produce the sound /s/ (as in the hissing sound of a snake). While doing that, place your thumb and your index and middle fingers near the middle of your throat. Do you feel any vibrations of your vocal cords?

Repeat the above while producing another sound /z/ (as in the buzzing of a bee). What do you notice this time?

Share your observations with your classmates.

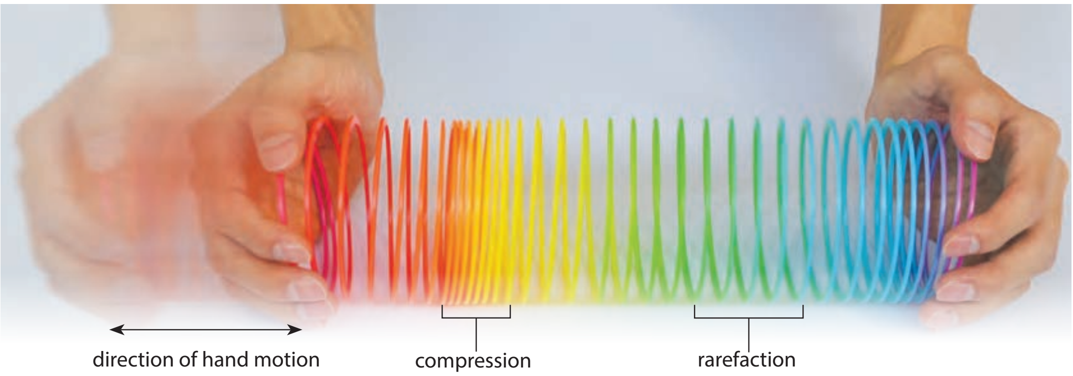
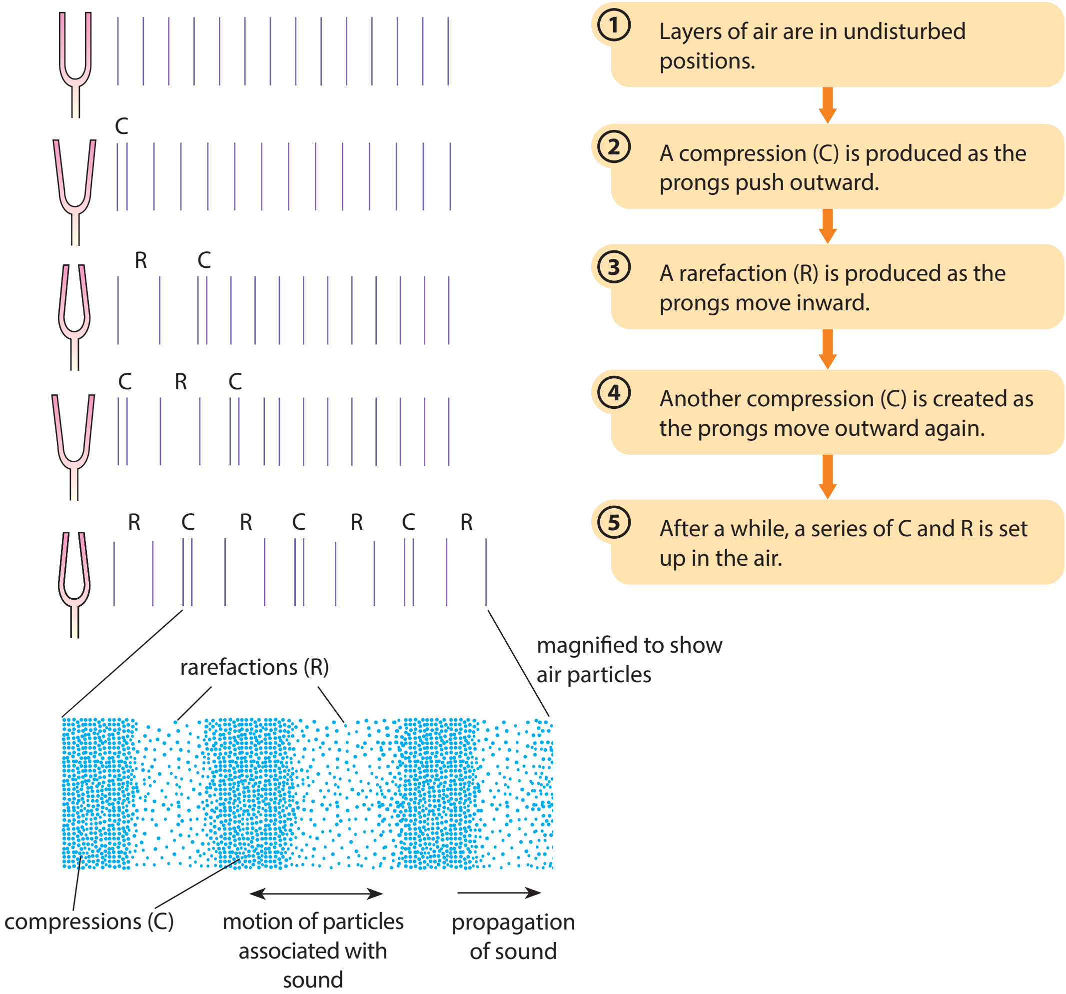


Figure 14.2 *Longitudinal wave in a Slinky spring*

Like all longitudinal waves, sound waves propagate as a series of *compressions* (C) and *rarefactions* (R).

- **Compressions** are regions where air pressure is higher than the surrounding air pressure.
- **Rarefactions** are regions where air pressure is lower than the surrounding air pressure.

Figure 14.3 shows how sound waves are produced by a vibrating tuning fork.



① Layers of air are in undisturbed positions.

② A compression (C) is produced as the prongs push outward.

③ A rarefaction (R) is produced as the prongs move inward.

④ Another compression (C) is created as the prongs move outward again.

⑤ After a while, a series of C and R is set up in the air.

Figure 14.3 *As a tuning fork vibrates, it shifts layers of air inward and outward, creating a series of compressions and rarefactions*

QUICK CHECK

There are less air particles in a region of compression than in a region of rarefaction.

True or false?

WORD ALERT

Audible: can be heard

What sounds are audible?

We can only hear sounds that are audible to us. The human ear is only capable of detecting sounds in a certain range of frequencies. The range of frequencies in which a person can hear is known as the *range of audibility*. For humans, this range is from **20 Hz to 20 000 Hz**.

The top and bottom values of the range are known as the *limits of audibility*. For the human ear, the lower limit is about 20 Hz and the upper limit is about 20 000 Hz.

Figure 14.4 shows examples of the range of audibility and the range of frequency of sounds.

Vibrating ruler

Human ears cannot hear low frequency sounds called **infrasound**. A vibrating ruler can be seen but not heard. This is because the frequency of the sound produced is below the lower limit of audibility of the human ear.

Dog whistle

Human ears cannot hear high frequency sounds called **ultrasound**. If you blow a dog whistle, a dog may bark in response, even though you do not hear any sound. This is because the frequency of the sound produced by the whistle is above the upper limit of audibility of humans but within that of dogs.

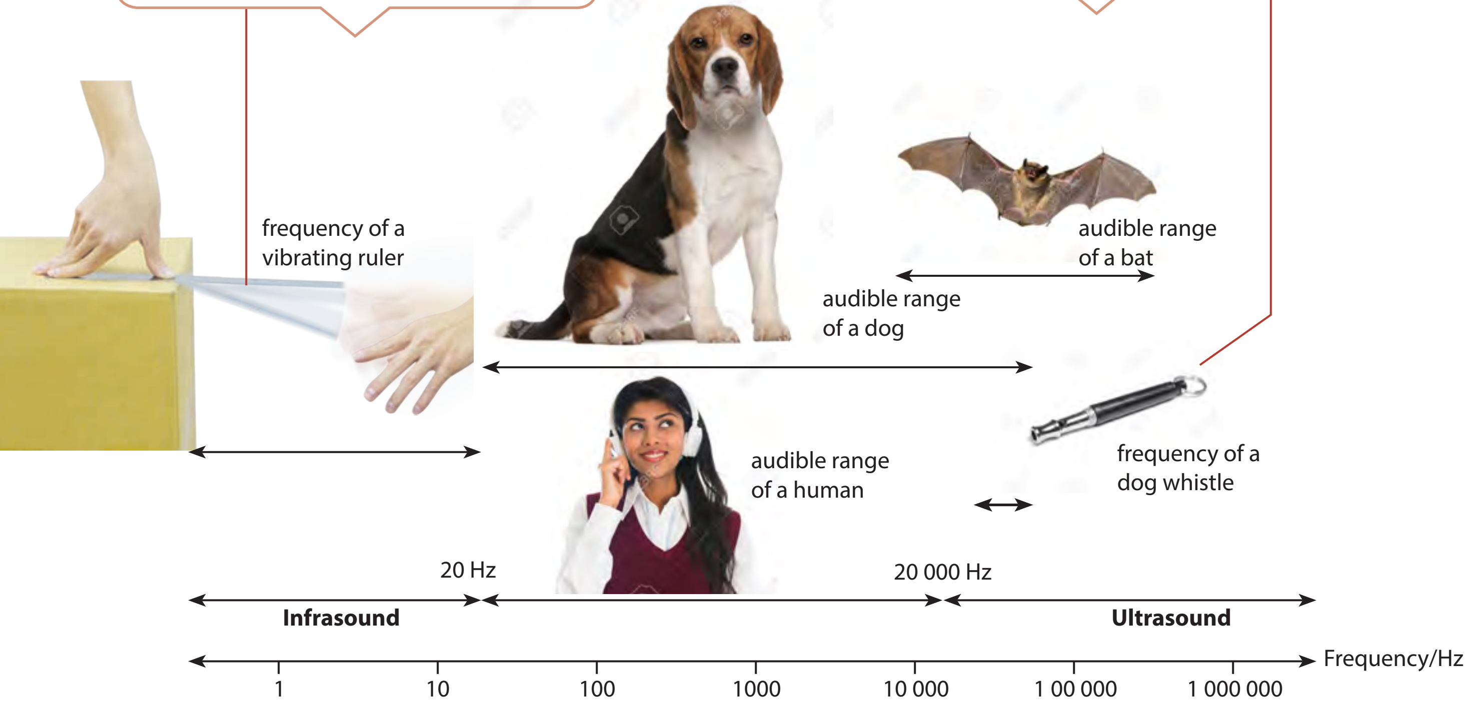


Figure 14.4 *Spectrum of sound frequencies*

Let's Practise 14.1

1 Read each sentence and state the meaning of each underlined term.

(a) *Sound is a longitudinal wave.*

(b) Ⓢ *Sound is transmitted as a series of compressions and rarefactions in air.*

2 A vibrating source produces ultrasound at a frequency of 40 kHz. Is this frequency within the audible range of the human ear? Give your reason.

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

LINK TWB

Exercise 14A, pp. XX–XX

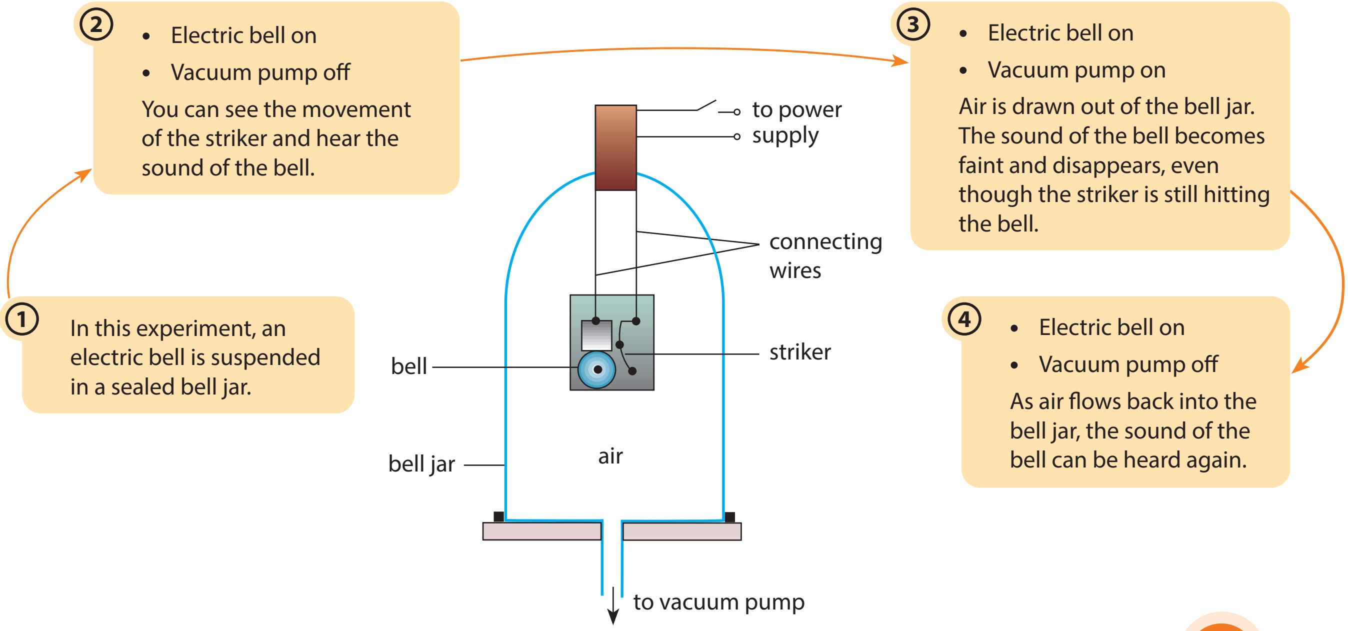
14.2 Transmission of Sound

In this section, you will learn the following:

- Know that a medium is needed to transmit sound waves.
- Know that the speed of sound in air is approximately 330–350 m/s.
- S Know that, in general, sound travels faster in solids than in liquids and faster in liquids than in gases.
- Describe a method involving a measurement of distance and time for determining the speed of sound in air.

Can sound be transmitted through a vacuum?

Unlike electromagnetic waves, *sound waves need a medium to travel* from one point to another. The bell jar experiment demonstrates this (Figure 14.5).



① In this experiment, an electric bell is suspended in a sealed bell jar.

②
- Electric bell on
- Vacuum pump off

You can see the movement of the striker and hear the sound of the bell.

③
- Electric bell on
- Vacuum pump on

Air is drawn out of the bell jar. The sound of the bell becomes faint and disappears, even though the striker is still hitting the bell.

④
- Electric bell on
- Vacuum pump off

As air flows back into the bell jar, the sound of the bell can be heard again.

Figure 14.5 *The bell jar experiment shows that sound cannot travel through a vacuum.*

QUICK CHECK

We can hear sound in a vacuum.

True or false?

S Medium of transmission

Any medium which contains particles that can vibrate will transmit sound. However, sound waves travel at different speeds in different media:

speed of sound < speed of sound < speed of sound
in gas in liquid in solid

Table 14.1 shows the approximate speed of sound in different media.

Table 14.1 *Speeds of sound in different media*

Medium	Air	Water	Iron	Granite
Approximate speed of sound/m/s	300	1500	5000	5400

How can we measure the speed of sound in air?

Let's Investigate 14A demonstrates one method of measuring the speed of sound in air. This method involves the measurement of distance and time.

Let's Investigate 14A

Objective

To measure the speed of sound in air by a direct method

Apparatus

Electronic starting pistol with light flash, stopwatch, measuring tape

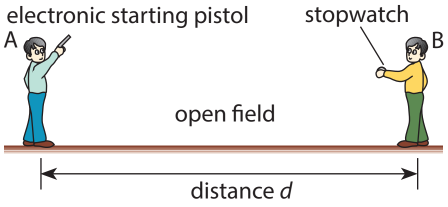


Figure 14.6

Procedure

1 Using a measuring tape, observers A and B are positioned at a known distance *d* apart in an open field (Figure 14.6).

2 Observer A fires an electronic starting pistol.

3 On seeing the flash of the starting pistol, observer B starts the stopwatch and then stops it when he hears the sound. The time interval *t* is then recorded.

Results and discussion

A typical set of data: $d = 800$ m, $t = 2.4$ s

$$\text{The speed of sound in air } v = \frac{\text{distance } d \text{ travelled by sound}}{\text{time taken } t}$$

$$= \frac{800 \text{ m}}{2.4 \text{ s}}$$

$$= 333 \text{ m/s}$$

The accuracy of the speed of sound in air *v* can be increased in two ways:

1 Repeat the experiment a few times, and calculate the average value of the speed of sound in air. Taking the average minimises the random errors that may occur while timing the interval.

2 Repeat the experiment but with the positions of observers A and B interchanged. This cancels the effect of wind on the speed of sound in air.

LINK PWB

Practical 14,
pp. XX–XX

Let's Practise 14.2

1 Can sound travel directly from one spaceship to another one nearby? Why?

2 A woman standing 1.00 km away from a storm hears the sound of thunder 3 s after she sees a flash of lightning. Calculate the speed of sound in air in m/s.

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

LINK TWB

Exercise 14B,
pp. XX–XX

14.3 Echoes and Ultrasound

In this section, you will learn the following:

- Describe an echo as the reflection of sound waves.
- Define ultrasound as sound with a frequency higher than 20 kHz.
- Ⓢ Describe the uses of ultrasound.

Echoes

What is an echo?

Figure 14.7 illustrates what an echo is.

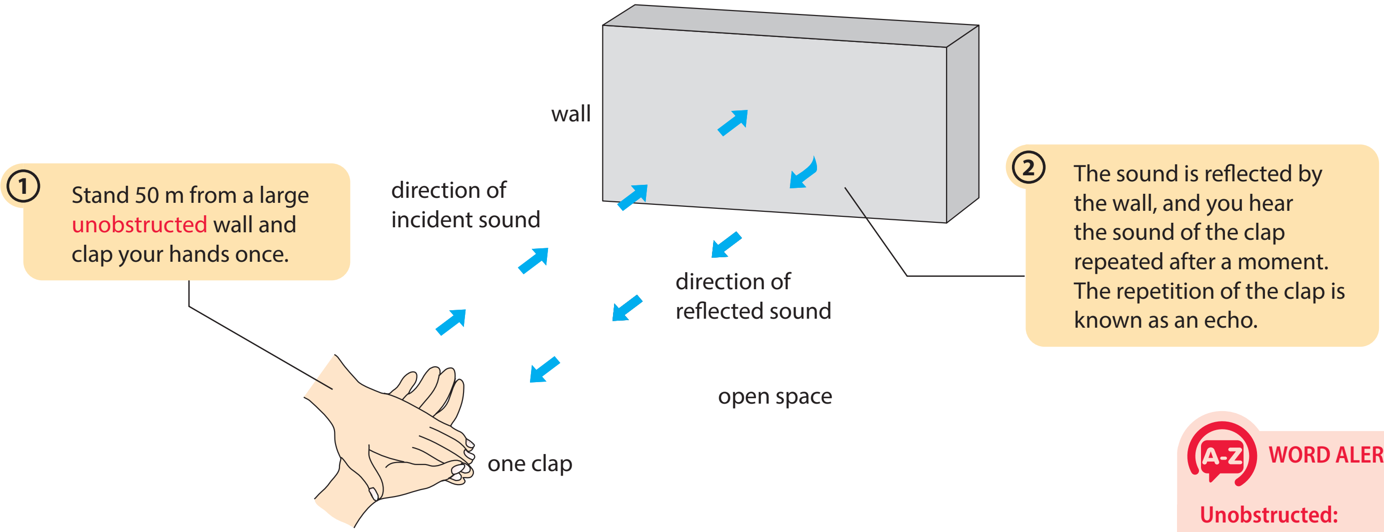


Figure 14.7 *Forming a single echo*

WORD ALERT

Unobstructed: not blocked

An **echo** is a reflection of sound waves.

How are echoes formed?

An echo is formed when a sound is reflected off hard, flat surfaces, such as a large wall or a distant cliff. The law of reflection of light also applies to sound waves. Figure 14.8 shows a simple experiment to illustrate the reflection of sound.

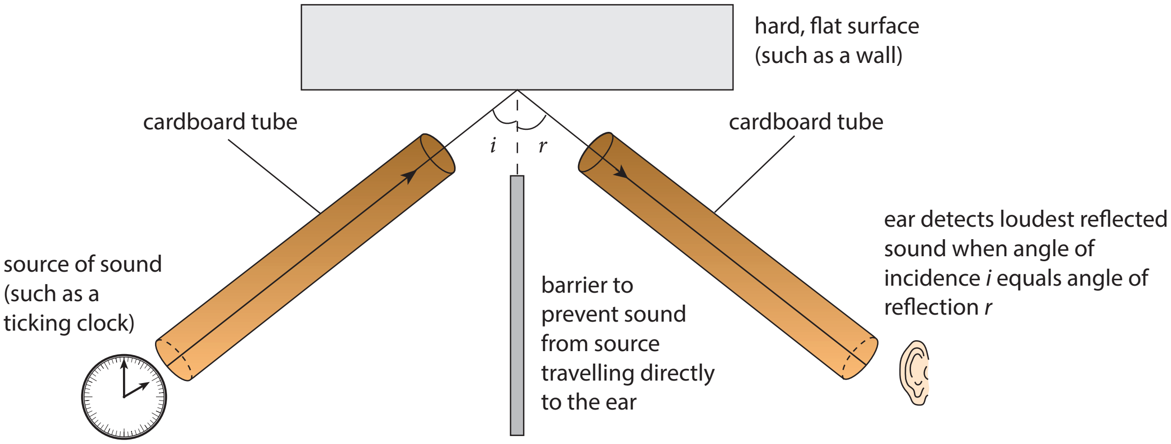


Figure 14.8 *Sound reflected off a surface*

HELPFUL NOTES

The word *sonar* is an acronym for the term ***s**ound **n**avigation **a**nd **r**anging*.

WORD ALERT

Cavities: holes or gaps

Foetuses: unborn babies

Ultrasound

What is ultrasound?

Ultrasound is sound with a frequency higher than 20 kHz.

In other words, ultrasonic frequencies are frequencies above the upper limit of the human range. Ultrasound has many uses. Bats and dolphins use ultrasound in echolocation (i.e. detecting the location of objects using echoes). Most sonar technologies also use ultrasound.

What are the uses of ultrasound?

Testing materials for quality control

Manufacturers of concrete use ultrasound to check for cracks or cavities in concrete slabs (Figure 14.9). Ultrasound can also be used to inspect metal pipes and measure the thickness of wooden boards.

① Ultrasound emerges from a transmitter.

② Ultrasound passes through the concrete slab and is received by a sensor.

③ By comparing the ultrasound emitted and received, the presence and location of defects can be identified.

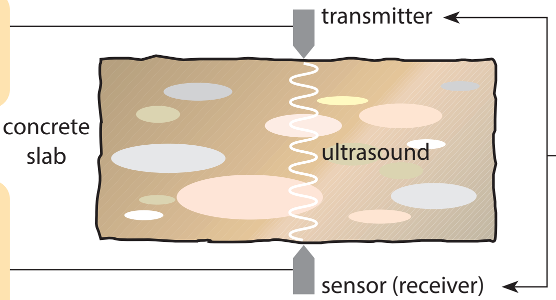


Figure 14.9 *Inspecting a concrete slab using ultrasound*

Medical scanning

Ultrasound can be used to obtain images of structures in the body. It is commonly used to examine the development of foetuses (Figure 14.10). Ultrasound is used instead of X-rays because it is less hazardous due to its lower energy.

Ultrasound pulses are sent into the womb of a pregnant woman via a transmitter. The time taken for the ultrasound pulses to be reflected is measured. From this, the depth of the reflecting surface within the womb can be derived, and an image is formed.

Figure 14.10 *A doctor scans the womb of a pregnant woman. The monitor shows an ultrasound image of the foetus inside the womb.*

Sonar

Sonar is a type of technology that works based on echolocation. It is used by ships for navigation at sea and to detect the position of other vessels.

For example, we can find the depth of the sea or the position of shoals of fish using sonar. This is done by sending out a signal (a pulse of sound) and noting the time interval before the reflected signal (the echo) arrives (Figure 14.11).

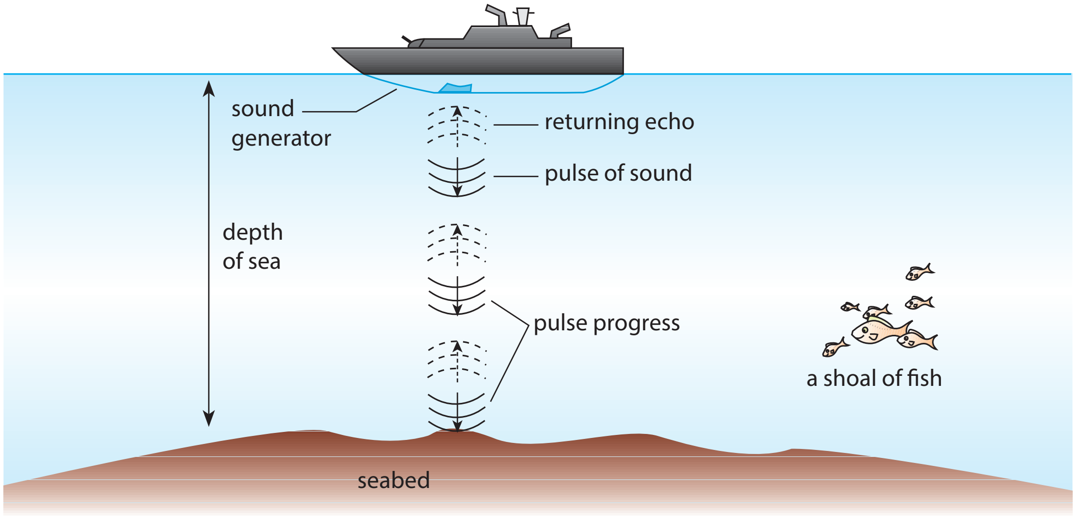


Figure 14.11 *A ship sends out a pulse of sound to determine the depth of the sea.*

Worked Example 14A

A ship uses a sonar as a depth sounder to measure the depth of a seabed. It sends a pulse of sound downwards into the sea. An echo from the seabed is received 0.3 s after the pulse is sent. If the speed of sound in water is 1500 m/s, determine the depth of the sea.

Solution

Given: Time for sound to travel to and back from seabed, $t = 0.3$ s

Speed of sound in water, $v = 1500$ m/s

Using $v = \frac{2d}{t}$, where d is the depth of the sea,

we get $d = \frac{vt}{2} = \frac{1500 \text{ m/s} \times 0.3 \text{ s}}{2} = 225 \text{ m}$

Let's Practise 14.3

1 A pulse of sound is transmitted from a ship towards the seabed. If the echo is received after 1 s, calculate the depth of the sea, given that the speed of sound in water is 1500 m/s.

2 Why is ultrasound preferred to X-rays for prenatal scanning, although both types of waves can be used to obtain images of internal organs?

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

ENRICHMENT
INFO

How Do Dolphins Navigate in Water?

Dolphins emit a series of clicks at about 100 kHz through their foreheads and receive the echoes through their lower jaws. From the frequencies and direction of the echoes, dolphins can deduce the nature and location of objects in their paths.

Figure 14.12 *Dolphins navigate underwater using echolocation.*

ENRICHMENT
THINK

Some bats use echolocation to help them find their prey in the dark. Others rely more on their sight to find food.

The common Asian ghost bat (Figure 14.13) can be found in South and Southeast Asia. From the photo, how do you think this bat find its food?

What would be an effective way to catch this bat? Explain how your method will work.

Figure 14.13 *Common Asian ghost bat*

LINK

Exercise 14C,
pp. XX–XX

14.4 Pitch and Loudness

In this section, you will learn the following:

- Describe how changes in amplitude and frequency affect the loudness and pitch of sound waves.

We experience a great variety of sounds every day. Some sounds are pleasant, whereas some are not. Pitch and loudness are among the characteristics of sound that help us determine whether a sound is pleasant.

QUICK CHECK

The pitch of a sound depends on its frequency.

True or false?

What affects the pitch of a sound?

We often describe sounds as being *high-pitched* or *low-pitched*. Do you know what causes a sound to be high-pitched or low-pitched?

Pitch is related to the frequency of a sound wave — the higher the frequency, the higher the pitch.

Pitch is relative. For example, a 200 Hz sound has a higher pitch compared to a sound of 100 Hz. However, the 200 Hz sound has a lower pitch compared to a sound of 400 Hz.

Two tuning forks of different lengths produce sounds of different pitch (Figure 14.14). This is because the tuning forks generate sound waves of different frequencies.

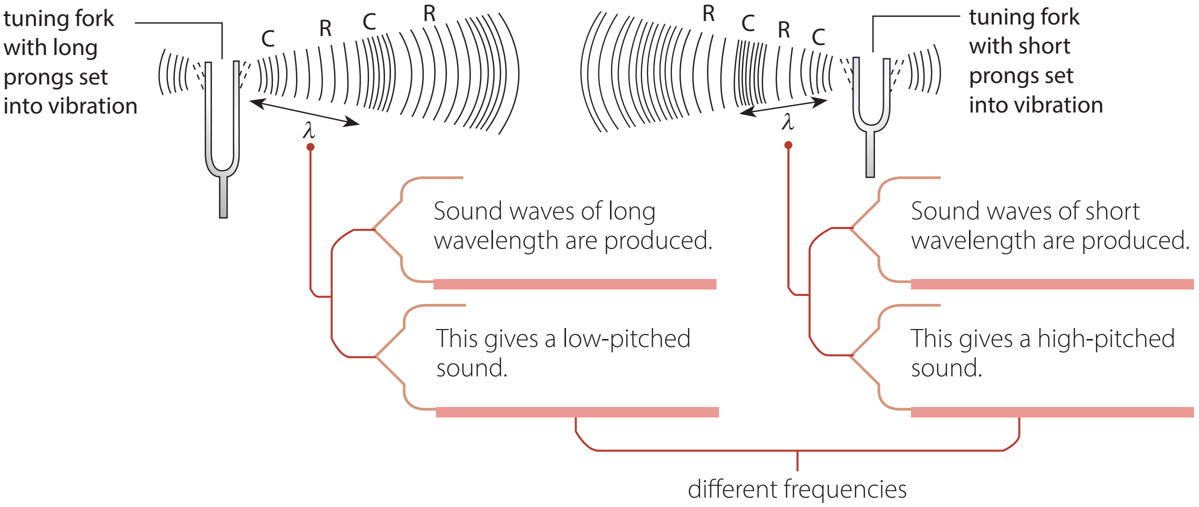


Figure 14.14 *Tuning forks with prongs of different lengths produce sounds of different pitch.*

To observe the waveforms of sound waves, we use a microphone and a cathode-ray oscilloscope (c.r.o.) (Figure 14.15).

① Sound waves are directed to the microphone.

② Sound waves are converted to electrical energy by the microphone.

③ The waveform is displayed on the c.r.o. screen as a displacement–time graph.

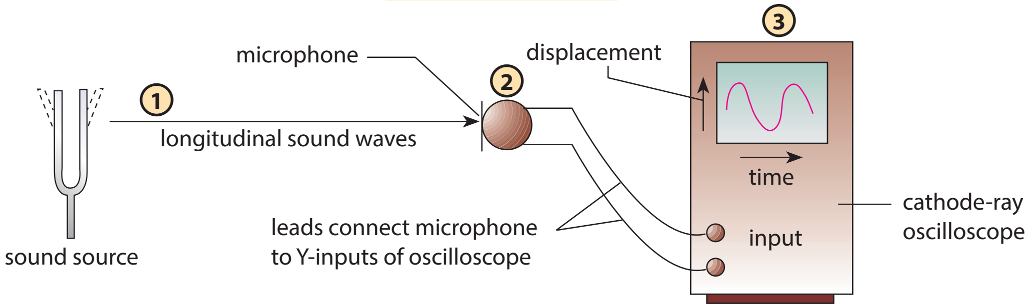


Figure 14.15 *A c.r.o. can be used to visualise sound waves.*

If the sound waves produced by the tuning forks in Figure 14.14 are channelled into a c.r.o., the resulting waveforms will look like the ones shown in Figures 14.16 and 14.17. Note that the same time base is used.

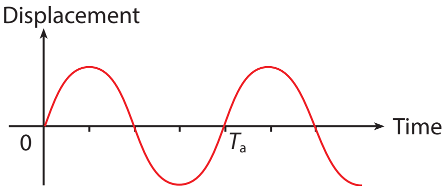


Figure 14.16 *The waveform for the tuning fork with long prongs.*

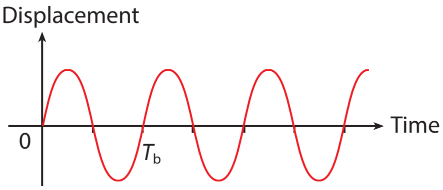


Figure 14.17 *The waveform for the tuning fork with short prongs.*

From Figures 14.16 and 14.17, the period T_a of the long tuning fork is longer than the period T_b of the short tuning fork.

Recall that frequency f is related to period T by the equation $T = \frac{1}{f}$. Since $T_a > T_b$, the frequency $f_a = \frac{1}{T_a}$ of the long tuning fork is lower than the frequency $f_b = \frac{1}{T_b}$ of the short tuning fork. Hence, the tuning fork with long prongs produces a sound with a lower pitch or frequency compared to the tuning fork with short prongs.

What affects the loudness of a sound?

To the human ear, the loudness of a sound is subjective. For a particular volume of sound, some people may find it loud, whereas others may find it soft.

Loudness is related to the amplitude of a sound wave — the larger the amplitude, the louder the sound. Figures 14.19 and 14.20 show two waveforms of the same frequency but with different amplitudes of vibration.

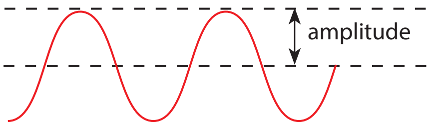


Figure 14.19 *A loud sound has a large wave amplitude.*

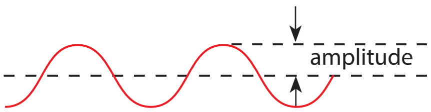


Figure 14.20 *A soft sound has a small wave amplitude.*

Let's Practise 14.4

1 Of these quantities — speed, frequency, wavelength, and amplitude — which is associated with the

(a) loudness of a sound; **(b)** pitch of a sound?

2 Compare in terms of loudness and pitch the sounds made by a mosquito flying near your ear and the croaking of a bullfrog.

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

ENRICHMENT *ACTIVITY*

Get several glass bottles of the same size and shape. Fill the bottles with different levels of water. Now, blow across the top of each bottle (Figure 14.18).

Why is there a difference in the pitch of each note?

In groups, try to play a simple song using bottles filled with different levels of water. Record which note each bottle plays. Then, explain how you managed to do this.

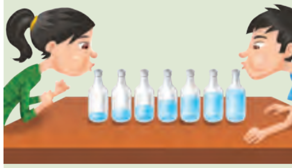


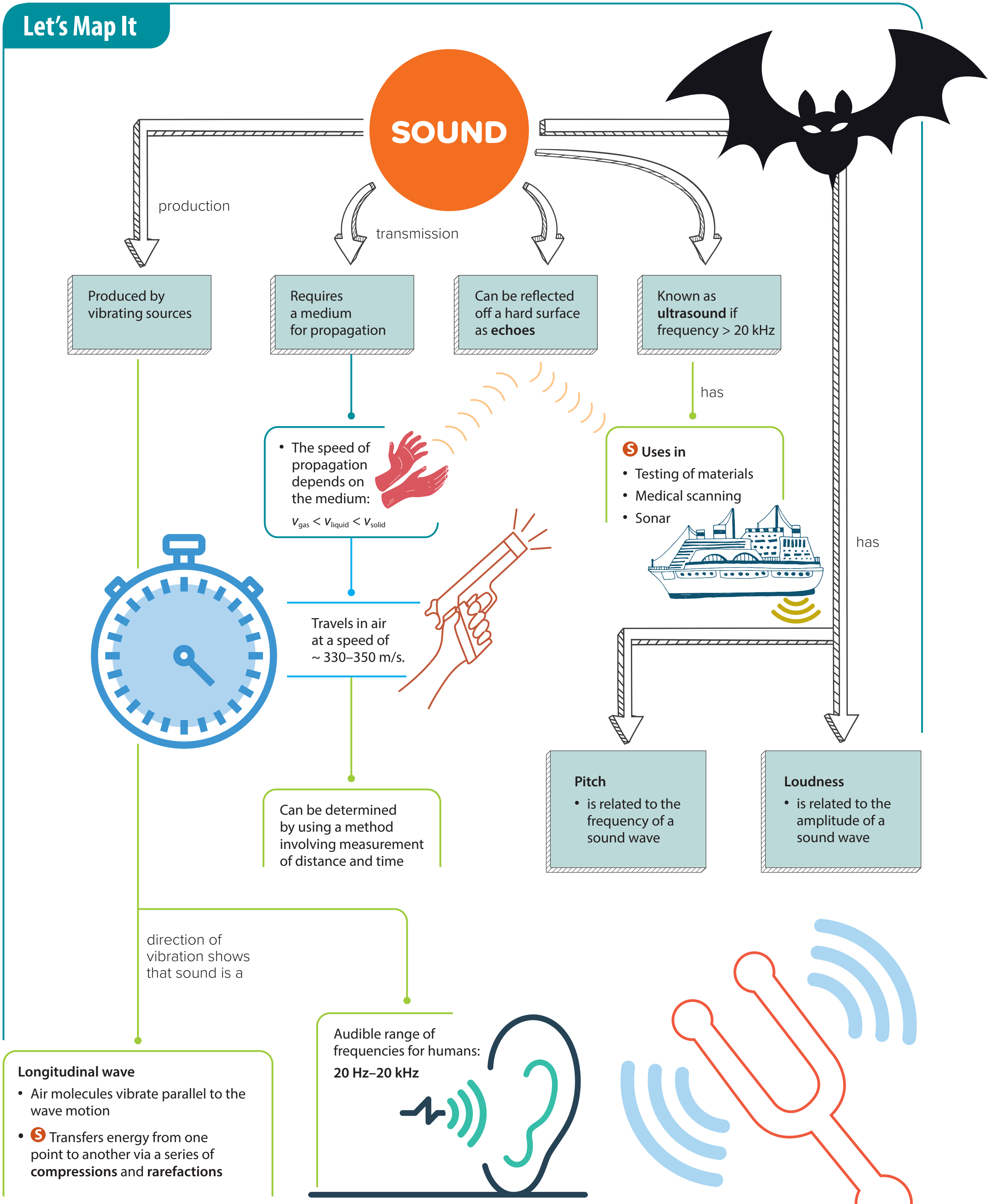
Figure 14.18

LINK

Exercises 14C–14D, pp. XX–XX

Exercise 14E Let's Reflect, p. XX

Let's Map It



SOUND

production

Produced by vibrating sources

transmission

Requires a medium for propagation

- The speed of propagation depends on the medium: $v_{\text{gas}} < v_{\text{liquid}} < v_{\text{solid}}$

Travels in air at a speed of ~ 330–350 m/s.

Can be determined by using a method involving measurement of distance and time

Can be reflected off a hard surface as **echoes**

Known as **ultrasound** if frequency > 20 kHz

has

S Uses in

- Testing of materials
- Medical scanning
- Sonar

has

Pitch

- is related to the frequency of a sound wave

Loudness

- is related to the amplitude of a sound wave

direction of vibration shows that sound is a

Longitudinal wave

- Air molecules vibrate parallel to the wave motion
- S Transfers energy from one point to another via a series of **compressions** and **rarefactions**

Audible range of frequencies for humans:

20 Hz–20 kHz

Let's Review

Section A: Multiple-choice Questions

1 A spaceship with astronauts on board orbits the Moon. The astronauts see an asteroid crashing onto the surface of the Moon. Why do they not hear the explosion caused by the crashing of the asteroid?

- **A** All the sound waves are absorbed by the surface of the Moon.
- **B** The sound waves are reflected from the surface of the spaceship.
- **C** The sound waves are unable to travel from the Moon's surface to the spaceship.
- **D** All the sound waves are absorbed by the surface of the spaceship.

2 Based on the information in Table 14.2, which statement correctly describes the speed of sound?

Table 14.2

Substance	Density/ g/cm^3	Speed of sound/ m/s
Lead	11.3	1200
Iron	7.87	5000
Oxygen	0.001 43	320
Air	0.001 29	330

- **A** The denser the substance, the lower the speed of sound.
- **B** As the density of the substance decreases, the speed of sound decreases.
- **C** The speed of sound is greater in metals than in gases.
- **D** The speed of sound increases as the density of the substance increases.

3 Figure 14.21 shows two boys, A and B, standing in front of a tall building. Both boys are facing the building. When boy A claps his hands once, boy B hears two claps that are 2 s apart.

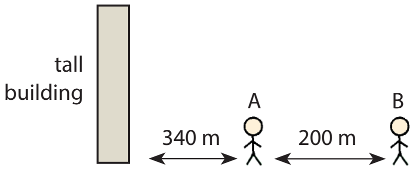


Figure 14.21

Based on the information given, what is the speed of sound in air?

- **A** 300 m/s
- **B** 340 m/s
- **C** 350 m/s
- **D** 500 m/s

4 A guitar plays a louder note but at a lower pitch compared to a violin. Which of the following is correct?

	Violin's amplitude	Guitar's frequency
A	Higher	Higher
B	Higher	Lower
C	Lower	Higher
D	Lower	Lower

Section B: Short-answer and Structured Questions

1 A bell is struck by a hammer.

(a) Briefly describe how sound is produced by the bell.

(b) Describe how the sound travels through air to reach the ear of the person striking the bell.

2 In an experiment, a ringing electric bell is suspended inside a bell jar by a thin string. A vacuum pump is then used to draw air out of the bell jar.

(a) When the vacuum pump is not switched on, the ringing of the bell can be heard. When the vacuum pump is switched on, the loudness of the bell decreases until only a very faint sound can be heard. Explain this observation.

(b) Describe and explain what will happen if the electric bell is not suspended by the string but rests on the base supporting the bell jar instead.

3 In an attempt to determine the speed of sound in air, observer A stands 500 m from observer B in an open space. Observer A starts the experiment by firing a flashgun towards the sky. Observer B starts the stopwatch when he sees the flash and stops the stopwatch when he hears the sound of the gun. They repeat the experiment three times and the timings recorded are 1.51 s, 1.55 s and 1.50 s.

(a) Calculate the average speed of sound in air.

(b) Suggest why the observers A and B should not stand 100 m apart for this experiment.

4 Ⓢ The approximate range of frequencies that the average human ear can detect is 20 Hz to 20 000 Hz.

(a) Dogs can detect ultrasound. Explain what this means.

(b) One application of ultrasound is medical diagnosis, where images of internal body parts are obtained. Describe how ultrasound is used to obtain the images of internal body parts.

Let's Review

5 **(a)** Describe how an echo is formed.

(b) Ⓢ Figure 14.22 shows a ship as it moves from positions A to F above a seabed. At each spot, the ship transmits sound pulses to the seabed to determine its depth profile. The speed of the sound pulses in the seawater is 1500 m/s.

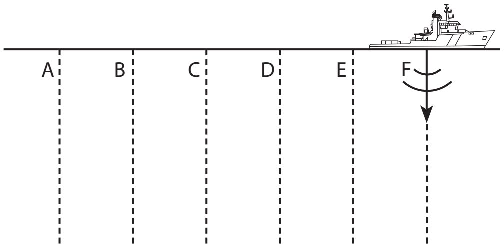


Figure 14.22

Figure 14.23 shows the time interval between each transmitted pulse and the reflected pulse received by the ship. Each thick line represents the transmitted pulse, while each thin line represents the corresponding reflected pulse.

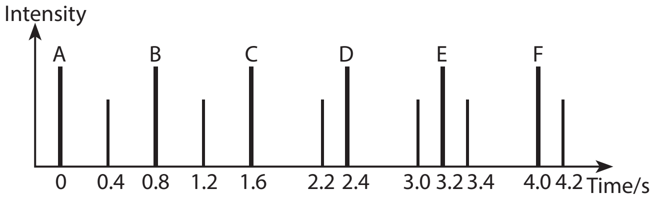


Figure 14.23

(i) Based on the data in Figure 14.23, calculate the depth of the seabed at each of the positions A to F.

(ii) On Figure 14.24, draw the rough depth profile of the seabed. Clearly label the depth of the seabed for each of the positions A to F.

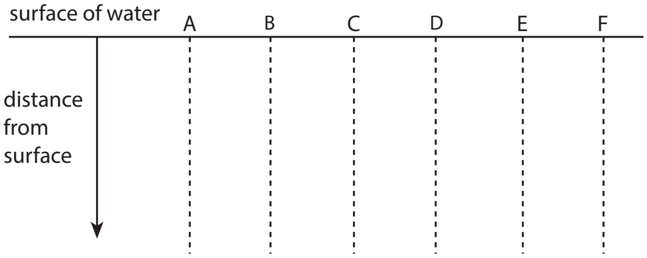


Figure 14.24

(iii) Calculate how long it takes to detect an echo from the seabed if the depth is 60 m.

6 **(a)** Two properties that are used to distinguish one musical sound from another are pitch and loudness. State the physical characteristic of sound waves to which

(i) pitch is related;

(ii) loudness is related.

(b) A student tries to produce notes of higher frequency by blowing a trumpet harder. Discuss whether the student will succeed.

CHAPTER

15

Simple Phenomena of Magnetism

PHYSICS WATCH

Scan this page to watch a clip on how a maglev train works.

This Shanghai Transrapid magnetic levitation (maglev) train is one of the fastest trains in the world. It has a top speed of 431 km/hr! It takes passengers from the airport to the city centre in merely seven minutes. Many passengers take pictures of the speed indicator as it climbs higher and higher.

The train floats above the track using magnets placed on the tracks and under the train. The floating of the train reduces frictional force acting on the wheels, thus allowing it to move at very high speeds and very quietly. To move the train forward, the poles of the magnets can be switched. Compared to burning fuel in a traditional train, the maglev train is a more environmentally-friendly vehicle.

QUESTIONS

- Imagine yourself sitting in a maglev train. Compared to a traditional train, what would be some differences?
- How does an object float?
- What do you think allows the train to float?
- How does floating help the train to move at a very high speed?

15.1 Magnets and Their Properties

In this section, you will learn the following:

- Describe the forces between magnets, and between magnets and magnetic materials.
- State the difference between magnetic and non-magnetic materials.
- Describe induced magnetism.

How were magnets discovered?

Long ago, people observed that special types of stone, known as lodestone (Figure 15.1), attracted iron objects. Around 800 years ago, it was discovered that objects made from lodestone pointed in the same directions when hung freely. Those directions were later known as the North and South poles of the Earth. Due to this property of showing the direction, lodestones are very useful navigation tools.

Lodestone is a naturally occurring magnet. Magnets and magnetic materials are found everywhere. They are used in many applications where two things are required to stick together or push away from each other.

Figure 15.1 *A lodestone attracting iron clips*

LINK

Find out what causes magnets to exert a magnetic force in Section 15.3 of this chapter.

What are the properties of magnets?

A magnet is an object that exerts a magnetic force. The magnetic force of a magnet causes it to display certain properties.

LINK

Recall how forces change the motion of an object in Chapter 4.

Magnets attract magnetic materials

The magnetic force exerted by a magnet can attract magnetic materials. The difference between magnetic and non-magnetic materials is the ability to be attracted by a magnet.

Magnetic materials are materials that can be attracted to a magnet.

Non-magnetic materials are materials that cannot be attracted to a magnet.

Table 15.1 lists some examples of magnetic and non-magnetic materials.

Table 15.1 *Examples of magnetic and non-magnetic materials*

Magnetic materials	Non-magnetic materials
Steel	Copper
Iron	Wood
Cobalt	Plastic
Nickel	Brass

This property of magnet is useful when we are separating magnetic materials from non-magnetic materials in a metal scrapyard.

LINK

Find out how magnetic materials can be separated from non-magnetic materials in Section 15.2 of this chapter.

The poles of magnets have the strongest magnetic force

The ends of a magnet are also known as poles. When we move a magnet close to a pile of iron nails, the iron nails are attracted to the poles of the magnet (Figure 15.2). The poles are where the magnetic force is the strongest.

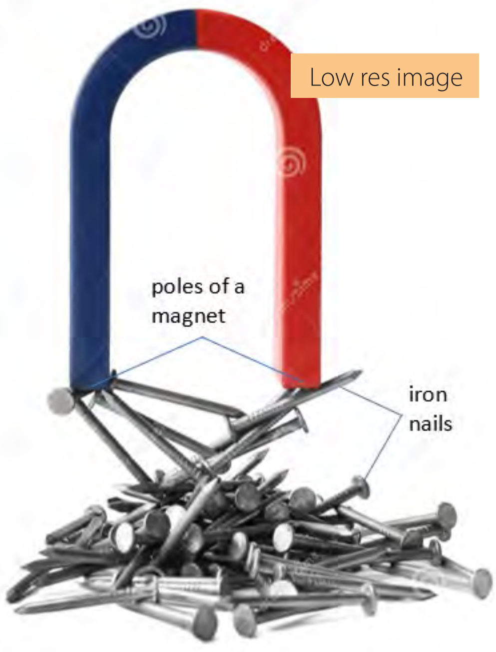


Figure 15.2 *The iron nails are attracted to the poles of the magnet.*

A freely suspended magnet points to the north–south direction

When a magnet is left suspended freely, it always points to the North and South Poles of the Earth (Figure 15.3).

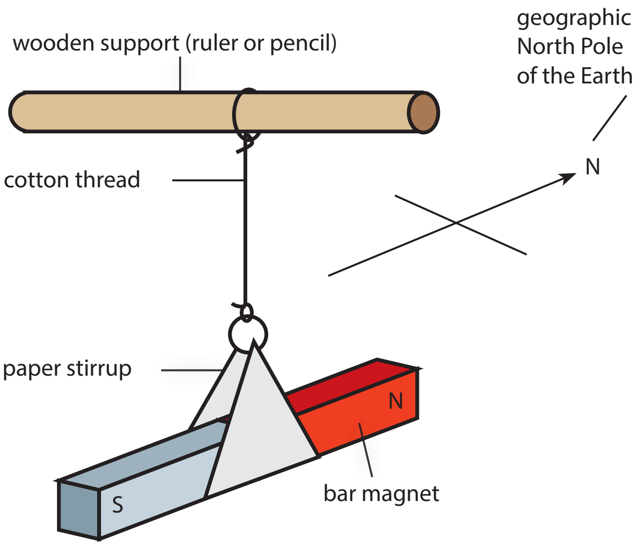


Figure 15.3 *A bar magnet always points to the north–south direction when suspended freely.*

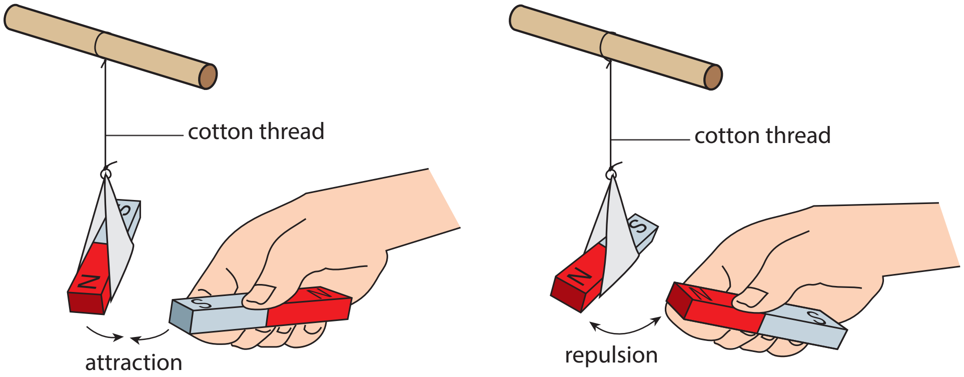
This is because the Earth behaves like a giant magnet and the magnetic force exerted by the Earth causes a freely suspended magnet to point in the north-south direction of the Earth. The poles of magnets are also known as north pole (N pole) and south pole (S pole) due to this property.

LINK

Find out how the Earth affects the direction of a freely suspended magnet in Section 15.3 of this chapter.

Like poles repel, unlike poles attract

When we bring two like poles (two north poles or two south poles) of two magnets together, the magnetic force between the poles of the magnets causes them to **repel** each other. When we repeat this with two unlike poles, the two magnets **attract** each other (Figure 15.4).



▲ Unlike poles attract.

▲ Like poles repel.

Figure 15.4 *Attracting and repelling magnets*

What is induced magnetism?

Magnets are made by magnetising magnetic materials. The process of magnetising a magnetic material is also known as **magnetic induction**.

When an unmagnetised paper clip is brought near a bar magnet, it is attracted to the magnet. When this happens, we say the paper clip has become an **induced magnet**. In turn, this induced magnet is able to attract other paper clips (Figure 15.5).

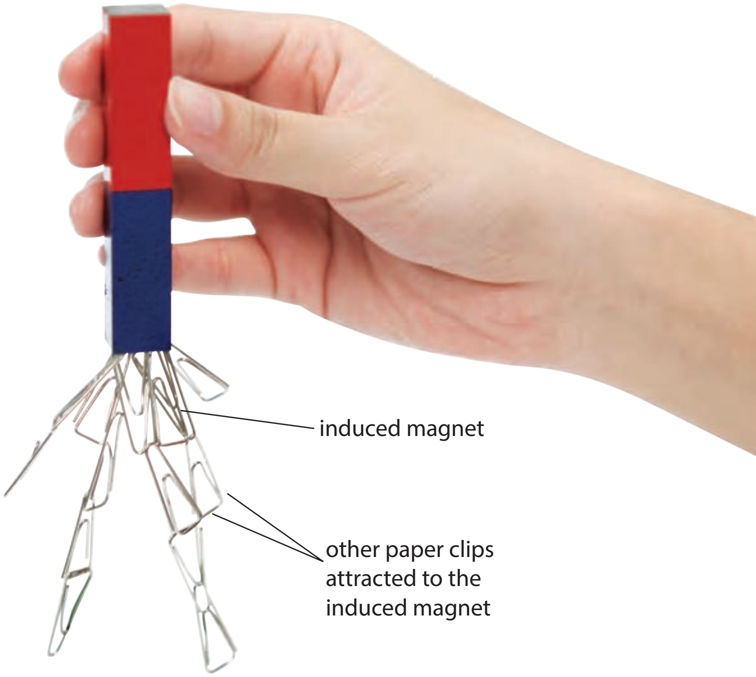


Figure 15.5 *Paper clips attracted by a magnet become induced magnets that attract other paper clips.*

The process of induction does not require physical contact. As shown in Figure 15.6, the magnet can induce magnetism in the iron bar by simply being near it. The N pole of the bar magnet induces an S pole in the nearer end of the iron bar and an N pole in its farther end.

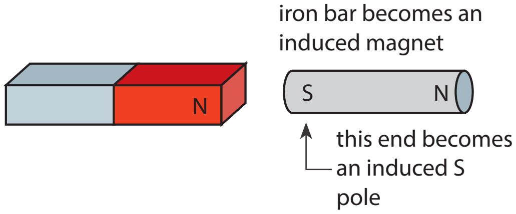


Figure 15.6 *A magnetic material is induced when a magnet is placed close to it.*

ENRICHMENT *ACTIVITY*

Design your own levitating toy using the properties of magnets. What property allows the toy to levitate?

Share your findings with the class.

QUICK CHECK

The N pole of a magnet will attract the S pole of another magnet.

True or false?

WORD ALERT

Levitate: float

Magnetising: making something to have the properties of a magnet

Induced: made to become, caused to happen

Magnetic materials can be magnetised because of the presence of *magnetic domains*. Each domain behaves like a small magnet, and we can represent them using arrows (Figure 15.7). The arrowhead shows the N pole and the back of the arrow shows the S pole.

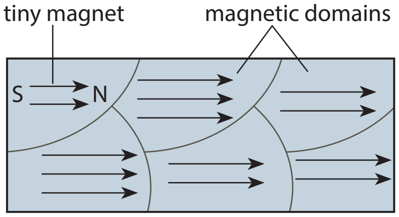
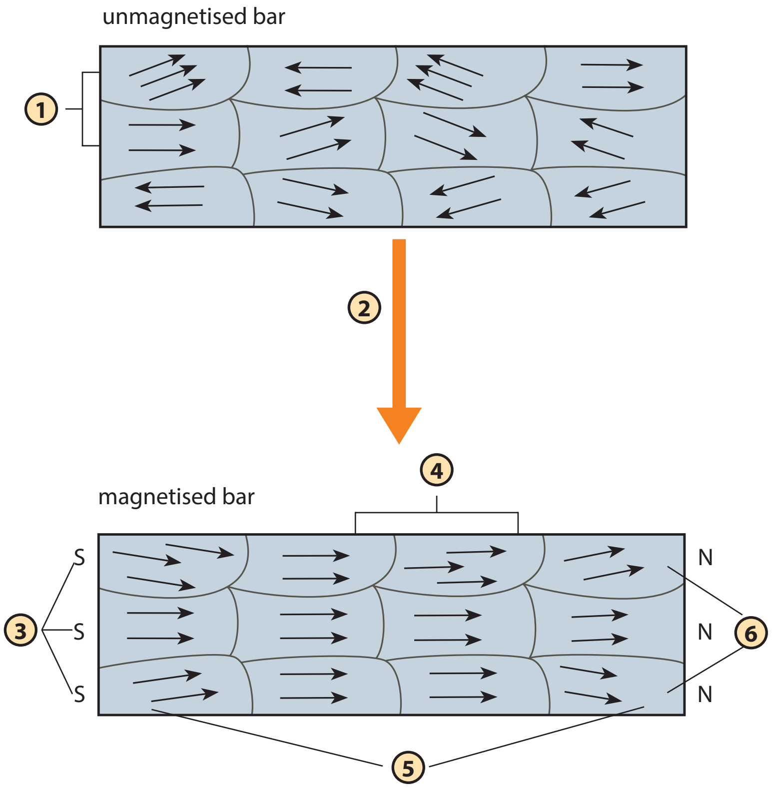


Figure 15.7 *Magnetic domains in a magnetic material*

Figure 15.8 explains how a magnetic material is magnetised.

① The magnetic domains in an unmagnetised bar point in random directions. There is no net magnetisation because the domains cancel one another out.

② The N pole of a magnet is placed on the left side of the unmagnetised bar.



③ The magnetic force from the magnet causes the S poles of the domains, nearest to the magnet, to be attracted to the magnet. All other domains rotate and point in the same direction, producing a net magnetisation.

④ Each arrow is arranged directly behind the arrow in front of it. Therefore, the N poles are cancelled out by the adjacent S poles.

⑤ The tiny magnets at both the ends are 'free'. This produces the effect of N or S poles at the ends. This allows the magnetised bar to behave like a magnet.

⑥ The tiny magnets at the ends tend to fan out due to repulsion between the like poles.

Figure 15.8 *The alignment of the domains causes a magnetic bar to be magnetised.*

PHYSICS WATCH

Scan this page to explore a simulation on magnetic induction.

ENRICHMENT *INFO*

Magnetic Resonance Imaging (MRI)

An MRI machine can take images of a patient's body by using very strong magnets. This is because we have many protons in our body, which act like tiny magnets. The movement of these tiny magnets caused by the strong magnets in the MRI machine can be studied to find out more about what is happening in our body.

▲ *An MRI image of the blood vessels in the brain*

QUICK CHECK

An S pole of a magnet was brought close to an iron bar. The iron bar was repelled by the magnet. The N pole of the same magnet was brought close to the iron bar. The iron bar was attracted to the magnet.

True or false?

Let's Practise 15.1

1 Give three examples of
  (a) magnetic materials;
  (b) non-magnetic materials.

2 State the properties of magnets.

3 In an experiment, a piece of wood is held between the N pole of a magnet and two iron nails (Figure 15.9).
  (a) Although wood is a non-magnetic material, the two nails are still attracted to the magnet when the piece of wood is held between the magnet and the nails. Suggest a reason for this.
  (b) It is observed that the pointed tips of the iron nails point away from each other. Why?

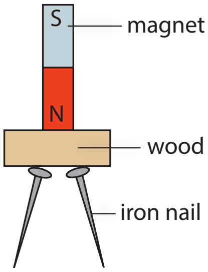


Figure 15.9

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

LINK TWB

Exercise 15A, pp. XX–XX

15.2 Temporary and Permanent Magnets

In this section, you will learn the following:

- State the differences between the properties of temporary and permanent magnets.
- Describe the uses of permanent magnets and electromagnets.

What are temporary and permanent magnets?

WORD ALERT A-Z

Temporary: lasting for a short time

Permanent: lasting for a long time

Both iron and steel are magnetic materials. Magnets made from iron are known as temporary magnets, while magnets made from steel are known as permanent magnets. This is because iron and steel have different magnetic properties.

Most types of iron are **magnetically soft**. A magnetically soft material can be easily magnetised and also lose its magnetism easily. Iron that is magnetically soft is also known as soft iron. Steel is **magnetically hard**. A magnetically hard material is difficult to magnetise, but once magnetised, retains its magnetism afterwards. The properties of soft iron and steel can be observed in Let's Investigate 15A.

ENRICHMENT *THINK*

What are some instances where a temporary magnet is preferred over a permanent magnet? How about the other way around?

Let's Investigate 15A

Objective

To compare the magnetic properties of soft iron and steel

Materials

Bar magnet, soft iron and steel bars of equal dimensions (20 cm in length), iron paper clips

Procedure

1 Let the N pole of the bar magnet attract one end of the soft iron bar. Dip the other end of the soft iron bar into a tray of paper clips. Record the maximum number of paper clips that are attracted to it.

2 Pull the magnet away from the soft iron bar. Observe what happens to the paper clips. Record the number of paper clips still attracted to the soft iron bar.

3 Now repeat steps 1 and 2 using the steel bar.

4 Repeat steps 1–3 and observe whether there are consistent differences in the observations between the two metal bars.

Observation and results

Figure 15.10 summarises what happens when we conduct the investigation.

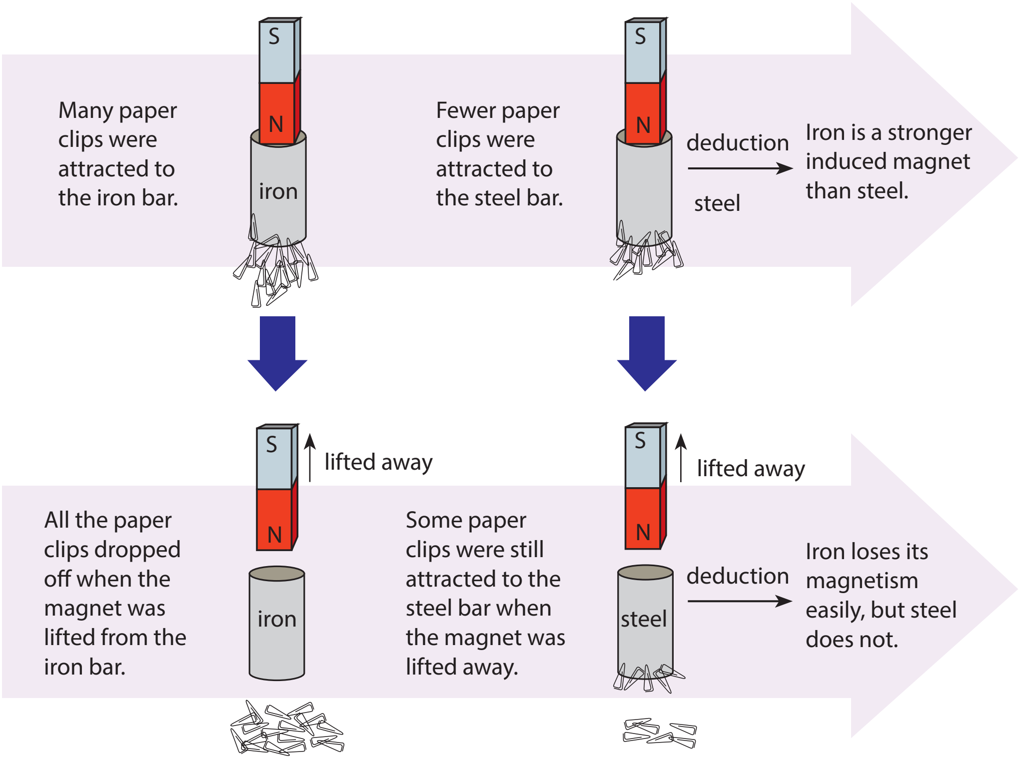


Figure 15.10

Conclusion

The different magnetic properties of soft iron and steel are summarised in the table below.

Table 15.2 *Magnetic properties of soft iron and steel*

Magnetic properties of soft iron	Magnetic properties of steel
• It is easily magnetised to become a stronger induced magnet.	• It is difficult to magnetise. Hence, it becomes a weaker induced magnet.
• It loses its magnetism easily.	• It does not lose its magnetism easily.

PHYSICS WATCH

Scan this page to explore a simulation on temporary and permanent magnets.

LINK

PWB

Practical 15A, pp. XX–XX

What can we do with permanent magnets and electromagnets?

Magnets are used in many parts of our lives. Permanent magnets are used when a constant magnetic force is needed. Electromagnets are used when a changing magnetic force is needed. Figure 15.12 shows how magnets are used in our daily lives.

LINK

An electromagnet is a type of temporary magnet. Placing a magnetically soft material within an electromagnet produces a stronger temporary magnet. You will learn more about this in Chapter 17.

Figure 15.12 *Uses of magnets*

Uses of permanent magnets

Magnetic door catches

Magnetic strips made of permanent magnets are fitted to the door of a refrigerator. When the door is closed, the attraction between the magnetic strip and the steel frame keeps the door closed.

Maglev trains

Magnetic levitation (maglev) trains use magnetic attraction and repulsion to levitate and move forward. As the trains are not in contact with the tracks, friction is reduced and the trains can move at high speeds.

Uses of temporary magnets

Electromagnets

Electromagnets are magnets that form when a current flows through a coil. This magnetic field can induce magnetism in a soft magnetic material to produce a temporary magnet.

Cranes use electromagnets to separate magnetic materials from non-magnetic materials in metal scrapyards.

LINK

Exercise 15B,
pp. XX–XX

Let's Practise 15.2

1 Figure 15.13 shows an experiment in which identical magnets are clamped to the ends of three metal bars. Each metal bar is made of a different metal — brass, iron and steel. The number of iron tacks picked up by each metal bar is shown. Identify metals 1, 2 and 3, and explain your answer.

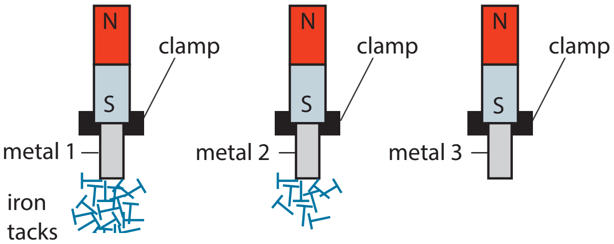


Figure 15.13

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

15.3 Magnetic Field

In this section, you will learn the following:

- Describe a *magnetic field* as a region in which a magnetic pole experiences a force.
- Draw the pattern and direction of magnetic field lines around a bar magnet.
- Describe the plotting of magnetic field lines with a compass and the use of a compass to determine the direction of the magnetic field.
- State that the direction of a magnetic field at a point is the direction of the force on the N pole of a magnet at that point.
- Ⓢ Explain that magnetic forces are due to interactions between magnetic fields.
- Ⓢ Know that the relative strength of a magnetic field is represented by the spacing of the magnetic field lines.

What is a magnetic field?

Every magnet has a region of space around it called a **magnetic field**. Earth behaves like a giant magnet and has its own magnetic field (Figure 15.14).

A magnetic material or magnetic pole placed in the magnetic field will experience a force. We have learnt in Section 15.1 that a freely suspended magnet points in the north–south direction. As the freely suspended magnet is placed in the magnetic field of Earth, the magnet experiences a magnetic force from Earth.

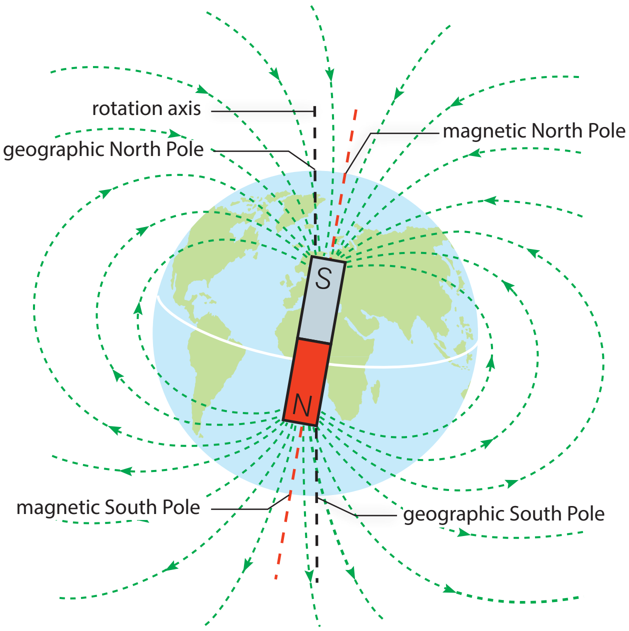


Figure 15.14 *Earth's magnetic field*

HELPFUL NOTES

We can use a compass to determine the direction of the magnetic field easily. The arrowhead of the compass shows the direction of the magnetic field at that point.

QUICK CHECK

A piece of wood placed in the magnetic field of a magnet experiences magnetic force.

True or false?

The arrangement of a group of magnetic field lines is called a **magnetic field pattern**.

The magnetic field pattern of a magnet shows us the magnetic force acting on a magnetic material or magnet placed in the field:

- The *direction* of the magnetic field lines at a point is the direction of the force on the N pole of a magnet at that point.
- Ⓢ The *relative strength* of the magnetic force is dependent on how closely packed the magnetic field lines are.

How can we visualise the magnetic field of a magnet?

A magnetic field is invisible. To visualise the pattern and direction of the magnetic field around a bar magnet, we can use a **plotting compass**, which is a small magnet. When a plotting compass is placed near a bar magnet, their opposite poles will attract each other. The procedure is described in Let's Investigate 15B.

Let's Investigate 15B

Objective

To determine the shape and direction of the magnetic field lines around a bar magnet

Materials

Bar magnet, plotting compass, plain paper, pencil

Precautions

- Perform this experiment away from other magnetic materials such as steel, iron and nearby electrical cables.
- Check that the compass needle is free to rotate about the pivot at its centre.

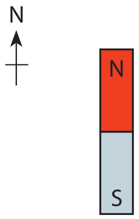


Figure 15.15

Procedure

1. Put the bar magnet at the centre of a piece of paper. Ensure that its N pole points to the north (Figure 15.15). Use a compass to help you determine the north direction.
2. Trace the outline of the magnet, and indicate its N pole and S pole.
3. Starting near one pole of the magnet, mark the positions of the ends, S and N, of the compass needle with pencil dots X and Y respectively. Move the compass so that the S end is at Y and mark the new position of the N end with a third dot Z (Figure 15.16).
4. Repeat the process of marking the dots until you reach the other pole. Join the dots and this will give a single magnetic field line.
5. Determine the direction of the field line by checking the arrow of the compass needle. The compass needle should point to the S pole of the magnet as shown in Figure 15.15.
6. Repeat steps 3 to 5, starting at different points near the N pole until several field lines have been drawn. Try to keep the field lines symmetrical by going above and below the magnet on the piece of paper.

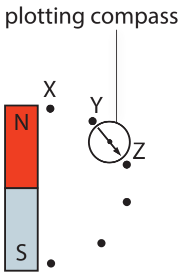


Figure 15.16

Observations and conclusion

- The magnetic field lines appear to leave the North pole and end at the South pole of the magnet, with a pattern similar to that in Figure 15.17.
- The direction of the magnetic field lines can be determined using a compass.
- S The field lines are more concentrated at the poles. This is because the field lines are closest together on the diagram at the poles. We learnt that the magnetic force is the strongest at the poles. Hence, we can conclude that the closer the magnetic field lines, the stronger the magnet.

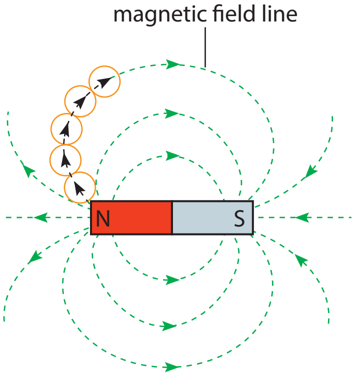


Figure 15.17 *Field lines around a bar magnet*

LINK PWB

Practical 15B, pp. XX–XX

S We learnt that every magnet has a magnetic field. The plotting compass is a tiny magnet. *The interaction of the magnetic fields of the bar magnet and the plotting compass results in a magnetic force*. This magnetic force exerted by the bar magnet on the plotting compass needle rotates the needle to point along one of the bar magnet's field lines. This explains why we can use a plotting compass to plot the magnetic field lines around a magnet.

Let's Practise 15.3

1 Figure 15.18 shows a plotting compass placed at a position near a bar magnet.

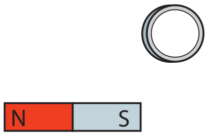


Figure 15.18

(a) Draw the magnetic field lines around the bar magnet.

(b) Determine the direction of the arrow in the plotting compass at that position.

(c) The bar magnet is then replaced with a stronger bar magnet. Draw the magnetic field lines around the stronger bar magnet.

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

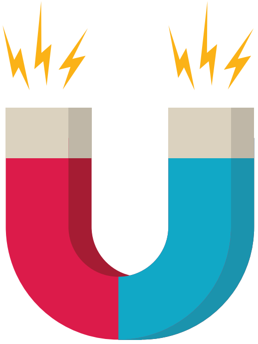
LINK TWB

Exercise 15C–15D, pp. XX–XX

Exercise 15E Let's Reflect, p. XX

Let's Map It

MAGNETISM



Magnet

have the following properties

- Attract magnetic materials
- Have a north pole and a south pole, with the strongest magnetic force
- When suspended freely, rest in north-south direction
- Obey the laws of magnetism (like poles repel, unlike poles attract)

due to

Magnetic force

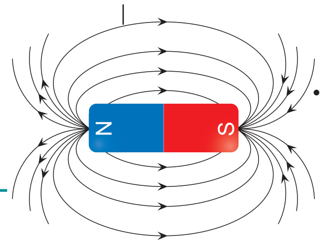
caused by

Ⓢ Interactions between magnetic fields

which is

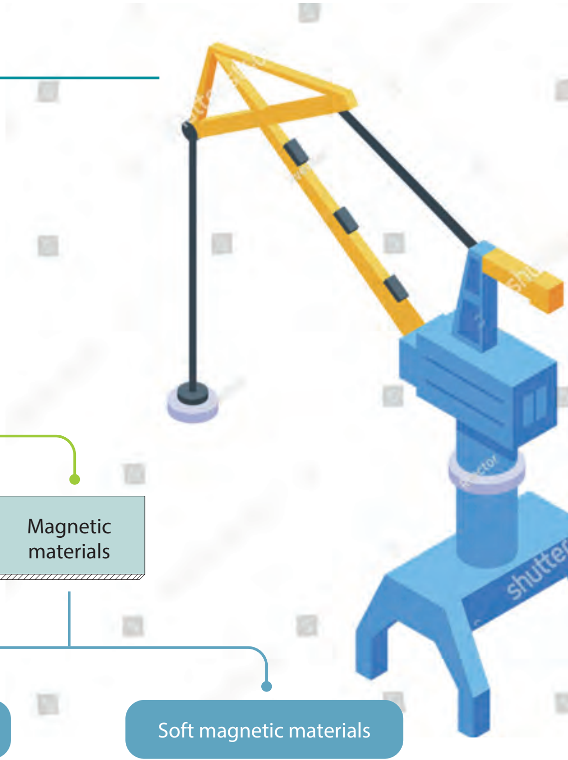
Visualised using plotting compass

magnetic field line



where

- The direction of the magnetic field lines at a point is the direction of the force on the N pole of a magnet at that point.
- Ⓢ The relative strength of the magnetic force is dependent on how closely packed the magnetic field lines are.



Magnetic materials

Hard magnetic materials which are difficult to magnetise through

Soft magnetic materials which are easy to magnetise through

Induced magnetism

to form

Permanent magnets used in

- Magnetic door catches
- Maglev trains

Temporary magnets used in

- Maglev trains
- Electromagnets

Let's Review

Section A: Multiple-choice Questions

1 In which of the following set-ups will all three magnets repel one another?

A

B

C

D

2 Figure 15.19 shows a small compass placed near the centre of a bar magnet.

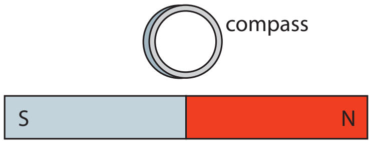
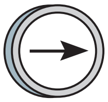


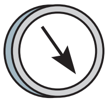
Figure 15.19

In which direction will the compass needle point?

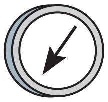
A



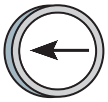
B



C



D



3 Figure 15.20 shows part of a magnetic relay. M is the magnet located inside the coil. L is the armature that is attracted to M when a current flows through the coil. S is the stopper that cushions the impact of L on M during attraction. It prevents L and M from being damaged during collision.

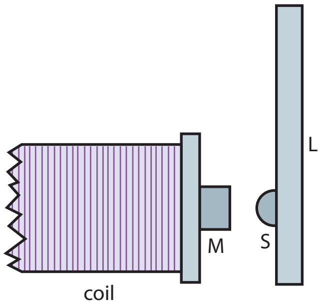


Figure 15.20

Which of the following gives the best combination of materials for M, L and S?

	M	L	S
A	Iron	Copper	Rubber
B	Iron	Iron	Iron
C	Iron	Iron	Rubber
D	Plastic	Iron	Rubber

Section B: Short-answer and Structured Questions

1 Steel is known as a magnetically hard material. It can be made into a permanent magnet through induced magnetism.

(a) State what is meant by the term "magnetically hard"?

(b) Explain how magnetism is induced in a steel.

(c) Other than steel, name a magnetic material that is magnetically soft.

2 Describe an experiment to determine the shape and direction of the magnetic field lines around a bar magnet.

3 Ⓢ Explain what causes magnetic forces

(a) between magnets;

(b) between magnets and magnetic materials.

4 Figure 15.21 shows a rod of unmagnetised steel placed inside a solenoid. When the switch is closed, current flows through the solenoid and the steel rod is magnetised.

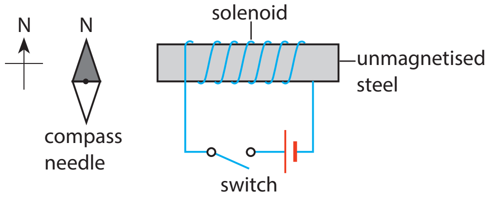


Figure 15.21

(a) Describe the motion of the compass needle when the switch is closed and then opened some time later.

(b) Describe how the experimental set-up in Figure 15.21 can be used to distinguish a steel rod from an iron rod. List any additional materials that will be used.

5 Figure 15.22 shows a soft iron bar placed near a bar magnet.

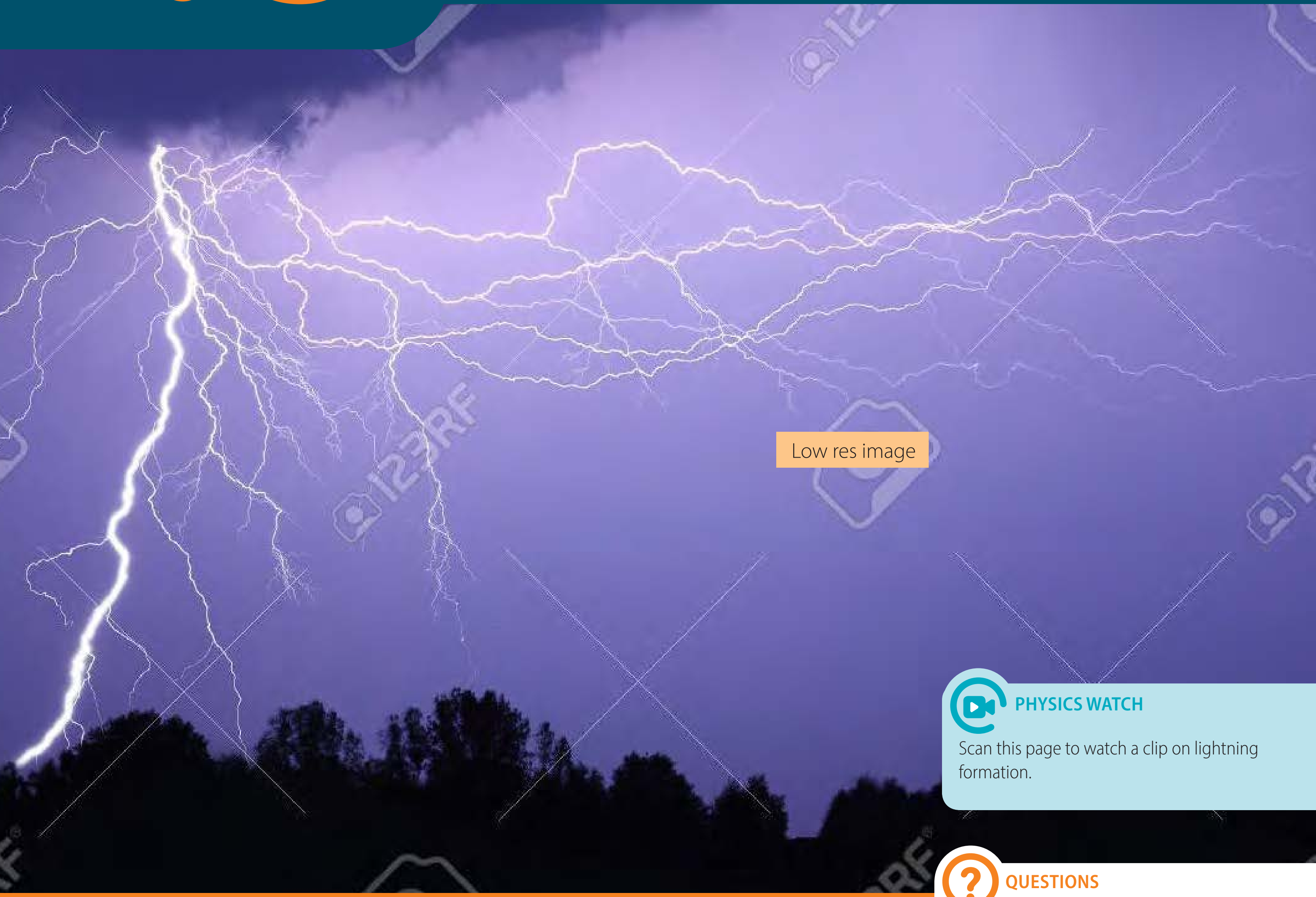
Figure 15.22

(a) Draw the magnetic field pattern of the soft iron bar shown in Figure 15.22. Indicate the poles of the induced magnet and the direction of the field lines.

(b) Using a diagram, outline how you can check your answer in (a) with an experiment using a plotting compass.

CHAPTER

16 Electrical Quantities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PHYSICS WATCH

Scan this page to watch a clip on lightning formation.

QUESTIONS

- What do you think causes lightning?
- Why do you think lightning strikes frequently in the Himalayas?
- What precautions should you take to avoid being hit by lightning during a thunderstorm?

Lightning is a spectacular sight, but be sure to observe it from a safe place. According to statistics, Asia has the second-most number of lightning hotspots. Very high rates of lightning activity can be found along the high regions of the Himalayas.

Daggar is a small town about 100 km from Islamabad, the capital of Pakistan. It lies near the north-western ridges of the Himalayas. Daggar recorded 143 lightning hits per year, making it the top lightning hotspot in Asia.

16.1 Electric Charge

In this section, you will learn the following:

- State that there are positive and negative charges.
- State that positive charges repel other positive charges, negative charges repel other negative charges, but positive charges attract negative charges.
- Describe simple experiments to show the production of electrostatic charges by friction and to show the detection of electrostatic charges.
- Explain the charging of solids by friction involves only a transfer of negative charge (electrons).
- Describe an experiment to distinguish between electrical conductors and insulators.
- Recall and use a simple electron model to explain the difference between electrical conductors and insulators and give typical examples.

When you rub a balloon against your hair, the balloon attracts your hair (Figure 16.1). Why?

Both the balloon and your hair acquire a static electric charge due to the friction from rubbing. These charges cause the attraction between the balloon and your hair. How do objects become charged by rubbing?

WORD ALERT

Static: not moving

Simple electron model

To understand how objects become charged by rubbing, we must first understand that all objects are made up of tiny particles called atoms. Let's use a simple electron model to understand what makes up an atom.

Figure 16.1 *Rubbing a balloon against your hair charges both the balloon and your hair.*

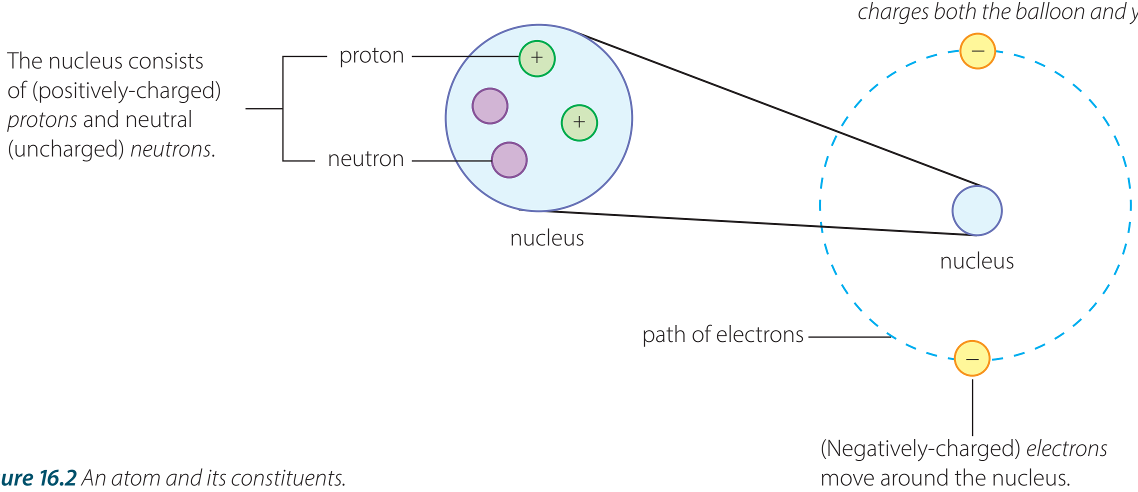


Figure 16.2 *An atom and its constituents.*

In an atom, there is a central **nucleus**. The nucleus is made up of **protons** and **neutrons**. Around the nucleus are the orbiting **electrons**. There are positive and negative charges in the atom. Protons are the positive charges while electrons are the negative charges.

An atom has an equal number of electrons and protons — it is electrically neutral. An atom becomes charged when the number of electrons and protons is not equal. This occurs when electrons are removed from or added to the atom. If electrons are removed, the atom becomes positively charged. If electrons are added, the atom becomes negatively charged. Let us now look at Let's Investigate 16A to find out how a glass rod can be charged by the movement of electrons.

Let's Investigate 16A

Objective

To show how a glass rod can be charged by friction

Materials

Rubber mat, two glass rods, silk, a few pieces of paper

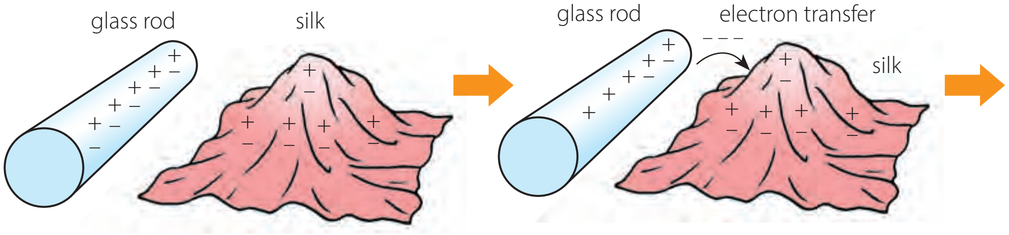
Procedure

1. Stand on a rubber mat and hold a glass rod
2. Rub the glass rod with a piece of silk for three minutes. Label this rod A
3. Bring the glass rod close to a few pieces of paper.
4. Observe what happens to the pieces of paper.
5. Label the second glass rod B.
6. Bring the rod B to the pieces of paper. Observe what happens.

Observation

The pieces of paper are attracted to rod A but not rod B.

Discussion

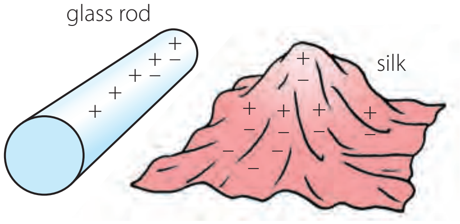


Before rubbing, the glass rod and the piece of silk are electrically neutral, i.e. they each contain an equal number of protons and electrons.

- Different materials have different **affinities** for electrons, i.e. some materials attract electrons weakly, whereas others attract electrons strongly.
- When the glass rod and the piece of silk are rubbed together, the atoms at their surfaces are disturbed.
- Some electrons from the atoms at the surface of the glass rod are transferred to the piece of silk.

WORD ALERT A-Z

Affinities: natural attraction



As the glass rod loses electrons, it becomes positively charged. As the piece of silk gains electrons, it becomes negatively charged.

Figure 16.3 *Charging by friction*

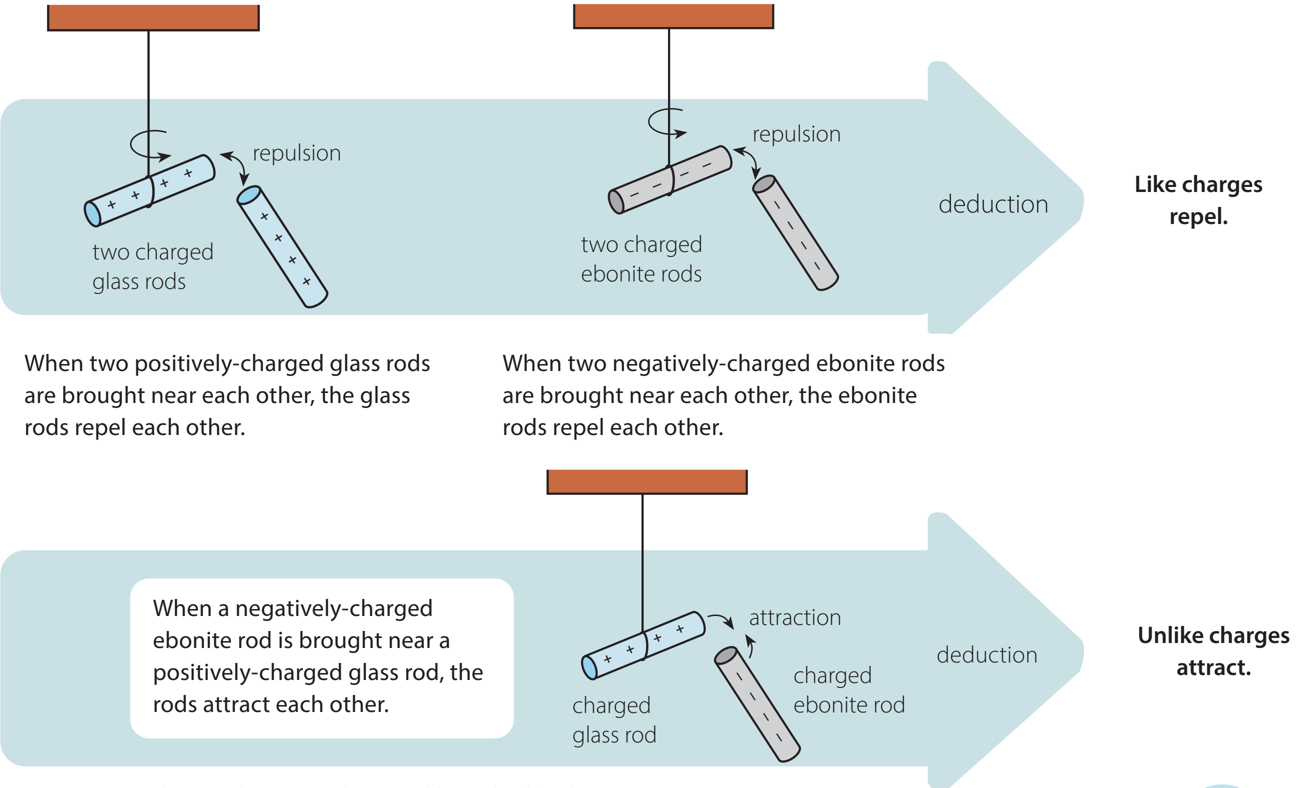
LINK PWB

Practical 16A, pp. XX–XX

Conclusion
A material can become charged when rubbed with another material. This is because *rubbing transfers electrons* from one material to the other material.

Interactions between charges

Positive charges repel other positive charges. Negative charges repel other negative charges. Positive charges attract negative charges.



When two positively-charged glass rods are brought near each other, the glass rods repel each other.

When two negatively-charged ebonite rods are brought near each other, the ebonite rods repel each other.

When a negatively-charged ebonite rod is brought near a positively-charged glass rod, the rods attract each other.

Figure 16.4 *Repulsion and attraction between like and unlike charges*

The glass rod and the ebonite rod are examples of electrical insulators. Electrical insulators are materials in which electrons are not free to move about. Electrical insulators can be charged by friction as they gain or lose electrons when they are rubbed together.

Materials in which electrons are free to move about are electrical conductors. All metals are conductors. Let us check if a material is a conductor or an insulator using Let's Investigate 16B.

PHYSICS WATCH

Scan this page to explore a simulation on how friction can cause an electric shock.

Let's Investigate 16B

Objective
To check which materials are conductors and which are insulators

Materials
1.5V dry cell, crocodile clips with connecting wires, switch, copper rod, aluminium rod, glass rod, wooden rod (ideally the same dimensions for all the rods), 1.5V rated lamp

Precautions

Make sure that you perform this experiment with a low voltage and never use the circuit without the lamp. If it is omitted, the wires can heat up very quickly and has the capacity to cause a burn.

WORD ALERT

Omitted: left out, excluded

Procedure

1 Connect the dry cell, crocodile clips with connecting wires, the lamp and the switch as shown in Figure 16.5.

2 Close the switch. If the circuit has been built correctly and the components are functioning, the lamp should light up.

3 Connect the copper rod between the dry cell and the switch as shown in Figure 16.6.

4 Close the switch.

5 Observe whether the lamp lights up.

6 Repeat steps 3 to 5 with the other rods.

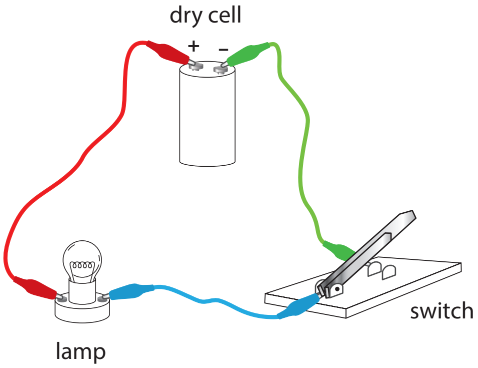


Figure 16.5

Observation

The lamp lit up when the copper rod and the aluminium rod were connected. The lamp did not light up when the glass rod and the wooden rod were connected.

Conclusion

For some materials, when the switch was closed, the lamp lit. These materials are called *electrical conductors*. Examples of electrical conductors are copper, aluminium and silver. For some materials, when the switch was closed, the lamp did not light. These materials are called *electrical insulators*. Examples of electrical insulators are plastics, wood and glass.

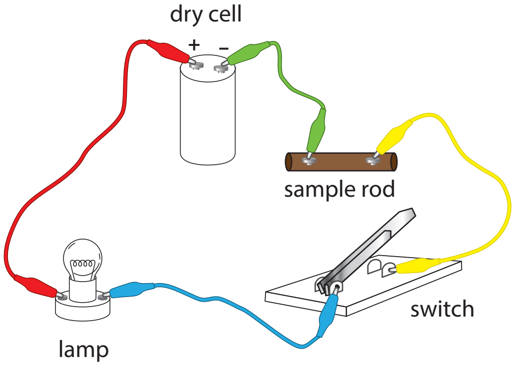


Figure 16.6

LINK PWB

Practical 16A, pp. XX–XX

Let's Practise 16.1

1 State the two types of electric charges.

2 Two polythene rods are each rubbed with wool. When the two rods are suspended and brought close to each other.

   (a) Describe what is observed.

   (b) Explain what is observed.

3 Explain the difference between an electrical insulator and an electrical conductor.

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

LINK TWB

Exercise 16A, pp. XX–XX

Ⓢ

16.2 Electric Field

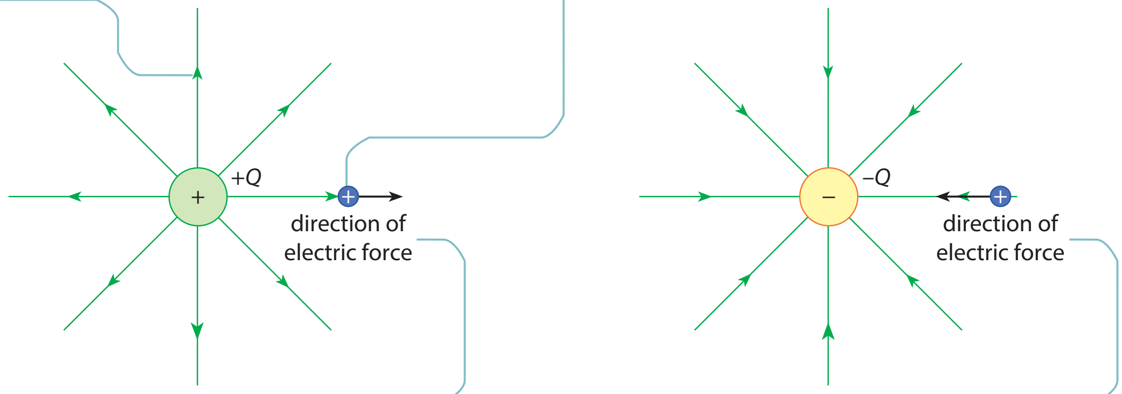
In this section, you will learn the following:

- Ⓢ Describe an electric field as a region in which an electric charge experiences a force.
- Ⓢ State that the direction of an electric field at a point is the direction of the force on a positive charge at that point.
- Ⓢ Describe simple electric field patterns, including the direction of the field around a point charge, a charged conducting sphere and between two oppositely charged parallel conducting plates.

Just like the magnetic field that is around a magnet, there is an electric field around every charge, represented by lines and arrows. An electric field is a region in which an electric charge experiences a force (Figure 16.7).

The arrowheads on the lines indicate the direction of the electric field.

When another positive charge is being placed in the electric field, it will experience an electric force in the direction of the arrowheads.



The direction of electric force is away from the positive charge. The positive charge is repelled.

The direction of electric force is towards the negative charge. The positive charge is attracted.

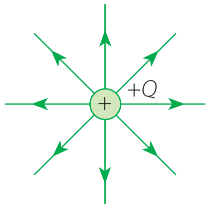
Figure 16.7 *Direction of electric force on a test charge in an electric field*

Therefore, the direction of an electric field at a point is the direction of the force on a positive charge at that point.

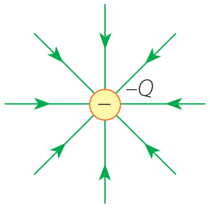
Figure 16.8 shows the simple electric field pattern around different charged objects.

Electric field pattern

Around a point charge

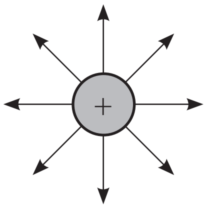


The electric field lines of a positive charge are directed away from the charge.



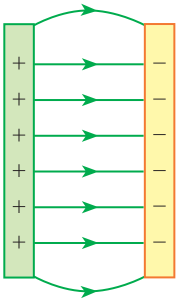
The electric field lines of a negative charge are directed towards the charge.

Around a charged conducting sphere



The electric field lines of a charged conducting sphere is directed away from the charge

Between two parallel charged plates



- The electric field lines start from positive plate and end on negative plate.
- The field is uniform near the middle of the plates, where the electric fields are parallel.

Figure 16.8 *Simple electric field pattern around different charged objects.*

LINK

Recall from Chapter 15 that

- the direction of the field lines shows the direction of a force; and
- the strength of the field is dependent on how closely packed the filled lines are.

HELPFUL NOTES

The field lines around the conducting sphere are very much the same as that for a point charge.

Consider a sphere of radius R that the has a charge of Q on it. The electric field line pattern outside the sphere is exactly the same as a point charge Q at the centre of that sphere.

ENRICHMENT *THINK*

There are no electrical field lines inside a sphere of charge Q. Explain why.

LINK TWB

Exercise 16B,
pp. XX–XX

Let's Practise 16.2

1 S Compare the direction of an electric field at a point and the direction of the force on a positive charge at that point.

2 S Sketch the electric field lines due to an isolated negative charge.

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

16.3 Electric Current

In this section, you will learn the following:

- Know that electric current is related to the flow of charge.
- S State that charge is measured in coulombs.
- S Define *electric current*; recall and use the equation $I = \frac{Q}{t}$.
- S State that conventional current is from positive to negative and that the flow of free electrons is from negative to positive.
- Describe electrical conduction in metals in terms of the movement of free electrons.
- Describe the use of ammeters, analogue and digital, with different ranges.
- Know the difference between direct current (d.c.) and alternating current (a.c.).

HELPFUL NOTES

Throughout this book, we will refer to conventional current unless otherwise stated.

What is electric current?

An object becomes charged if electrons are added to or removed from it. When the charged object is provided with a conducting path, electrons start to flow through the path from or to the object.

When electrons move, we say that an electric current is produced. An electric current is formed by moving electrons. Therefore, electric current is related to the flow of charge.

S An electric charge, Q, is measured in **coulombs (C)**. The amount of charge carried by an electron or proton is 1.6×10^{-19} C.

Electric current is the charge passing a point per unit time. The SI unit of electric current is the **ampere (A)**.

In symbols, electric current is given by:

$\boldsymbol{I = \frac{Q}{t}}$ where I = current (in A);

Q = charge (in C);

t = time taken (in s).

What is conventional current?

Before the discovery of electrons, scientists believed that an electric current consisted of moving positive charges. Although this belief was later proven wrong, the idea is still widely held. This is because the discovery of electron flow did not affect the basic understanding of an electric current, which is the movement of charges. This 'movement' of positive charges is called *conventional current*.

Conventional current is from positive to negative and that the flow of free electrons is from negative to positive.

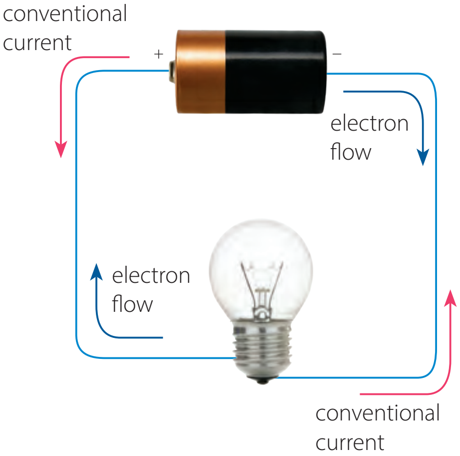


Figure 16.9 *Conventional current versus electron flow*

An electric current is actually caused by the flow of electrons from a negatively charged terminal to a positively charged terminal. This is because the electrons are repelled by the negatively charged terminal and attracted to the positively charged terminal. This movement of electrons is known as *electron flow*.

Figure 16.9 shows the difference between conventional current and electron flow.

Why are metals electrical conductors?

You have learnt previously that metals are electrical conductors. This is because the electrons in a piece of metal can leave their atoms and move about in the metal as *free electrons*. When connected to an energy source, these free electrons will be drove around the conducting path and a current is formed.

How do we measure electric current?

Since electric current is the flow of electric charges, we can measure electric current by determining the amount of electric charges that pass through a conductor per unit time.

One ampere is the electric current produced when one coulomb of charge passes a point in a conductor in one second.

An **ammeter** (Figure 16.10) is used to measure the magnitude and direction of an electric current in an electric circuit.

Figure 16.10 *An analogue ammeter*

The ammeter should be connected in series with the component whose current is to be measured (Figure 16.11). Conventional current flows into the ammeter through the positive '+' or red terminal and leave through the negative '–' or black terminal.

To measure current using the ammeter, we should take note of the following:

- It is important to get the correct range for the ammeter. When the current flowing through the ammeter is beyond the range of the ammeter, i.e. current is too large, the ammeter will be damaged. Therefore, ammeters have current ratings in which the largest current can be safely read.

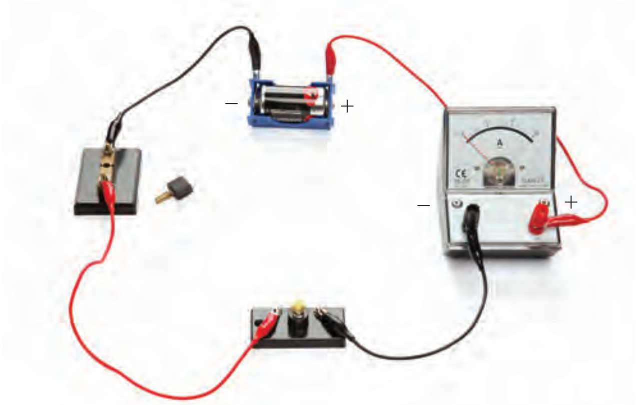


Figure 16.11 *An ammeter connected in series to measure the current* I

- When the ammeter chosen has a rating that is too large for the current, the ammeter will not detect the current accurately. The meter reading will likely to be too close to zero for reading to be effective.
- Ammeters can be either analogue (with a moving needle) or digital (with a numerical readout that changes). Essentially, the primary difference between an analogue ammeter and a digital ammeter is the display.

Alternating current and direct current

Electrical devices are designed to function with either **alternating current (a.c.)** or **direct current (d.c.)**. Direct current is used in electronic circuits and is supplied by batteries, cells and solar panels. Many mains supplies around the world provide alternating current. *Direct current flows in a single direction only, whereas alternating current changes direction frequently*.

LINK

You will learn more about series circuit in Chapter 17.

ENRICHMENT
THINK

The ampere is in fact defined more officially in terms of a magnetic force. Use the Internet to find out how the ampere is defined officially.

Share your answer with the class.

Worked Example 16A

The current in a lamp is 0.2 A. If the lamp is switched on for two hours, what is the total electric charge that passes through the lamp?

Solution

Given: Current $I = 0.2$ A

$$\text{Time } t = 2\text{ h} \times \frac{60\text{ min}}{1\text{ h}} \times \frac{60\text{ s}}{1\text{ min}}$$

$$= 7200\text{ s}$$

$$I = \frac{Q}{t}$$

$$0.2\text{ A} = \frac{Q}{7200\text{ s}}$$

Total electric charge $Q = 0.2\text{ A} \times 7200\text{ s} = 1.4 \times 10^{-3}\text{ C}$

Let's Practise 16.3

1 Ⓢ State the equation that relates electric charge to electric current.

2 Ⓢ State the SI unit of current.

3 Ⓢ Calculate how many electrons make a coulomb.

4 Describe how to use an ammeter.

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

LINK TWB

Exercise 16C,
pp. XX–XX

16.4 Electromotive Force and Potential Difference

In this section, you will learn the following:

- Define *electromotive force (e.m.f.)*
- Know that e.m.f. is measured in volts (V).
- Ⓢ Recall and use the equation for e.m.f. $E = \frac{W}{Q}$.
- Define *potential difference (p.d.)*
- Know that the p.d. between two points is measured in volts (V).
- Ⓢ Recall and use the equation for p.d. $V = \frac{W}{Q}$.
- Describe the use of voltmeters, analogue and digital, with different ranges.

How do currents occur?

In any complete circuit there must be an energy provider, often a battery or dry cell, and an energy user, such as a lightbulb or resistor.

The energy provider supplies the energy to drive a charge around the circuit. The work done by a source in moving a unit charge is known as the electromotive force or e.m.f. The e.m.f. is measured in **volts (V)**.

Electromotive force (e.m.f.) is the electrical work done by a source in moving a unit charge around a complete circuit.

In symbols, electromotive force is given by

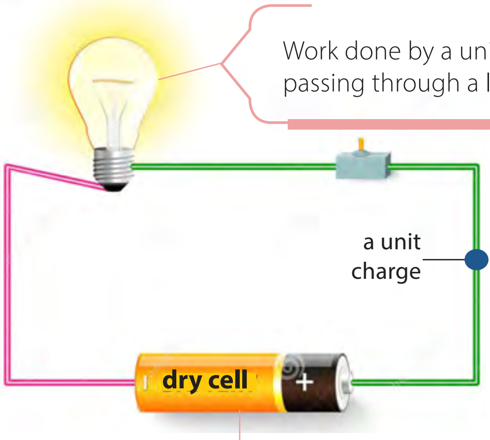
$E = \frac{W}{Q}$ where E = e.m.f (in V);
W = work done (in J);
Q = charge (in C).

When a charge passes through a particular electrical component in the circuit, there is work done on the component. This work done per unit charge is known as the potential difference, or p.d. The p.d. between two points, i.e. across a component, is measured in **volts (V)**.

Potential difference (p.d.) is the work done by a unit charge passing through a component.

In symbols, potential difference is given by

$V = \frac{W}{Q}$ where V = p.d. (in V);
W = work done (in J);
Q = charge (in C).



Work done by a unit charge passing through a lamp = p.d.

Work done by a dry cell to move a unit charge around the circuit = e.m.f.

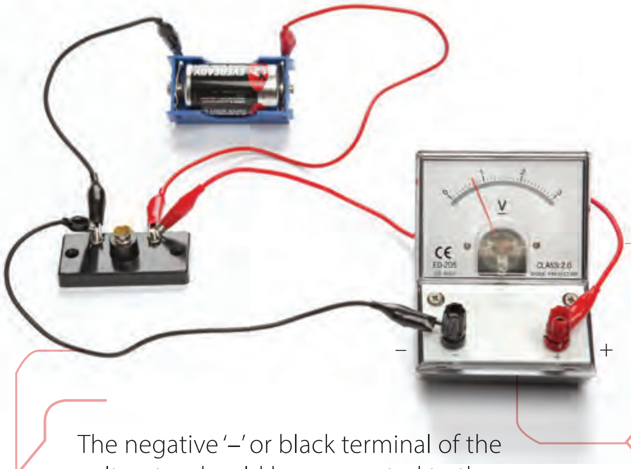
Figure 16.12 *Difference between e.m.f. and p.d.*

How do we measure e.m.f. and p.d.?

A **voltmeter** (Figure 16.13) is used to measure the e.m.f. of a dry cell or the p.d. across a component.

The voltmeter should be connected *in parallel* with the dry cell or the component that is to be measured (Figure 16.14).

Figure 16.13 *An analogue voltmeter*



The positive '+' or red terminal of the voltmeter should be connected to the positive '+' terminal of the cell.

The negative '–' or black terminal of the voltmeter should be connected to the negative '–' terminal of the cell.

Similar to ammeters, voltmeters can be either analogue or digital.

Figure 16.14 *A voltmeter connected in parallel to measure the p.d. across the lamp*

Figure 16.15 *A digital multimeter can be used to measure current, e.m.f. or p.d.*

QUICK CHECK

The e.m.f. is a force.

True or false?

HELPFUL NOTES

Do not confuse e.m.f. and p.d., even though they have the same unit. The e.m.f. is provided by a source of electrical energy, but p.d. refers to the electrical energy converted to other forms by a circuit component.

LINK

You will learn more about parallel circuit in Chapter 17.

ENRICHMENT *INFO*

Useful electric shocks

While electric shocks can kill, they can also be used to save lives. Have you ever seen defibrillators in public places (Figure 16.16)? A defibrillator is a device that can save the life of a person who is having a heart attack. It is connected to a power source and generates a potential difference so that an electric current flows through the heart. The heart is given a controlled electric shock to 'jolt it back to life' (i.e. to make it start pumping blood again).

Figure 16.16

LINK TWB

Exercise 16D, pp. XX–XX

Worked Example 16B

The e.m.f. of a dry cell is 1.5 V. What is the energy provided by the cell to drive 0.4 C of charge around a circuit?

Solution

Given: e.m.f. $E = 1.5$ V

charge $Q = 0.4$ C

Using $E = \frac{W}{Q}$, where W = energy provided by the cell,

$W = EQ$

$= (1.5\text{ V})(0.4\text{ C})$

$= 0.6\text{ J}$

Worked Example 16C

A charge of 4.00 x 10^4 C flows through an electric heater. If the amount of electrical energy converted into thermal energy is 9.00 MJ, calculate the potential difference across the ends of the heater.

Solution

Given: charge $Q = 4.00 \times 10^4$ C

energy $W = 9.00 \times 10^6$ J

By definition, potential difference $V = \frac{W}{Q}$

$$= \frac{9.00 \times 10^6\text{ J}}{4.00 \times 10^4\text{ C}}$$

$= 225\text{ V}$

Let's Practise 16.4

1 Describe the difference between e.m.f. and p.d.

2 S The potential difference across a light bulb is found to be 3.0 V. The current flowing through it is 0.40 A.

(a) Calculate how much charge flows through the light bulb in 2.0 minutes.

(b) Calculate how much energy is dissipated by the charge calculated in (a).

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

16.5 Resistance

In this section, you will learn the following:

- Recall and use the equation for resistance $R = \frac{V}{I}$.
- Describe an experiment to determine resistance using a voltmeter and an ammeter and do the appropriate calculations.
- Ⓢ Sketch and explain the current-voltage graphs for a resistor of constant resistance, a filament lamp and a diode.
- Ⓢ Recall and use the relationships for a metallic electrical conductor.
- State, qualitatively, the relationship of the resistance of a metallic wire to its length and to its cross-sectional area.

What is resistance?

Resistance is the measure of how difficult it is to pass an electric current through a conductor, such as a wire. When resistance is high, it is more difficult for charges to pass through the wire. Therefore, current will be reduced.

QUICK CHECK

The higher the resistance, the easier it is for current to flow.

True or false?

The **resistance** R of a component is the potential difference V across it divided by the current I flowing through it.

In symbols, the resistance of a component is given by

$\boldsymbol{R = \frac{V}{I}}$ where R = resistance of the component (in Ω)

V = p.d. across the component (in V)

I = current flowing through the component (in A)

From the definition of resistance, we can see that for a given p.d., the higher the resistance, the smaller the current passing through.

The SI unit of resistance is the **ohm (Ω)**. One ohm is the resistance of a component when a potential difference of one volt applied across the component drives a current of one ampere through it.

Worked Example 16D

A potential difference of 240 V applied across the heating coil of an electric kettle drives a current of 8 A through the coil. Calculate the

(a) resistance of the coil;

(b) new current flowing through the coil if the potential difference applied is changed to 220 V.

Solution

(a) Given: voltage $V = 240$ V

current $I = 8$ A

By definition, $R = \frac{V}{I} = \frac{240}{8} = 30\ \Omega$

(b) Given: voltage $V = 220$ V

From **(a)**, resistance $R = 30\ \Omega$.

Thus, $I = \frac{V}{R} = \frac{220}{30} = 7.3$ A

How do we measure resistance?

Circuit components such as wires and lamps have resistance. We can measure their resistances by measuring the current flowing through them and the p.d. across them. Figure 16.17 shows a current, I, flowing through a lamp and a potential difference, V, across it. With these two quantities, we can calculate the resistance of the lamp.

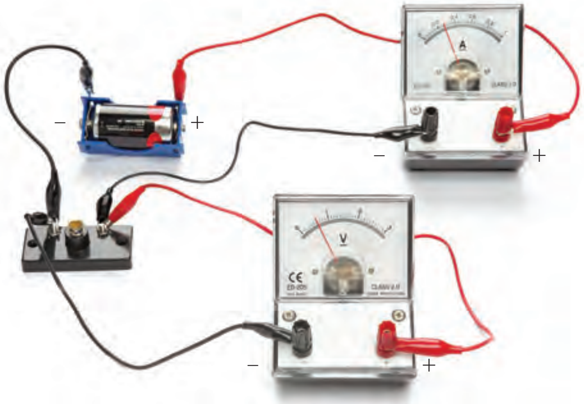


Figure 16.17 *Circuit to determine the resistance of a lamp*

Let's Investigate 16C

Objective

To determine the resistance of an ohmic resistor (which has low resistance) using a voltmeter and an ammeter

Materials

Voltmeter, ammeter, variable resistor, two 2 V dry cells, resistor R of unknown resistance

Procedure

1 Set up a circuit diagram as shown in Figure 16.18.

2 As a safety precaution, adjust the variable resistor to the maximum resistance. This is so that the initial current that flows in the circuit is small, to minimise the heating effect of the circuit.

3 Record the ammeter reading I and the voltmeter reading V.

4 Adjust the variable resistor to allow a larger current to flow in the circuit. Again, record the values of I and V.

5 Repeat step 4 to obtain at least five sets of I and V readings.

6 Plot V/V against I/A. Determine the gradient of the graph.

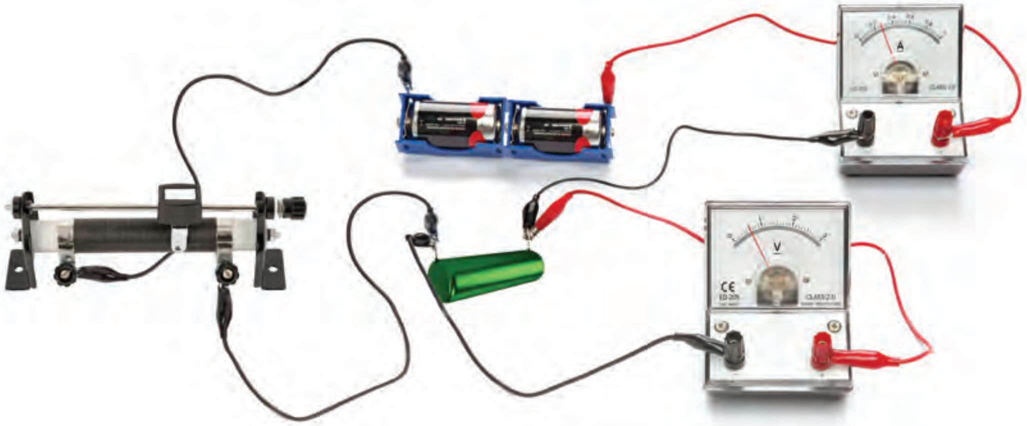


Figure 16.18

Observation and Discussion

The gradient of the graph gives the resistance of the resistor R (Figure 16.19). Note that the resistance of a conductor can be found using the gradient of the graph only if it is ohmic (i.e. it has a constant resistance).

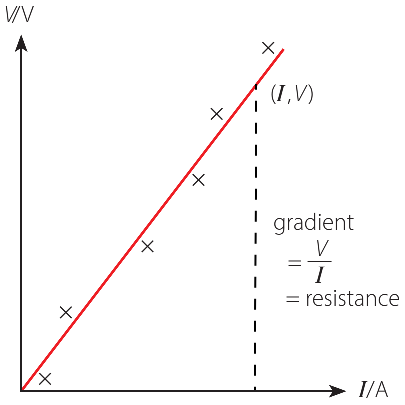


Figure 16.19

LINK

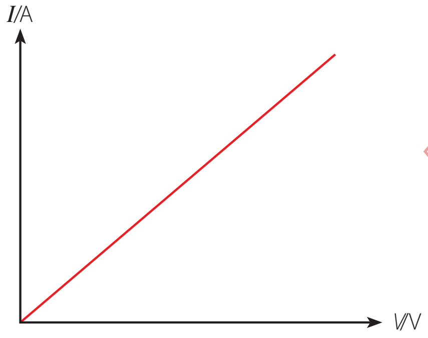
Practical 16C, pp. XX–XX

Ohm's Law

In 1826, German physicist Georg Ohm discovered that when physical conditions (such as temperature) are constant, the electric current in a metallic conductor is directly proportional to the potential difference across it. This relationship is known as *Ohm's Law*.

Ohm's Law states that the current passing through a metallic conductor is directly proportional to the potential difference across it, provided that physical conditions (such as temperature) remain constant.

According to Ohm's Law, the resistance of metallic conductors remains constant under steady physical conditions. Conductors that obey Ohm's Law are known as *ohmic conductors*. Figure 16.20 shows the characteristic I–V graph of an ohmic conductor at a constant temperature.



The graph
- is a straight line that passes through the origin;
- has a constant gradient that is equal to the inverse of the resistance R of the conductor.

Note: Since $\frac{1}{R}$ = constant, R = constant.

Figure 16.20 Characteristic I–V graph of an ohmic conductor

Conductors that do not Ohm's Law are known as *non-ohmic conductors*. The current flowing through non-ohmic conductors does not increase proportionally with the potential difference. In other words, the resistance R of such conductors can vary.

We can differentiate between ohmic and non-ohmic conductors using their I–V graphs. The I–V graphs of non-ohmic conductors are not straight lines. The $\frac{V}{I}$ ratio is not a constant, as non-ohmic conductors do not have constant resistances.

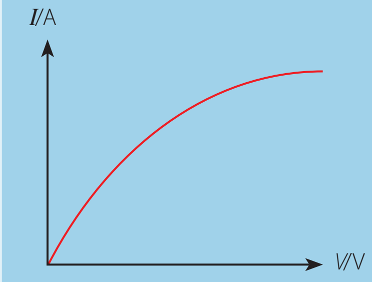
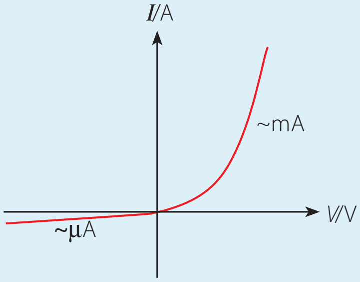
QUICK CHECK

Based on Ohm's law, current increases with increasing potential difference.

True or false?

Table 16.1 shows the characteristic curved I–V graphs of non-ohmic conductors.

Table 16.1 Characteristic I–V graphs of some non-ohmic conductors.

Non-ohmic conductor	Function	I–V graph	Description of graph
Filament lamp 	The filament lamp (or the light bulb) converts electrical energy to light and heat energy.	 	• As the currents increase, the devices generate more heat, and thus their temperatures increase. • As temperature increases, the resistance of the filament lamp increases. • The I–V graph of the filament lamp shows that the resistance $\left(\frac{V}{I}\right)$ increases with temperature.
Semiconductor diode 	A semiconductor diode is a device that allows current to flow in one direction only (the forward direction).	 	• The I–V graph of a semiconductor diode shows that when a p.d. is applied in the forward direction, the current flow is relatively large. This means the resistance is low in the forward direction. • When the p.d. is applied in the reverse direction, there is almost no current flow. This means the resistance is very high in the reverse direction.

Worked Example 16E

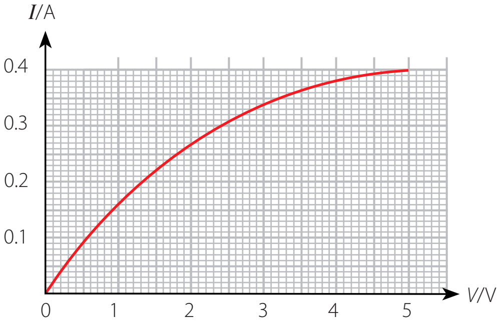


Figure 16.21

Figure 16.21 shows how the current I in the filament of a lamp depends on the potential difference V across it.

(a) Calculate the resistance of the filament when the potential difference is 1.0 V.

(b) Describe how the resistance of the filament changes, if at all, when the p.d. across it increases.

Solution

(a) From the graph, when $V = 1.0$ V, $I = 0.16$ A

By definition,

resistance $R = \frac{V}{I} = \frac{1.0\text{ V}}{0.16\text{ A}} = 6.25\ \Omega \approx 6.3\ \Omega$

(b) The gradient of the graph decreases as the p.d. increases. This means that the ratio $\frac{V}{I}$, which is the resistance R of the filament, increases when the p.d. across it increases.

HELPFUL NOTES

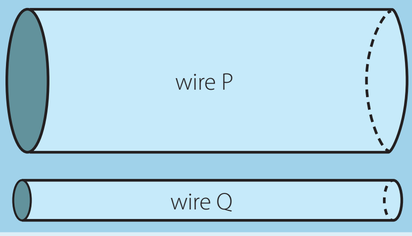
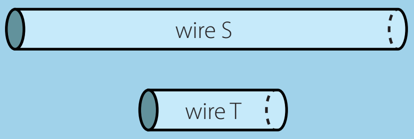
The SI unit of energy is the joule (J).

Resistivity

According to Ohm's Law, the resistance *R* of a metallic conductor is a constant if the physical conditions remain the same. However, if temperature increases, the resistance of the metallic conductor will also increase. Besides temperature, the resistance *R* of a conductor also depends on

- its length *l*;
- its cross-sectional area *A* (or thickness).

Table 16.2 *shows the relationship between resistance and the cross-sectional area and length of a wire.*

Relationship between resistance and cross-sectional area	**Relationship between resistance and length**
	
• Wires P and Q have the same length and are made of the same material. • The cross-sectional area of wire P is larger than that of wire Q.	• Wires S and T have the same cross-sectional area and are made of the same material. • Wire S is longer than wire T.
Experiments have shown that when the cross-sectional area of a wire is increased, its resistance decreases proportionally. In other words, the resistance *R* is inversely proportional to the cross-sectional area *A* when the length and type of material are the same.	Experiments have shown that when the length of a wire is increased, its resistance increases proportionally. In other words, the resistance *R* is directly proportional to the length *l* when the cross-sectional area and type of material are the same.

From Table 16.2, we can conclude the resistance of a metallic wire is

- directly proportional to its length;
- inversely proportional to its cross-sectional area.

Let's Practise 16.5

1 Ⓢ Describe how the resistance of the filament in a lamp varies with temperature.

2 Describe how the resistance of a wire varies with

(a) its length, and

(b) its cross-sectional area.

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

QUICK CHECK

The resistance of a conductor only depends on its length and cross-sectional area.

True or false?

PHYSICS WATCH

Scan this page to explore a simulation on resistivity.

PWB LINK

Practical 16D, pp. XX–XX

TWB LINK

Exercise 16E, pp. XX–XX

16.6 Electrical Energy and Electrical Power

In this section, you will learn the following:

- Understand that electric circuits transfer energy from a source of electrical energy to the circuit components and then into the surroundings.
- Recall and use the equation for electrical power $P = IV$.
- Recall and use the equation for electrical energy $E = IVt$.
- Define the kilowatt-hour (kW h) and calculate the cost of using electrical appliances where the energy unit is the kW h.

How does the energy get around?

Electric circuits transfer energy from a source of electrical energy such as the electrical cell or mains supply to the circuit components and then into the surroundings. Energy is transferred through the movement of electrons around *conducting materials* such as the lamps or resistors. In *insulating materials*, where electrons are not free to move about, there will not be electrical currents. When current flows through electrical components, energy will be dissipated in the form of heat, light or other energy. This energy is then transferred to the surrounding.

Electrical power

The SI unit of power is the **watt (W)**. One watt is equal to one joule per second. To represent large quantities of power, we often introduce prefixes such as kilo or mega. Therefore, large quantities of power are expressed in kilowatt or the megawatt.

Since power is the amount of work done per second, power P can be given by

$P = \frac{(W \text{ or } E)}{t}$ …(1) where P = power (in W)
W = work done (in J)
E = electrical energy converted (in J)
t = time (in s)

Earlier in this chapter, you have learnt the equations relating potential difference, work done, charge and current.

$I = \frac{Q}{t}$ …(2) where I = current (in A)
Q = charge (in C)
t = time (in s)
$V = \frac{W}{Q}$ V = potential difference (in V)
$W = QV$ …(3) W = work done (in J)

Substituting (3) into (1), we get

$\mathrm{P} = \frac{QV}{t}$ …(4)

Since, $I = \frac{Q}{t}$ from (2),

$P = IV$

We also know that from (1), the electrical energy E can be expressed as follows:

$E = Pt = IVt$

HELPFUL NOTES

The SI unit of energy is the joule (J).

Calculating the cost of electricity consumption

An electricity meter measures a household's electricity consumption. The amount of electrical energy transferred to an appliance depends on its *power*, and on the duration of *time* it is switched on for. The joule is a tiny amount of energy and charging for each joule (or large numbers of joules) makes energy bills difficult to understand. Therefore, the kilowatt hour (kWh) is used as a unit of energy for calculating electricity bills.

1 kWh is the electrical energy converted by a 1 kW appliance used for 1 hour.

For example, a common household electrical heater has a power rating of approximately 2 kW. When it is being used for 1 hour, the energy consumption is 2 kW h. A filament lamp has a power rating of approximately 0.1 kW. When it is being used for 1 hour, the energy consumption is 0.1 kW h.

QUICK CHECK

The watt is the SI unit of power

True or false?

Worked Example 16F

If a power supply company charges 27 cents for each kW h of electrical energy used, calculate the total cost of using a 3 kW electric kettle for 20 minutes and a 100 W filament bulb for 5 hours.

Solution

Electrical energy used by electric kettle,

$E_1 = P \times t = 3\ \text{kW} \times \frac{20}{60}\ \text{h} = 1\ \text{kW h}$

Power P of the filament bulb $= 100\ \text{W} = 0.1\ \text{kW}$

Electrical energy used by the bulb,

$E_2 = 0.1\ \text{kW} \times 5\ \text{h} = 0.5\ \text{kWh}$

$$
\begin{aligned}
\text{Total energy used } E &= E_1 + E_2 \\
&= 1\ \text{kWh} + 0.5\ \text{kWh} \\
&= 1.5\ \text{kWh}
\end{aligned}
$$

$$
\begin{aligned}
\text{Hence, the total cost} &= 1.5\ \text{kWh} \times 27\ \text{cents} \\
&= 40.5\ \text{cents} \\
&= \$0.41
\end{aligned}
$$

Let's Practise 16.6

1 A 240 V mains power supply delivers a current of 9.0 A through an air conditioner. Calculate the power supplied in kilowatts.

2 The air conditioner in question **1** is used for 1.5 hours each day for 30 days. The electricity tariff is $0.27 per kWh. Calculate the cost of using the air conditioner for this period of time.

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

TWB LINK

Exercises 16F–16G, pp. XX–XX

Exercise 16H Let's Reflect. p. XX

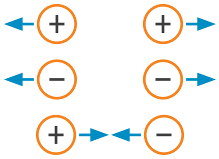
Let's Map It

CHARGE Q
(SI unit: C)

can be categorised into

Positive and negative charges

interacts as follows

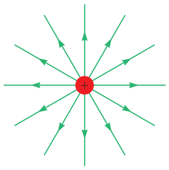


- Like charges repel
- Unlike charges attract

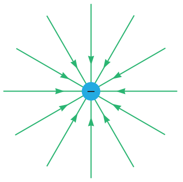
generates

Electric field

- Is a region in which an electric charge experiences a force



Electric field lines
- Directed away from a positive charge
- Directed towards a negative charge



moving charges produce

Electric current *I* (SI unit: A)

where

$I = \frac{Q}{t}$
where
t = time

Electricity

Electrical energy
$E = IVt$

Power
$P = IV$

non-moving charges produce

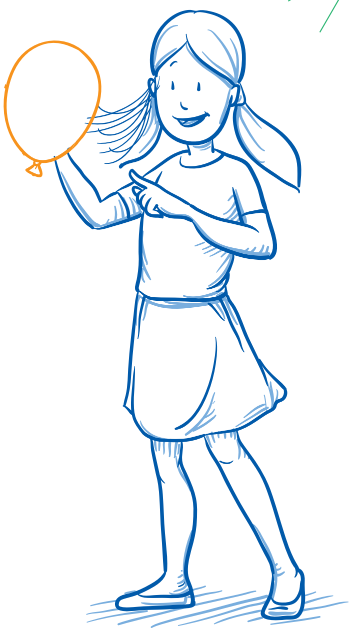
Static electricity

is due to the build up of charges on the surfaces of

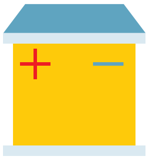
Electrical insulators

for example through

Friction



related to



Electromotive force E (SI unit: V)

where

$E = \frac{W}{Q}$
where
W = work done by source to drive a unit charge around the circuit

Potential difference V (SI unit: V)

where

$V = \frac{W}{Q}$
where
W = work done to drive a unit charge through a component

Related to

Resistance R (SI unit: Ω)

- Resistance is directly proportional to the length of the conductor
- Resistance is inversely proportional to the cross-sectional area of the conductor

where

$R = \frac{V}{I}$

Let's Review

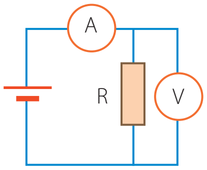
Section A: Multiple-choice Questions

1 Ⓢ A resistor converts 350 J of electrical energy to other forms of energy. What is the amount of charge that flows through it when a p.d. of 7 V is applied across it?

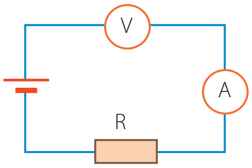
A 0.20 C
B 50 C
C 350 C
D 2450 C

2 Which of the following set-ups cannot be used to determine the resistance of resistor R?

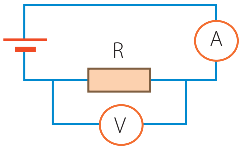
A



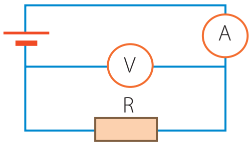
B



C



D



3 The ammeter reading in the circuit below is 1 A. Which of the following could be the voltmeter reading and resistance of the resistor?

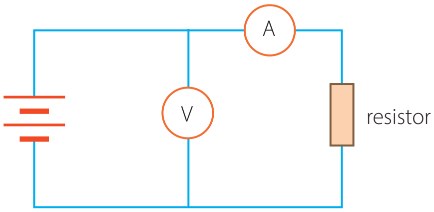


Figure 16.22

	Voltmeter reading	Resistance
A	1 V	2 Ω
B	4 V	0.25 Ω
C	10 V	10 Ω
D	12 V	6 Ω

4 Which of the following can be used to calculate electrical power?

A potential difference ÷ current
B potential difference × current
C current × resistance
D potential difference ÷ resistance

5 A small heater has a rating of 15 V, 4 A. How much energy does it consume if it is turned on for 2 minutes?

A 7.5 J
B 120 J
C 450 J
D 7200 J

6 The kilowatt-hour is a unit of _______.

A power
B energy
C charge
D voltage

7 A person uses a 3 kW oven for 1 hour and a 2 kW air conditioner for 6 hours. Calculate the total cost if 1 kWh of electrical energy costs 5.0 cents.

A 15 cents
B 30 cents
C 60 cents
D 75 cents

Section B: Short-answer and Structured Questions

1 Figure 16.23 shows the electrical information on the charger of a laptop computer.

Figure 16.23

(a) Based on the information in Figure 16.23, show that the output current of this charger is 4.74 A.

(b) Calculate the amount of electrical energy (in kWh) consumed in one month (30 days), if the laptop is connected to the charger 6 hours a day.

Let's Review

2 Two resistance wires, A and B, are connected in parallel to a power source of e.m.f. 5.0 V. Figure 16.24 shows the voltage–current relationship of the two wires.

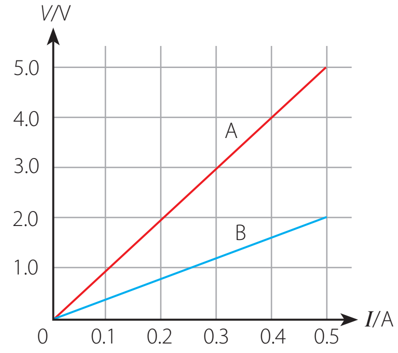


Figure 16.24

(a) Calculate the resistance of wire A and wire B.

(b) Ⓢ If both wires are made of the same material and have the same thickness, what can you conclude about their lengths? Explain your answer.

(c) Calculate the currents flowing through wire A and wire B.

3 **(a)** Ⓢ What is the relationship between current I and charge Q? State their respective SI units.

(b) Ⓢ A positively-charged sphere carrying a charge of 0.4 mC is earthed using a wire.

- **(i)** Calculate the average current flowing through the wire if the time taken to discharge the sphere is 0.2 s.
- **(ii)** Draw a labelled diagram showing the direction of conventional current flow.

4 **(a)** What do you understand by the terms current and potential difference?

(b) Ⓢ A potential difference of 12 V causes 2.0×10^{20} electrons to pass a point in awire in 1.0 minute. Calculate the

- **(i)** amount of charge that passes the point in 1.0 minute, given that the charge of each electron is 1.6×10^{19} C;
- **(ii)** electric current in the wire;
- **(iii)** resistance of the wire.

5 A light bulb is connected to a 6.0 V e.m.f. supply. An experiment is carried out to measure the current flowing through the bulb as the potential difference across it is varied. The results are shown in Table 16.3.

Table 16.3

V/V	I/mA
0	0
1.0	0.5
2.0	1.1
3.0	1.6
4.0	2.1
5.0	2.5

(a) Plot a graph of potential difference against current, using the values from Table 16.3.

(b) Using the graph drawn in (a), determine the resistance of the bulb when the potential difference across it is 2.5 V.

(c) The 6.0 V e.m.f. supply is replaced with a 10.0 V e.m.f. supply.

- **(i)** Determine the potential difference applied across the bulb if the current flowing through it is 0.32 mA.
- **(ii)** Explain how it is possible for a 10.0 V e.m.f. supply to produce a current of 0.32 mA.

6 **(a)** The V–I graphs for two conductors, A and B, at a steady temperature are shown in Figure 16.25. Deduce the resistances of A and B.

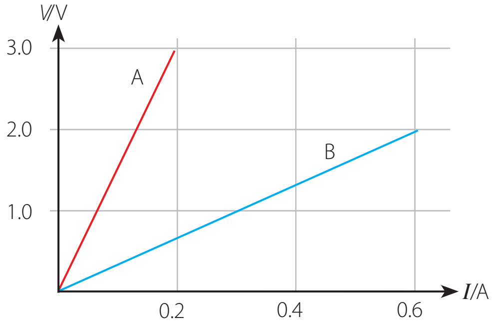


Figure 16.25

(b) Ⓢ Both conductors are made of the same material and have the same length.

- **(i)** Which conductor is thicker?
- **(ii)** What is the ratio of their cross-sectional areas?

(c) Do the conductors A and B obey Ohm's Law? Explain your answer.

(d) Ⓢ Sketch the graphs of current I against p.d. V for a

- **(i)** filament lamp;
- **(ii)** semiconductor diode.

CHAPTER 17

Electrical Circuits and Electrical Safety

PHYSICS WATCH

Scan this page to watch a clip on using electricity to light up our cities.

The photo shows China's city of Shenzen at night during a light show. Complex electrical circuits are used to light up the buildings and streets. How did we progress from the first dim light bulbs to the amazingly colourful cityscapes we see today?

When the filament lamp was invented in the late 19th century, no one really knew how it would revolutionise the world the way it did. People could read, play, work, socialise and travel the streets in more relative safety. They don't have to rely on burning material and risk burning everything down to the ground.

QUESTIONS

- What electrical components are needed in the electrical circuits to light up the city?
- What are some causes of power blackout in a city that are related to electrical circuits?
- What can be done to prevent such a power blackout?

17.1 Circuit Diagrams and Components

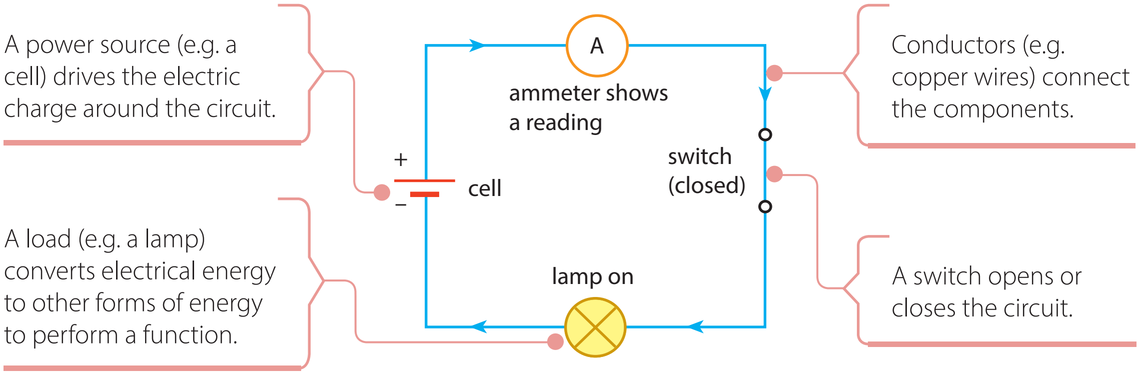
In this section, you will learn the following:

- Draw and interpret circuit diagrams containing common circuit components and know how these components behave in the circuit.
- **S** Draw and interpret circuit diagrams containing diodes and light-emitting diodes (LEDs) and know how these components behave in the circuit.

How to draw and interpret circuit diagrams?

Drawing circuit diagrams

To help us solve problems involving electric circuits, it is useful to learn how to draw circuit diagrams. Circuit diagrams represent electric circuits. Figure 17.1 shows the four main components of an electric circuit.



A power source (e.g. a cell) drives the electric charge around the circuit.

A load (e.g. a lamp) converts electrical energy to other forms of energy to perform a function.

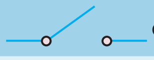
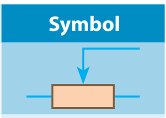
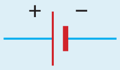
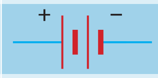
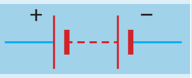
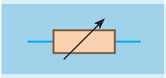
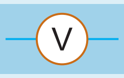
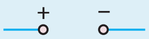
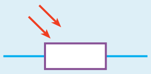
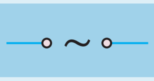
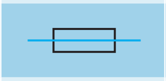
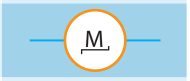
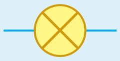
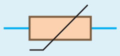
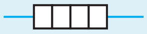
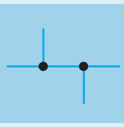
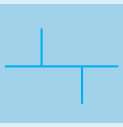
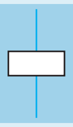
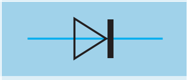
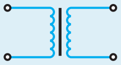
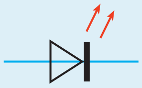
Conductors (e.g. copper wires) connect the components.

A switch opens or closes the circuit.

Figure 17.1 *Main components of an electric circuit*

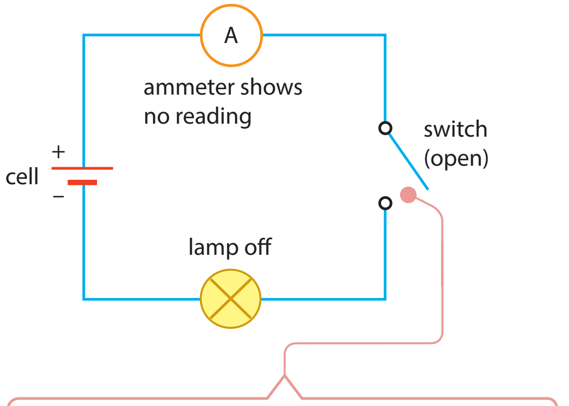
Table 17.1 shows the circuit symbols for some other common circuit components.

Table 17.1 *Circuit symbols*

Device	Symbol	Device	Symbol	Device	Symbol
Switch	 or 	Potential divider		Galvanometer	
Cell		Fixed resistor		Ammeter	
Battery	 or 	Variable resistor (rheostat)		Voltmeter	
D.c. power supply		Light-dependent resistor (LDR)		Generator	
A.c. power supply		Fuse		Motor	
Lamp		NTC thermistor		Heater	
Wires joined	 or 	Relay		Magnetising coil	
				S Diode	
Wires crossed		Transformer		**S** Light-emitting diode (LED)	

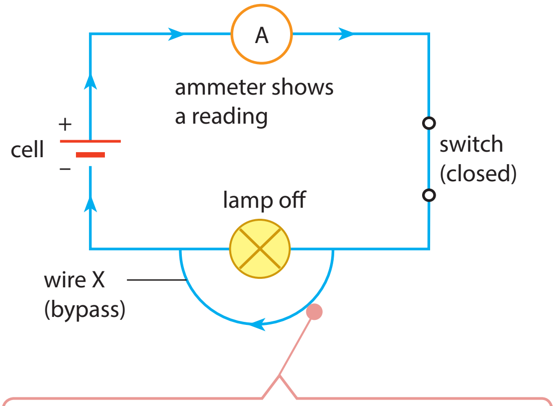
Interpreting circuit diagrams

It is important to be able to understand different arrangements of circuit symbols in circuit diagrams. Figures 17.2 and 17.3 show how we can interpret two circuit diagrams.



- The lamp is unable to light up as the switch is open, i.e., there is a break in the circuit.
- A break in the circuit means that current cannot flow through it.
- Besides open switches, breaks in circuits can occur due to loose connections, or missing or broken wires.

Figure 17.2 *Open circuit*



- The circuit is closed, yet the lamp remains unlit. This is because there is an alternative path of lower resistance (wire X) for current to flow through.
- Therefore, the current does not flow through the lamp.
- We call this a short circuit.

Figure 17.3 *Short circuit*

Circuit components are put to use for diverse purposes. Table 17.2 states the uses of some of these components. They are further described in various places in this chapter and the next.

Table 17.2 *Uses of some circuit components*

Component	Uses	See section
Potential divider	• Provide a fraction of a cell's e.m.f. to another part of a circuit • Can be used in sensing circuits	17.4
NTC thermistors	• Used as temperature sensors In temperature controlled circuits	17.4
Fuses	• For circuit safety	17.5
Generator	• Converts kinetic energy into electrical energy	18.2
Magnetising coil/relay	• Electromagnets and associated uses	18.3
Motors	• Converts electrical energy into kinetic energy	18.5
Transformer	• Transforms a potential difference to either a higher or lower potential difference with high efficiency	18.6

Why is a diode useful?

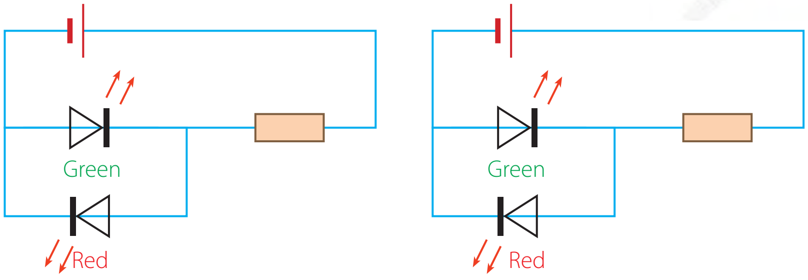
Some components, such as filament lamps, work equally well whether alternating current (a.c.) or direct current (d.c.) flows into them.

Other components, particularly many electronic parts, will only work with specific d.c. voltages and may break if subjected to a.c. voltages.

Diodes are components that allow current to flow through them in one direction only. Arrangements of diodes can indicate the direction of current flow so that appropriate action can be taken or can convert a.c. into d.c.

Current direction indication

Consider a dry cell which is connected to a light emitting diode (LED). Figure 17.4 shows how an arrangement of two diodes can show which direction the current is flowing. If the dry cell is connected in the first orientation, the green LED will light up. If the dry cell is reversed, then the red LED will light up.



Green LED lights up

Red LED lights up

Figure 17.4 LEDs indicate the direction of current flowing in a circuit

A.c. rectification

Figure 17.5(a) shows a resistor connected to an a.c. power supply. The current-time graph below it shows the direction and magnitude of current through the resistor. In Figure 17.5(b)(i), the diode is the correct way around to allow current through. In Figure 17.5(b)(ii), the diode will not allow current to flow as shown by the horizontal lines in the graph below it. If a component in an electrical circuit is sensitive to current direction, the presence of a diode protects the component.

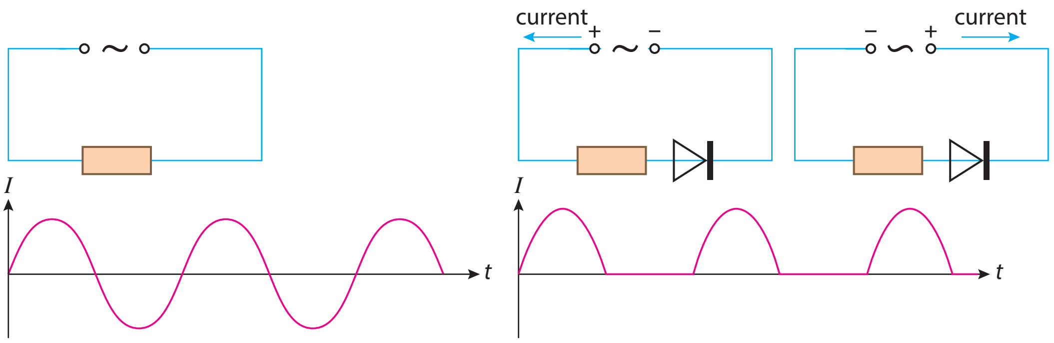
ENRICHMENT THINK

This method of a.c. rectification is wasteful as the current is only useful for 50% of the time. It is known as *half-wave rectification*. The rest of the time, the energy is merely dissipated as heat.

How could an arrangement of four diodes provide *full-wave rectification*, so that the design is more efficient?

(a) A.c power supply connected to a resistor

(b) A.c power supply connected to a resistor and a diode



A.c. current not rectified

A.c. current rectified

Figure 17.5 Rectified and unrectified a.c. current

WORD ALERT

Rectified: to set right, i.e., setting the current to flow in one direction

Let's Practise 17.1

1 Describe what is meant by an open circuit.

2 S Describe the basic function of a diode.

3 S Draw an electrical circuit that lights

  (a) a red LED when current is flowing in one direction around the circuit;

  (b) a green LED when current flows in the opposite direction.

4 S Explain a use of diodes in a practical circuit.

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

LINK TWB

Exercise 17A, pp. XX-XX

17.2 Series Circuits

In this section, you will learn the following:

- Know how to construct and use series circuits.
- Calculate the combined e.m.f. of several sources in series.
- Know that the current at every point in a series circuit is the same.
- S Explain that the sum of the currents into a junction is the same as the currents out of the junction.
- S Recall and use in calculations, the fact that the total p.d. across the components in a series circuit is equal to the sum of the individual p.d.s across each component.
- Calculate the combined resistance of two or more resistors in series.

In this chapter, you will learn how series and parallel arrangements of circuits affect current, potential difference and resistance.

In a **series circuit**, the components are connected one after another in a single loop (Figure 17.6). A series circuit has only one path through which electric charge can flow.

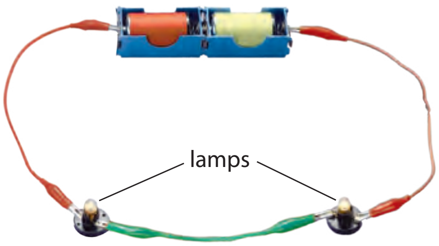


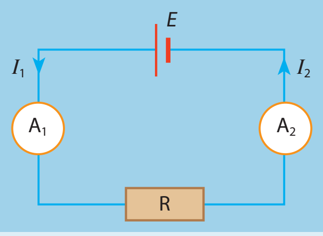
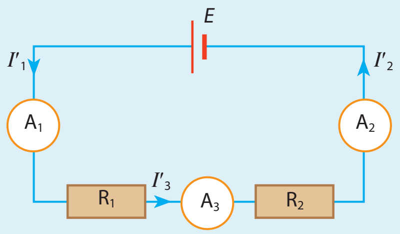
Figure 17.6 *Two lamps connected in series*

Notice that in Figure 17.6 there are two dry cells in series. When cells are arranged in series, the resultant e.m.f. is the sum of all the e.m.f.s of the cells. For example, if both cells in Figure 17.6 had an e.m.f. of 1.5 V, then the combined e.m.f. would be 3.0 V.

Does current in a series circuit change?

Table 17.3 shows two electric circuits that can be set up to measure the current at various points in a series circuit.

Table 17.3 *Current in series circuits*

Circuit	Ammeter reading	Conclusion
Single resitor R  	$I_1 = I_2$	The same current flows into and out of resistor R.
Resistors R_1 and R_2 in series  	$I'_1 = I'_2 = I'_3$	The same current flows through R_1 and R_2.

HELPFUL NOTES

The currents in the two circuits in Table 17.3 are not the same. They will be the same if $R = R_1 + R_2$. You will learn the effect of combining resistors in series later.

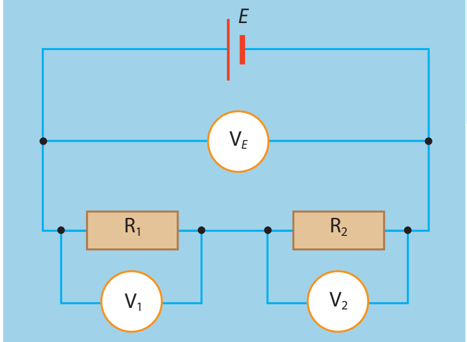
We can see that *the current at every point in a given series circuit is the same.*

S No charge can escape or be introduced at any point in the circuit. This is known as the *conservation of charge*. It explains why the current through components in series must be the same.

How to calculate total p.d across a series circuit?

Table 17.4 shows an electric circuit in which the resistors are arranged in series. It is set up to measure the potential difference across the resistors in the circuit.

Table 17.4 *P.d. across resistors in a series circuit.*

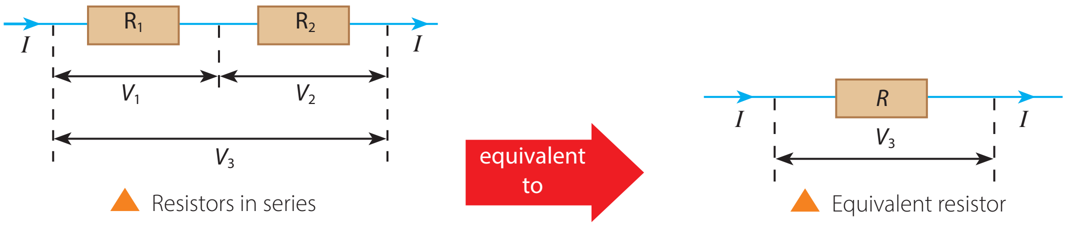
Circuit	Ammeter reading	Conclusion
Resistors R_1 and R_2 in series  	$V_E = V_1 + V_2$	The p.d. V_E across the whole circuit is equal to the sum of the p.d.s across R_1 and R_2.
	$E = V_E$	The e.m.f. E of the electrical source is equal to V_E.

For *n* resistors placed in series, the p.d. V_E across the whole circuit (i.e. across all of the components) is equal to the sum of the p.d.s across each component.

$$\boldsymbol{V_E = V_1 + V_2 + \ldots + V_n}$$

How to calculate combined resistance in series?

Figure 17.7 shows how we can find the combined or effective resistance *R* of two resistors, R_1 and R_2, that are connected in series.



- The current I that flows through R_1 and R_2 is the same because they are connected in series.
- Since $V = IR$, $V_1 = IR_1$

  $V_2 = IR_2$
- From the equation $V_E = V_1 + V_2$, we know that

  $V_3 = V_1 + V_2 = IR_1 + IR_2 = I(R_1 + R_2)$

  Therefore, $\frac{V_3}{I} = R_1 + R_2$.

- The resistors R_1 and R_2 can be replaced by a single resistor R with a resistance *R*.
- The resistor R has the potential difference or voltage V_3 across it and the current I flowing through it.

  $\frac{V_3}{I} = R$

$R = R_1 + R_2$

Figure 17.7 *Combined resistance of resistors in series*

For *n* resistors in placed in series, the combined resistance is the sum of all the resistances.

$$\boldsymbol{R = R_1 + R_2 + \ldots + R_n}$$

Worked Example 17A

Figure 17.8 shows three resistors of values 2 Ω, 4 Ω and 6 Ω connected in series to a 6 V dry cell.

(a) Calculate the combined resistance of the three resistors.

(b) What is the current measured by **(i)** ammeter A_1; **(ii)** ammeter A_2?

(c) Calculate the p.d. across each resistor.

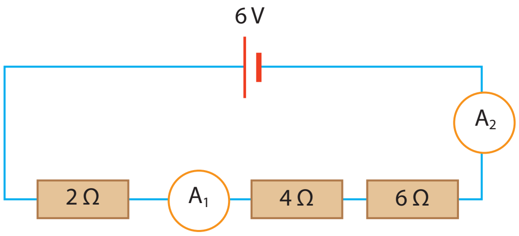


Figure 17.8

Solution

(a) Combined resistance $R = R_1 + R_2 + R_3 = (2 + 4 + 6)\ \Omega = 12\ \Omega$

(b) **(i)** Since V = 6 V and combined resistance $R = 12\ \Omega$,

$$I = \frac{V}{R} = \frac{6\text{ V}}{12\ \Omega} = 0.5\text{ A}$$

The current measured by ammeter A_1 is 0.5 A.

(ii) Since the circuit is connected in series, the current measured by ammeter A_2 is also 0.5 A.

(c) Let V_1, V_2 and V_3 be the p.d.s across the 2 Ω, 4 Ω and 6 Ω resistors respectively.

Using $V = IR$,

$V_1 = IR_1 = 0.5\text{ A} \times 2\ \Omega = 1\text{ V}$

$V_2 = IR_2 = 0.5\text{ A} \times 4\ \Omega = 2\text{ V}$

$V_3 = IR_3 = 0.5\text{ A} \times 6\ \Omega = 3\text{ V}$

Note: (1) $V_1 + V_2 + V_3 = 6\text{ V}$ = e.m.f. of the cell

(2) The p.d. across a resistor of a larger resistance in a series circuit is greater than the p.d. across a resistor of a smaller resistance.

QUICK CHECK

The combined resistance of resistors in series is the sum of all of the resistances.

True or false?

17.3 Parallel Circuits

In this section, you will learn the following:

- Know how to construct and use parallel circuits.
- State that, for a parallel circuit, the current from the source is larger than the current in each branch.
- **S** Recall and use in calculations, the fact that the sum of the currents into a junction in a parallel circuit is equal to the sum of the currents that leave the junction.
- **S** Recall and use in calculations, the fact that the p.d. across an arrangement of parallel resistors is the same as the p.d. across one branch in the arrangement of the parallel resistors.
- **S** Calculate the combined resistance of two resistors in parallel.
- State that the combined resistance of two resistors in parallel is less than that of either resistor by itself.
- State the advantages of connecting lamps in parallel in a lighting circuit.

In a **parallel circuit**, the components are connected to the e.m.f. source in two or more loops (Figure 17.9). A parallel circuit has *more than one path through which electric charge can flow*.

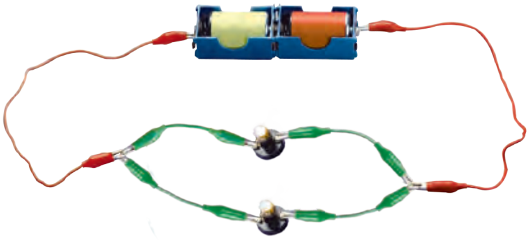


Figure 17.9 *Two lamps connected in parallel*

QUICK CHECK

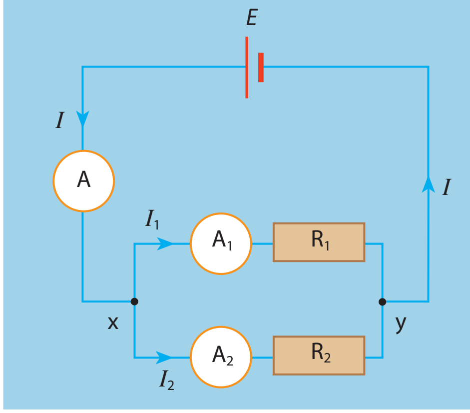
The current is the same at different points of a parallel circuit.

True or false?

How does current flow in a parallel circuit?

Table 17.5 shows an electric circuit in which the resistors are arranged in parallel. It is set up to measure the current at various points in the circuit.

Table 17.5 *Currents at various points of a parallel circuit*

Circuit	Ammeter reading	Conclusion
Resistors R_1 and R_2 in parallel 	$I = I_1 + I_2$	• The current I flowing from the cell splits at junction x into I_1 and I_2. • Currents I_1 and I_2 later recombine into I at junction y.

We can see that *the current from the source is larger than the current in each branch*.

For *n* branches in parallel, the main current ***I*** is the sum of all the currents in each branch.

$$I = I_1 + I_2 + \dots + I_n$$

LINK

Recall that $Q = It$ and so $I = \frac{Q}{t}$.

Refer to Chapter 16.

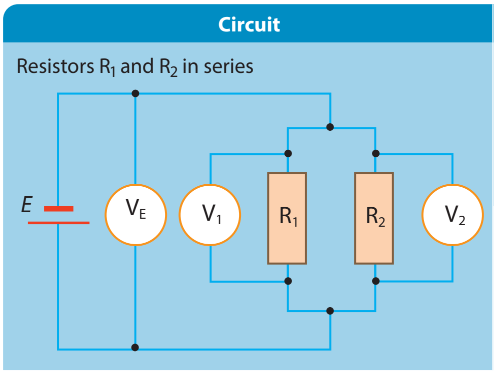
In other words, in a parallel circuit, the sum of the individual current in each of the parallel branches is equal to the main current flowing into or out of the parallel branches. This is because charge is conserved and current is the rate of flow of charge. When a number of electrons enter junction x, the same number of electrons must leave junction x. Similarly, when a number of electrons enter junction y, the same number of electrons must leave junction y.

Does p.d across a parallel circuit change?

Table 17.6 shows an electric circuit in which all the resistors are arranged in parallel. It is set up to measure the p.d across each resistor, and the p.d. across all the resistors in the circuit.

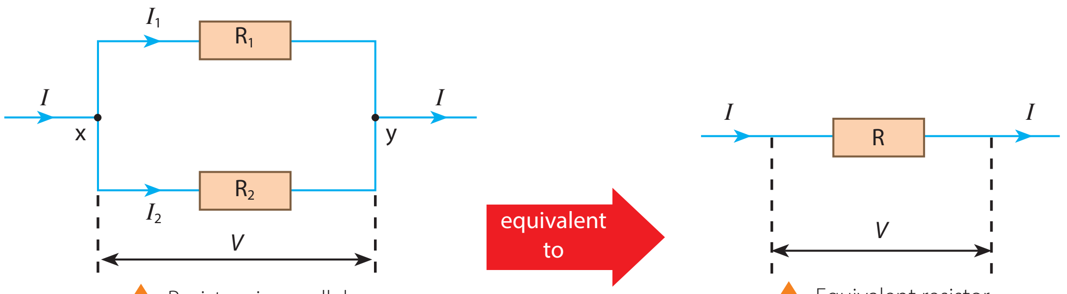
In a parallel circuit, the p.d.s across separate parallel branches are the same.

Table 17.6 *P.d across resistors in a paralle circuit*

Circuit	Ammeter reading	Conclusion
Resistors R_1 and R_2 in series 	$V_E = V_1 = V_2$	The p.d. V_E across the whole circuit is equal to the sum of the p.d.s across R_1 and R_2.
	$E = V_E$	The e.m.f. E of the electrical source is equal to V_E.

How to calculate combined resistance in parallel?

Figure 17.10 shows how we can find the combined resistance *R* of two resistors, R_1 and R_2, that are connected in parallel.



Resistors in parallel

Equivalent resistor

- The current I is split into I_1 and I_2 because R_1 and R_2 are connected in parallel.
- Since $I = \frac{V}{R}$, $I_1 = \frac{V}{R_1}$

  $I_2 = \frac{V}{R_2}$
- From the equation $I = I_1 + I_2$, we know that

  $I = \frac{V}{R_1} + \frac{V}{R_2}$

- The resistors R_1 and R_2 can be replaced by a single resistor R with a resistance *R*.
- The resistor R has the p.d. *V* across it and the current I flowing through it.

  $I = \frac{V}{R}$

$$\frac{V}{R} = \frac{V}{R_1} + \frac{V}{R_2}$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

Figure 17.10 *Combined resistance of resistors in parallel*

For two resistors in parallel,

$$\boldsymbol{\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}}$$

In other words, the **reciprocal** of the combined resistance of resistors in parallel, $\frac{1}{R}$, is equal to the sum of the reciprocal of all the individual resistances.

WORD ALERT

Reciprocal: the reciprocal of a number is obtained by dividing 1 by that number

Worked Example 17B

Figure 17.11 shows three resistors of values 3 Ω and 6 Ω connected in parallel to a 6 V dry cell.

(a) Calculate the combined resistance of the two resistors.

(b) What is the p.d. across each resistor?

(c) What is the current measured by ammeters A_1 and A_2?

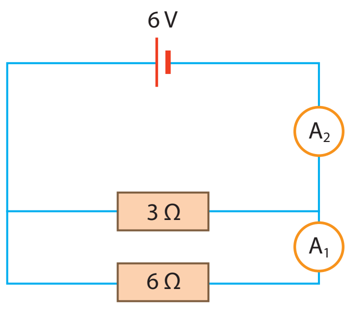


Figure 17.11

Solution

(a) $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{3\,\Omega} + \frac{1}{6\,\Omega} = \frac{3}{6\,\Omega}$

$\therefore R = 2\,\Omega$

(b) As the resistors are in parallel, the p.d. across each resistor is equal, i.e., 6 V.

Using $I = \frac{V}{R}$,

Current through the 6 Ω resistor $= \frac{6\text{V}}{6\ \Omega} = 1\text{ A}$

Current measured by ammeter $A_1 = 1\text{ A}$

Current through the 3 Ω resistor $= \frac{6\text{V}}{3\ \Omega} = 2\text{ A}$

Current measured by ammeter $A_2 = 2\text{ A} + 1\text{ A} = 3\text{ A}$

Alternatively, since $V = 6\text{ V}$ and combined resistance $R = 2\ \Omega$, current measured by ammeter $A_2 = \frac{6\text{ V}}{2\ \Omega} = 3\text{ A}$

QUICK CHECK

A circuit with just a resistor and a dry cell has a current of 1.2 A.

A second resistor is put in parallel with the first. The current through the dry cell remains the same.

True or false?

How can two resistors in parallel have less resistance than one resistor?

When another resistor is added in parallel to a resistor in a circuit, the combined resistance of the circuit *decreases*. It is *less than the resistance of either resistor by itself*. We can explain this using Figure 17.12. In a parallel circuit, the p.d. remains the same across each branch. When R_2 is connected in parallel to R_1, as shown in Figure 17.12, the current I in the circuit increases by I_2 (since $I = I_1 + I_2$).

The combined resistance $R\left(= \frac{V_E}{I}\right)$ therefore decreases. Connecting additional resistors in parallel to R_1 and R_2 further increases the current I. Thus, the combined resistance R is lowered.

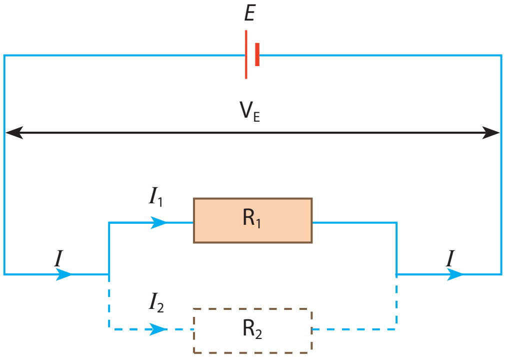


Figure 17.12 *Connecting an additional resistor in parallel to R_1 provides an additional path for the current to flow. Thus, the combined resistance is lowered.*

HELPFUL NOTES

Parallel connections can be represented in different ways in a circuit diagram. For example, a voltmeter connected in parallel with a circuit component (e.g. a cell) can be represented in the two ways shown in Figure 17.13.

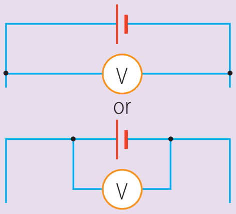
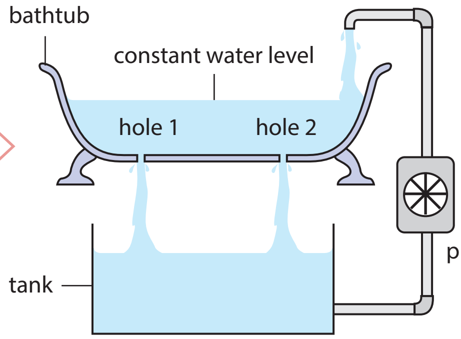


Figure 17.13 *Representing a voltmeter connected in parallel with a cell*

To understand the flow of current in a parallel circuit better, we can use the water-flow model (Figure 17.14), in which the

- flow of water represents current;
- water level in the bathtub represents potential difference;
- pump represents an electrical source.

- When hole 1 is unplugged, water flows out slowly.
- The pump is turned on to maintain a constant level of water in the bathtub.
- This is similar to an electrical source driving a current through a single resistor in a circuit.



- When holes 1 and 2 are unplugged, water flows out of the bathtub faster.
- The pump has to work faster to maintain the level of water in the bathtub.
- This is similar to an electrical source which is connected to two resistors in parallel in a circuit. The electrical source has to provide a larger power to drive a larger current to maintain the p.d.

Figure 17.14 *The water-flow model can represent current flow in a parallel circuit.*

So, in this model, having two holes in the bathtub means that the flow of water has increased. Thus, in a parallel electric circuit, the combined resistance must have decreased to cause a larger current flow for the same e.m.f.

Connecting lamps in series or parallel

What are the advantages of arranging circuit components in series or in parallel? To answer this question, let us consider the effects of different lamp arrangements on current (Figure 17.15). The lamps shown in Figure 17.15 are identical and each have a resistance of *R*.

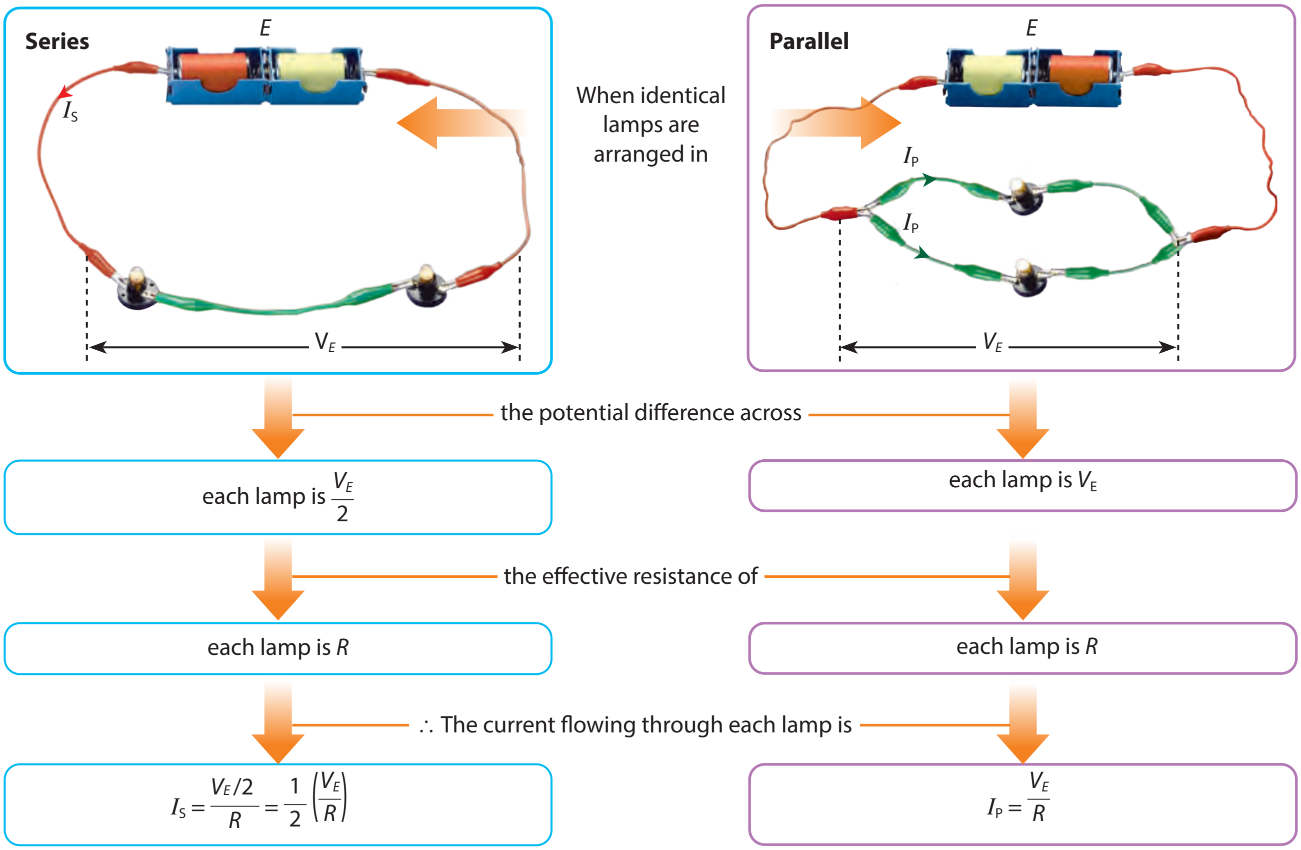


Figure 17.15 *Current in series and parallel arrangements*

What are the advantages and disadvantages of parallel circuits?

Advantages

- From Figure 17.15, it can be seen that the current flowing through each lamp in the series circuit is half that of the current flowing through each lamp in the parallel circuit. Therefore, lamps connected in parallel glow more brightly than when connected in series.
- When a lamp in a parallel circuit blows, the other lamps in the circuit will still work. This is because each parallel branch forms a complete circuit.

Disadvantages

- From Figure 17.15, it can be seen that the current flowing through the battery in the parallel circuit is $2I_P$, which is four times the current I_s in the series circuit. This means that the source in a parallel circuit provides a larger power and is depleted more quickly than in a series circuit.

A-Z **WORD ALERT**

Blows: burns out
Depleted: used up

Resistors in series and parallel in a circuit

The electric circuits in electrical devices typically have resistors in both series and parallel arrangements. How do we calculate the combined resistance? How do we find the current and p.d. across each resistor? The following worked examples will show us how.

Worked Example 17C

Calculate the combined resistance of the arrangements in Figures 17.16 and 17.17.

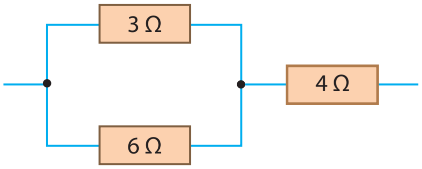


Figure 17.16

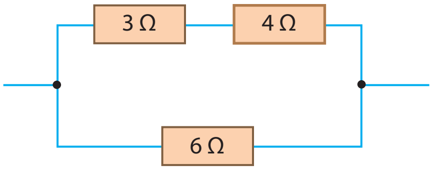


Figure 17.17

Solution

For Figure 17.16, the 3 Ω and 6 Ω resistors are in parallel.

Therefore, $\frac{1}{R} = \frac{1}{3\,\Omega} + \frac{1}{6\,\Omega} = \frac{3}{6\,\Omega}$. Their combined resistance $R = 2\,\Omega$.

Now, consider the circuit as comprising a 2 Ω resistor and a 4 Ω resistor in series (Figure 17.18).

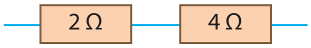


Figure 17.18

Hence, the combined resistance $R_T = 2\,\Omega + 4\,\Omega = 6\,\Omega$.

For Figure 17.17, the 3 Ω and 4 Ω resistors are in series.

Therefore, their combined resistance is $R = 3\,\Omega + 4\,\Omega = 7\,\Omega$.

Now, consider the circuit as comprising a 7 Ω resistor and a 6 Ω resistor in parallel (Figure 17.19).

Hence, $\frac{1}{R_T} = \frac{1}{7\,\Omega} + \frac{1}{6\,\Omega} = \frac{13}{42\,\Omega}$.

The combined resistance $R_T = 3.2\,\Omega$.

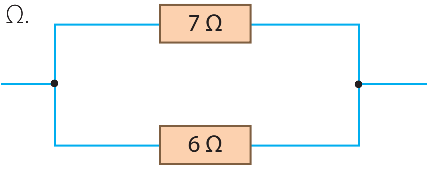


Figure 17.19

Worked Example 17D

The cell in Figure 17.20 has an e.m.f. of 6 V. Calculate the

(a) combined resistance of the two resistors connected in parallel;

(b) current I_1 from the cell;

(c) p.d.s across XY and YZ;

(d) currents I_2 and I_3.

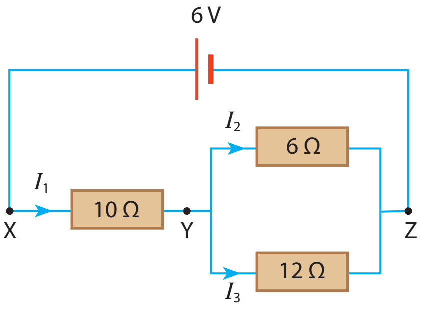


Figure 17.20

Solution

(a) Since the 6 Ω and 12 Ω resistors are in parallel, their combined resistance R is

$$\frac{1}{R} = \frac{1}{6\,\Omega} + \frac{1}{12\,\Omega}$$

$$R = \left(\frac{1}{6} + \frac{1}{12}\right)^{-1}\,\Omega = 4\,\Omega$$

(b) Now, consider the circuit as comprising a 10 Ω resistor and a 4 Ω resistor in series (Figure 17.21).

$\therefore$ The combined resistance R_T
$= 10\ \Omega + 4\ \Omega = 14\ \Omega$

Since the e.m.f. $E = 6$ V,

the current $I_1 = \dfrac{V}{R_T} = \dfrac{6\text{V}}{14\ \Omega} = 0.43$ A

(c) Let R_1 be the 10 Ω resistor.

Since $I_1 = 0.43$ A, then p.d. across XY is

$V_{XY} = I_1R_1 = 0.43\text{ A} \times 10\ \Omega = 4.3$ V

Since the circuit in Figure 17.20 is connected in series,

e.m.f. $E = V_{XY} + V_{YZ}$

$\therefore V_{YZ} = E - V_{XY} = 6\text{ V} - 4.3\text{ V} = 1.7$ V

(d) Since $V_{YZ} = 1.7$ V,

$I_2 = \dfrac{V_{YZ}}{R_2} = \dfrac{1.7\text{ V}}{6\ \Omega} = 0.28$ A

$I_3 = \dfrac{V_{YZ}}{R_3} = \dfrac{1.7\text{ V}}{12\ \Omega} = 0.14$ A

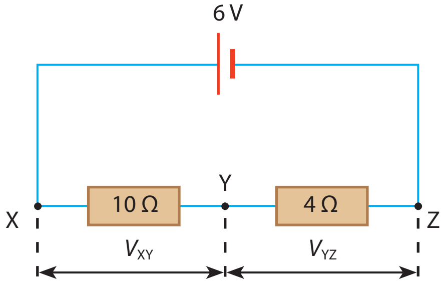


Figure 17.21

LINK

Practical 17, pp. XX–XX

Let's Practise 17.2 and 17.3

1 Figure 17.22 shows a 5 V cell connected to two resistors in parallel. The current flowing through resistor R is 0.2 A. Calculate
  (a) the resistance of resistor R;
  (b) the currents I_1 and I_2;
  (c) S the combined resistance of resistor R and the 50 Ω resistor;
  (d) the combined resistance of resistor R and the 50 Ω resistor if they are arranged in series instead.

2 State **one** major advantage of connecting lamps in parallel.

3 S A number of 4 Ω resistors are available. Draw diagrams to show how you can connect a suitable number of these resistors to give a combined resistance of
  (a) 12 Ω; **(b)** 2 Ω; **(c)** 9 Ω.

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

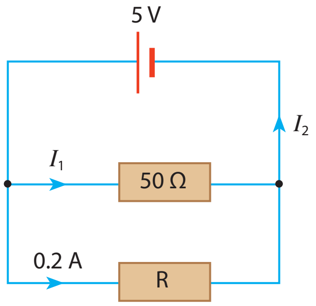


Figure 17.22

LINK

Exercise 17B, pp. XX-XX

17.4 Action and Use of Circuit Components

In this section, you will learn the following:

- Know that the p.d. across an electrical conductor increases as its resistance increases for a constant current.
- S Recall and use the equation for two resistors used as a potential divider: $\dfrac{R_1}{R_2} = \dfrac{V_1}{V_2}$
- S Describe the action of a variable potential divider.
- Recall what is Ohm's Law which you have learnt in Chapter 16.

LINK

Recall what is Ohm's Law which you have learnt in Chapter 16.

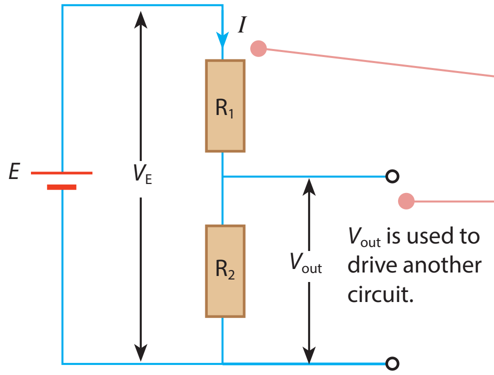
The p.d. across a conductor (such as a resistor or lamp) *increases as its resistance increases, provided that the current is constant*. This is a consequence of Ohm's Law. The use of potential dividers makes use of this concept.

What is a potential divider and how does it work?

Some electronic circuits, such as those found in radios and battery-operated toys, require an e.m.f. that is much smaller than that provided by a single cell. Potential dividers can be used to adjust voltages in these circuits.

A **potential divider** is a line of resistors connected in series. It is used to provide a fraction of the available p.d. from a source to another part of the circuit.

Figure 17.23 shows a potential divider with two fixed resistors. The cell supplies a voltage V_E that is divided into two potential differences across the resistors R_1 and R_2. The potential difference V_{out} across R_2 is then used to drive another part of the circuit.



The current through the resistors R_1 and R_2 is given by

$$I = \frac{V_E}{R_1 + R_2}$$

The potential difference V_{out} across R_2 is given by

$$V_{out} = IR_2 = \left(\frac{V_E}{R_1 + R_2}\right) \times R_2$$

Figure 17.23 *Calculating V_{out} in a simple potential divider*

ENRICHMENT *THINK*

Show how these two equations:

$$V_{out} = \left(\frac{R_2}{R_1 + R_2}\right) \times V_E$$

and $\frac{R_1}{R_2} = \frac{V_1}{V_2}$ are equivalent.

The equation for V_{out} in Figure 17.23 can be rewritten as

$$V_{out} = \left(\frac{R_2}{R_1 + R_2}\right) \times V_E \quad \text{or as}$$

$$\boldsymbol{\frac{R_1}{R_2} = \frac{V_1}{V_2}} \quad \text{where } V_1 = \text{p.d. across } R_1 \text{ and } V_2 = \text{p.d. across } R_2$$

From the above equation, we can see that the output p.d. V_{out} across R_2 is a fraction of the input p.d. V_E.

Worked Example 17E

What is the output voltage across the 20 Ω resistor in Figure 17.24?

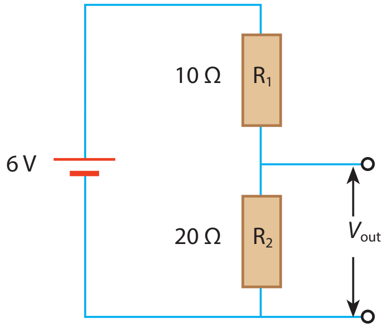


Figure 17.24

Solution

Given: $V_E = 6$ V, $R_1 = 10$ Ω, $R_2 = 20$ Ω

$$V_{out} = \left(\frac{R_2}{R_1 + R_2}\right) \times V_E = \left(\frac{20}{20 + 20}\right) \Omega \times 6\text{ V} = 4\ \Omega$$

Hence, the output voltage $V_{out} = 4$ V.

How are potential dividers useful?

Potential dividers that are used to *vary* the output voltage from a source are called **variable potential dividers**. They are used in electrical devices, such as stereo systems to vary the output voltage, and thus control the volume of the sound.

Variable potential dividers make use of variable resistors. Methods 1 and 2 show how two types of variable potential dividers are used to obtain a variable output voltage V_{out}.

Method 1

- This type of variable potential divider makes use of a rheostat R_1 (Figure 17.25). A **rheostat** is a variable resistor that is connected at two terminals.
- Since $V_{out} = \left(\frac{R_2}{R_1 + R_2}\right) \times V_E$, this means that when the resistance R_1 increases, the output voltage V_{out} decreases.
- To obtain a larger output voltage, the resistance R_1 should be decreased.

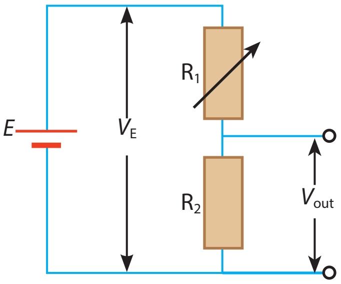


Figure 17.25 *A rheostat being used in a variable potential divider*

Method 2

- This type of variable potential divider makes use of a potentiometer (Figure 17.26). A **potentiometer** is a variable resistor that is connected at three terminals, shown as points A, B and C.
- Contact C is a sliding contact. Since resistance is proportional to length ($R \propto l$) for a fixed cross-sectional area, the position of C determines the ratio of resistance of AC to BC.
- When C is moved towards B, the resistance across AC (R_{AC}) becomes larger, and that across BC (R_{BC}) becomes smaller.
- $V_{out} = \left(\frac{R_{AC}}{R_{AC} + R_{BC}}\right) \times V_E$ where $(R_{AC} + R_{BC})$ is the total resistance of the resistor R, or

  $V_{out} = \left(\frac{AC}{AC + BC}\right) \times V_E$ where (AC + BC) is the length of the resistor R.

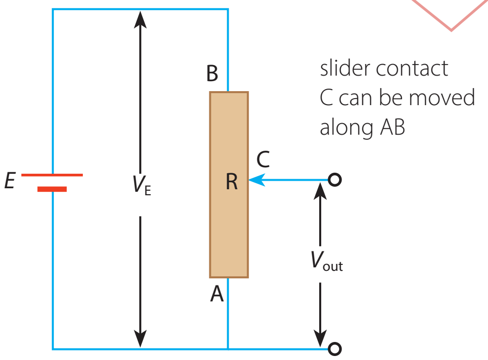


Figure 17.26 *A potentiometer used as a variable potential divider*

Figure 17.27 *A potentiometer is used in a dimmer switch to control the amount of light.*

Worked Example 17F

Figure 17.28 shows a 6 V cell connected to a potentiometer with a maximum resistance of 100 Ω. Calculate the output voltage V_{out} when the sliding contact is at

(a) A; **(b)** the midpoint between AB; **(c)** B.

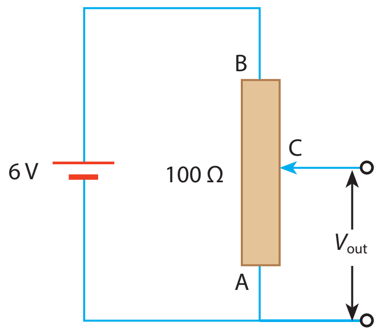


Figure 17.28

Solution

(a) When the contact is at A, the resistance across AC is zero.

Hence, the output voltage $V_{out} = 0$ V.

(b) When the contact is midway between AB, $R_{AC} = 50\ \Omega$ and $R_{BC} = 50\ \Omega$.

Hence, the output voltage is

$$V_{out} = \left(\frac{R\mathrm{AC}}{R_{AC} + R_{BC}}\right) \times V_E = \left(\frac{50}{50 + 50}\right) \Omega \times 6\ \mathrm{V} = 3\ \Omega$$

(c) When the contact is at B, $R_{AC} = 100\ \Omega$ and $R_{BC} = 0\ \Omega$.

Hence, output voltage V_{out} = input voltage = 6 V.

What components can be present in a variable potential divider?

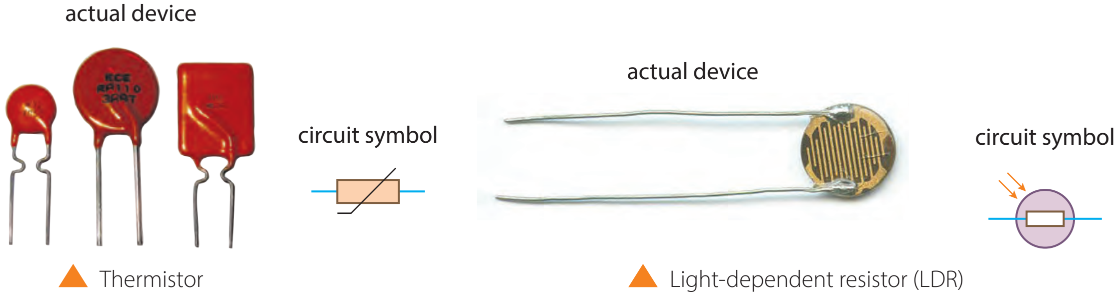
Input transducers are electronic devices that respond to changes in physical conditions, such as temperature and light. They can be used in potential dividers to vary the output voltage. This enables electronic systems to respond to changes in the physical conditions.

Input transducers are widely used in control systems, electrical instruments and electronic communications. Examples include thermistors, LDRs, microphones, photocells, thermocouples and pressure sensors.

In this section, we will learn how the thermistor and the light-dependent resistor (LDR) (Figure 17.29) work. These transducers work in potential dividers to control the output voltage according to changes in physical conditions.

ENRICHMENT ACTIVITY

Find out about other environment-sensitive resistors. Discuss with your class how these resistors work. One example could be a pressure-sensitive resistor.



▲ Thermistor ▲ Light-dependent resistor (LDR)

Figure 17.29 *Thermistors and LDRs are examples of input transducers*

LINK

Recall that the resistance of a metallic conductor increases with temperature which you have learnt in Chapter 16.

NTC thermistors, however, behave in the opposite manner.

Thermistors

A **thermistor** is a resistor whose resistance varies with temperature. An NTC thermistor has resistance that decreases as its temperature increases. The sensitivity of the thermistor to temperature allows it to be used in the circuits of appliances that measure or control temperature.

S Figure 17.30 shows the use of an NTC thermistor R_{TH} in a potential divider.

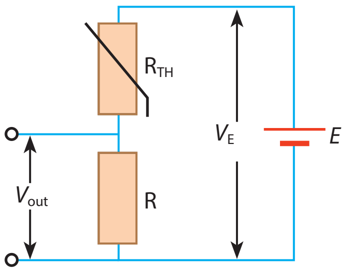
The output voltage is given by

$$V_{out} = \left(\frac{R}{R + R_{TH}}\right) \times V_E$$

where R_{TH} = resistance of the thermistor (in Ω);

R = resistance of the fixed resistor (in Ω);

V_E = voltage supplied by electrical source (in V).



The resistance R_{TH} of the NTC thermistor decreases as its temperature increases. Hence, the output voltage V_{out} also increases with temperature.

Figure 17.30 *NTC thermistor in a potential divider*

By using a voltmeter to measure V_{out}, we can derive the temperature. The output voltage V_{out} can also be used for other purposes, such as controlling switches that turn temperature alarms on or off.

QUICK CHECK

Thermistors are sensitive to visible light.

True or false?

Light-dependent resistors (LDRs)

A **light-dependent resistor (LDR)** has a resistance that decreases as the amount of light shining on it increases, and vice versa. Figure 17.31 in Worked Example 17G shows the effect of an LDR in a potential divider.

Worked Example 17G

Figure 17.31 shows an LDR, R_{LDR}, in a potential divider with a fixed resistor R of resistance 10 kΩ. The cell has an e.m.f. of 9 V. The resistance R_{LDR} of the LDR in two rooms, A and B, is given in Table 17.7

Table 17.7

Room	Resistance of LDR, R_{LDR} / kΩ
A	100
B	5

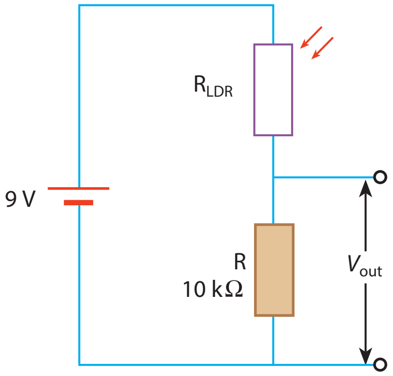


Figure 17.31

(a) One of the rooms had its lights switched off when the resistance of the LDR was measured. Based on your understanding of LDRs, which room was it? Why?

(b) S Calculate the output voltage V_{out} across the fixed resistor R when the LDR is placed in rooms A and B.

Solution

(a) Room A; the resistance of an LDR increases when the amount of light shining on it decreases. Since the LDR has a higher resistance in room A, it is likely to be the room with its lights switched off.

(b) S The output voltage V_{out} across resistor R is given by $V_{out} = \left(\frac{R}{R + R_{LDR}}\right) \times V$

In room A, $R_{LDR} = 100$ kΩ. Then $V_{out} = \left(\frac{R}{R + R_{LDR}}\right) \times V = \left(\frac{10}{10 + 100}\right)$ kΩ × 9 V = 0.82 V

In room B, $R_{LDR} = 5$ kΩ. Then $V_{out} = \left(\frac{R}{R + R_{LDR}}\right) \times V = \left(\frac{10}{10 + 5}\right)$ kΩ × 9 V = 6.0 V

Worked Example 17G shows how the output voltage of a potential divider varies with the amount of light shining on the LDR. When the light intensity increases, the resistance R_{LDR} decreases. This results in a higher V_{out}. The sensitivity of the LDR to light intensity allows it to be used in devices that measure light intensity (e.g. light meters) and in automatic streetlights (Figure 17.32).

Figure 17.32 *LDRs are used in streetlights. This enables the streetlights to automatically switch on when it is dark.*

Let's Practise 17.4

1 Ⓢ Figure 17.33 shows a potential divider with a thermistor and a fixed resistor R of resistance 100 Ω connected to a 6 V cell. The resistance R_{TH} of the thermistor is 500 Ω at 0°C and 50 Ω at 100°C. Calculate the voltmeter readings at these two temperatures.

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

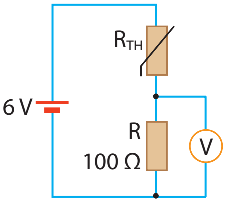


Figure 17.33

LINK TWB

Exercise 17C, pp. XX–XX

17.5 Electrical Safety

In this section, you will learn the following:

- State the hazards of damaged insulation, overheating cables, damp conditions and excess current from overloading of plugs, extension leads, single and multiple sockets when using a mains supply.
- Know that a mains circuit consists of a live wire (line wire), a neutral wire and an earth wire.
- Explain why a switch must be connected to the live wire for the circuit to be switched off safely.
- Explain the use and operation of trip switches and fuses, and choose appropriate fuse ratings and trip switch settings.
- Explain why the outer casing of an electrical appliance must be either non-conducting (double-insulated) or earthed.
- State that a fuse without an earth wire protects the circuit and the cabling for a double-insulated appliance.

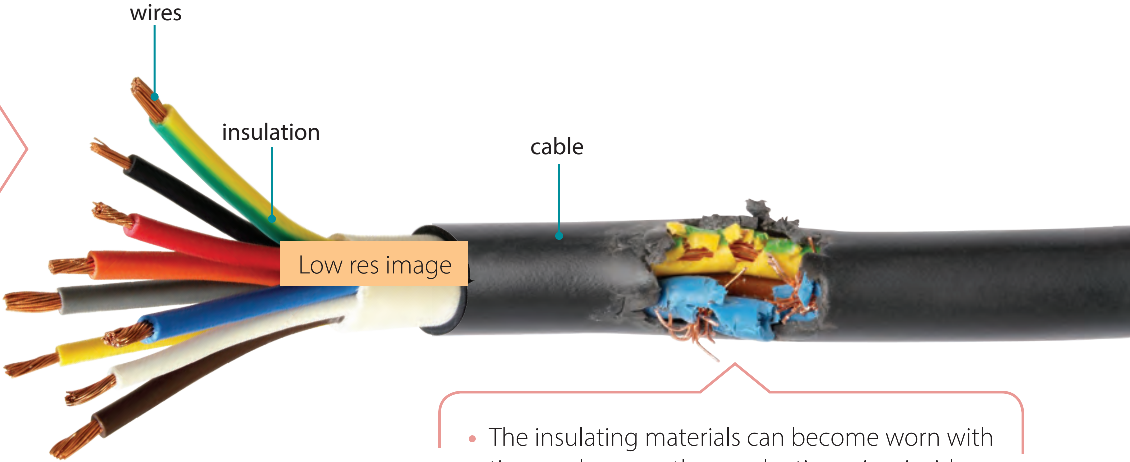
Electrical hazards

Electrical faults in appliances or circuits can cause fires and electric shocks. Electricity can be a hazard when electrical insulation is damaged, cables are overheated, or conditions are damp.

Damaged insulation

Figure 17.34 describes how damaged insulation can be dangerous.

- Wires that carry electricity from the voltage supply to electrical appliances are wound together to form cables.
- These cables are enclosed by insulating materials such as PVC or rubber.



- The insulating materials can become worn with time and expose the conducting wires inside.
- The exposed conducting wires can cause electric shocks if touched.

Figure 17.34 *Damaged insulation on an electrical cable*

Overheating of cables

Overheated cables can cause fires. Two common causes of overheated cables are listed below:

1 **Overloaded power sockets**
When a power socket is overloaded with many appliances, an unusually large current flows through the wires (Figure 17.35).

2 **Use of inappropriate wires**
The resistance of a conducting wire is inversely proportional to its cross-sectional area. This means that a thin wire has a higher resistance and generates more heat, compared to a thick wire. Therefore, when appliances are being wired, manufacturers must make sure that the wires are of appropriate thickness. Generally, thin wires are used for appliances that need less power, such as lamps, while thick wires are used for appliances that need more power, such as kettles.

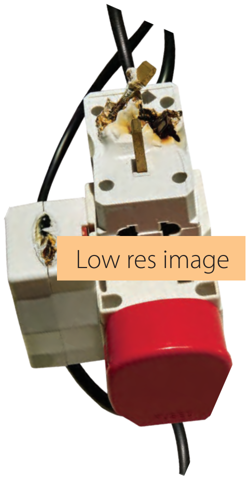


Figure 17.35 *Overloading a power socket can damage plugs and appliances.*

LINK

Recall this relationship between resistance and cross-sectional area which you have learnt in Chapter 16.

Damp conditions

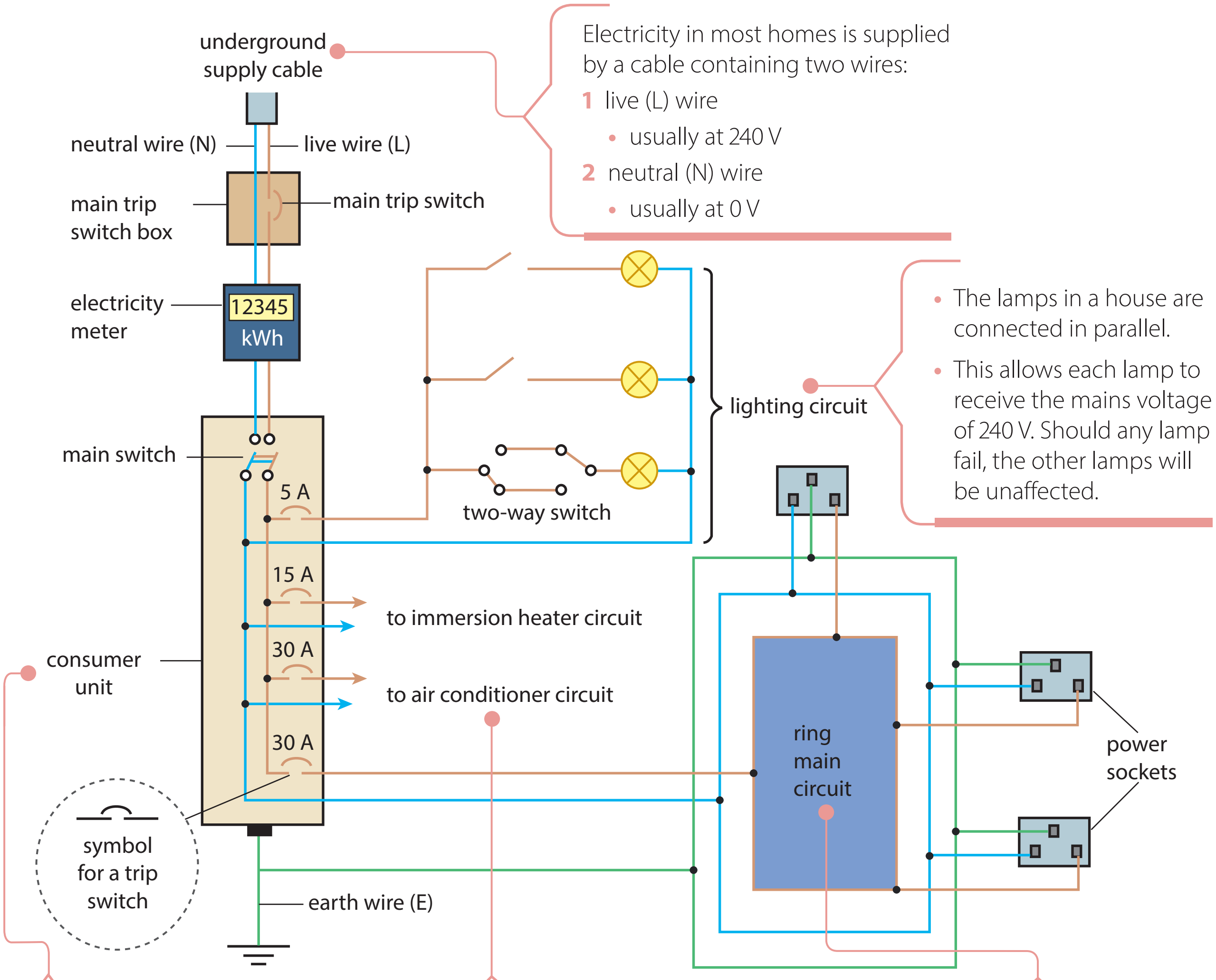
Many electrical accidents occur in damp conditions. For example, a hair dryer on a wet sink (Figure 17.36) can cause electric shocks if the conducting wires are exposed or have damaged insulation.

Water in contact with the uninsulated electrical wires provides a conducting path for current. As the human body can only withstand an alternating current of about 50 mA, a large current will cause burns, uncoordinated contraction of the heart muscles, or even death. Therefore, electrical appliances should be kept in dry places and handled with dry hands.

Figure 17.36 *A hair dryer connected to a socket is left on a wet sink. This can be very dangerous.*

What does a typical mains circuit in the home look like?

Various safety features are installed in the circuits in our homes. Figure 17.37 shows a circuit in the home.



Electricity in most homes is supplied by a cable containing two wires:

1. live (L) wire
   - usually at 240 V
2. neutral (N) wire
   - usually at 0 V

- The lamps in a house are connected in parallel.
- This allows each lamp to receive the mains voltage of 240 V. Should any lamp fail, the other lamps will be unaffected.

The consumer unit trip switch box contains

- a main switch;
- several trip switches, which lead to the common circuits in the house.

- Water heaters and air conditioners tend to draw more current from the mains than other household appliances.
- Therefore, the trip switches connected to their circuits have higher current ratings.

- This circuit supplies electricity to all the wall sockets in the house.
- With the ring arrangement, the current can flow to any socket.
- Besides the live and neutral wires running a complete ring around the house, an earth (E) ring circuit is added for safety reasons.

Figure 17.37 *Typical home circuitry*

WORD ALERT

Draw: use

HELPFUL NOTES

Trip switches are also known as *circuit breakers*.

What features in the mains circuit keep us safe in the event of a fault?

Safety features that can be found in our homes are listed below:

1 Trip switches
2 Fuses
3 Switches
4 Earthing
5 Three pin plugs
6 Double insulation

Trip switches

Trip switches are safety devices that can switch off the electrical supply in a circuit when large currents flow through them. Without trip switches, a surge of current can damage home appliances or even start a fire.

Figure 17.38 shows the trip switches in a consumer unit. The trip switches are labelled with various cut-off currents, such as 10 A and 16 A. Trip switches are connected to live wires. Should there be a current surge due to a fault, the trip switches will trip and cut off the current to the appliances. This ensures that the appliances are isolated from the mains, and the users do not get electric shocks.

WORD ALERT

Trip: shut down

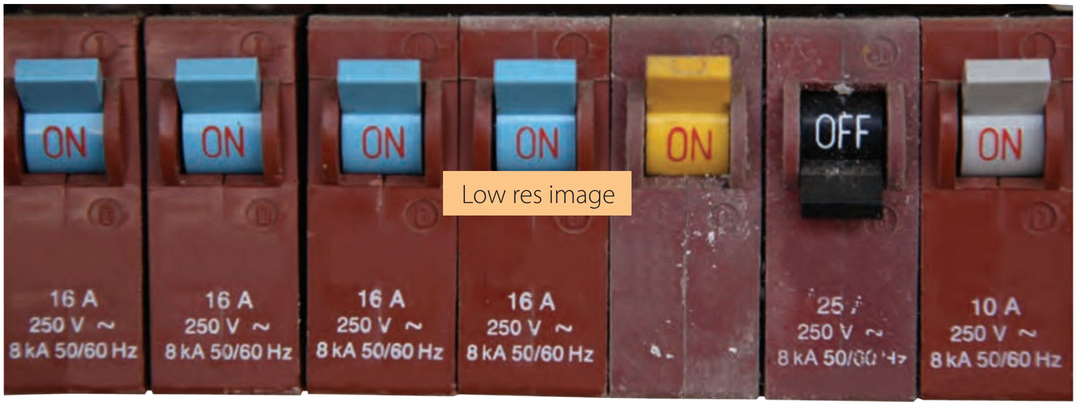


Figure 17.38 *Trip switches in a consumer unit*

Trip switches can be reset by switching them on again. This should be done only after the fault in the circuit has been corrected.

Fuses

A **fuse** is a safety device added to an electrical circuit to prevent excessive current flow. It has the same function as a trip switch. However, a fuse must be replaced after it blows, whereas a trip switch can be reset after it trips.

A fuse consists of a short piece of wire (Figure 17.39). The wire is made thin so that when a large current flows through it, it heats up and melts. When a fuse blows, a gap is created in the circuit. The circuit is opened, and current stops flowing through the circuit.

All fuses have a rated value. This value indicates the maximum current that can flow through a fuse before it blows. In general, fuses with thicker wires can conduct larger currents before blowing, and therefore have higher rated values. Typical household fuses are rated at 1 A, 2 A, 3 A, 5 A, 10 A and 13 A.

PHYSICS WATCH

Scan this page to watch a clip of an experiment to study the working principle of a fuse.

For safety reasons, the following points should be considered when selecting and

installing fuses:

- The fuse of an electrical appliance should have a rated value that is slightly higher than the appliance the electrical appliance draws under normal operating conditions.
- The fuse should be connected to the live wire. This is done so that the current to the appliance will be cut off immediately after a large current melts the fuse wire inside the cartridge. The appliance will not be at a potential of 240 V.
- The mains power supply must be switched off before replacing a fuse.

Figure 17.39 *A cartridge fuse contains a thin metal wire, which melts when a large current flows through it.*

QUICK CHECK

If a fuse blows, it is safe to just replace the fuse and carry on using the device.

True or false?

HELPFUL NOTES

Water heaters draw more current than most appliances and therefore consume more power. Save electricity by only using water heater on cold days.

Worked Example 17H

A hot water heater is rated at 2880 W, 240 V. Calculate the operating current, and suggest a suitable rating for a fuse to protect the heater from overheating.

Figure 17.40 *Water heater*

Solution

Given: Power P of heater = 2880 W

Voltage V = 240 V

Let I = operating current.

Using $P = VI$, $I = \frac{P}{V} = \frac{2880\text{ W}}{240\text{ V}} = 12\text{ A}$

A suitable fuse will have a fuse rating that is slightly higher than the operating current of the water heater. Thus, a 13 A fuse will be suitable.

Worked Example 17I

The following appliances are operating in a kitchen circuit:

- 50 W fruit blender
- 800 W microwave oven
- 400 W refrigerator
- 1.5 kW electric kettle

Electricity is supplied to the kitchen at 240 V. The kitchen circuit is protected by a trip switch with a rating of 20 A.

(a) What is the current flowing through the trip switch when all the appliances are operating at the same time?

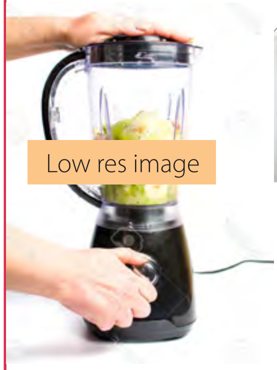
(b) Does the trip switch trip?

Solution

(a) Since all the appliances are operating at the same time, the total power P = 50 W + 400 W + 800 W + 1500 W = 2750 W

Using $P = VI$, $I = \frac{P}{V} = \frac{2750\text{ W}}{240\text{ V}} = 11.5\text{ A}$

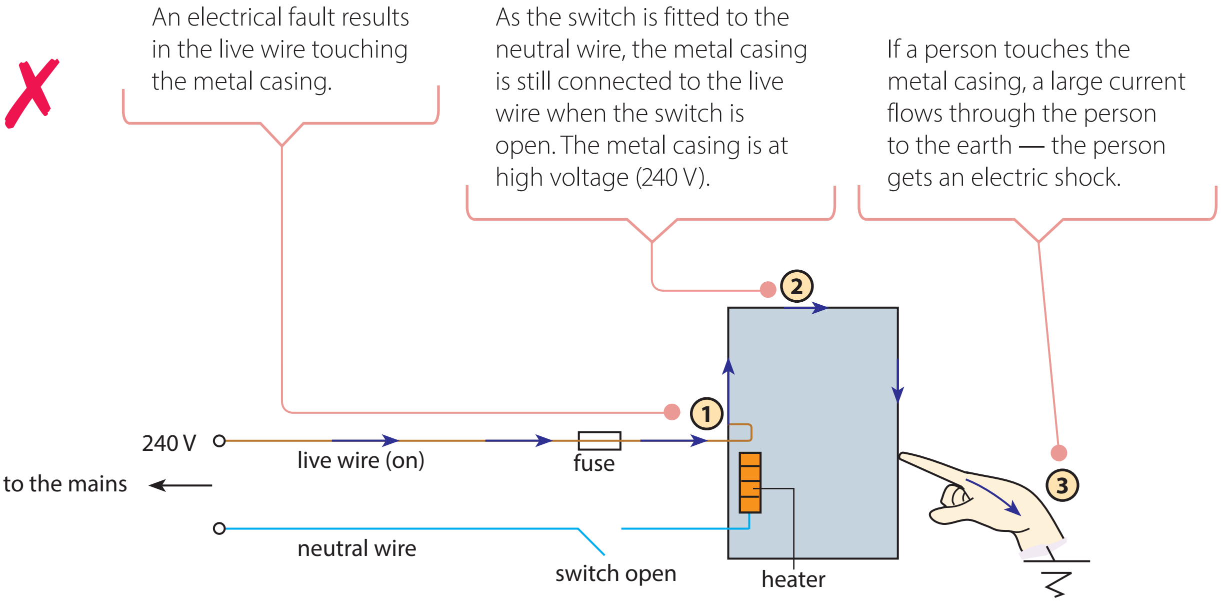
(b) As the current is lower than the rating of the trip switch, the trip switch does not trip, and all the appliances can operate safely.



Switches

Switches are designed to break or complete an electrical circuit. They should be fitted to the live wire of the appliance.

For example, if an electrical fault causes the metal casing of an appliance to be at high voltage, a switch on the live wire can disconnect the voltage supplied to the metal casing. Figures 17.42 and 17.42 show how a switch fitted to the neutral wire does not prevent electric shocks, while a switch fitted to the live wire does.

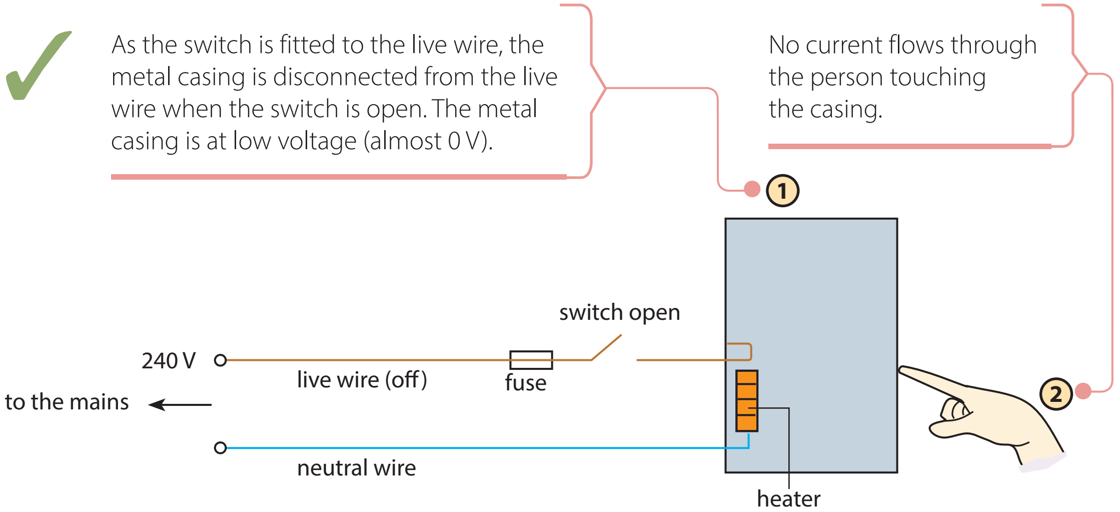

✗

An electrical fault results in the live wire touching the metal casing.

As the switch is fitted to the neutral wire, the metal casing is still connected to the live wire when the switch is open. The metal casing is at high voltage (240 V).

If a person touches the metal casing, a large current flows through the person to the earth — the person gets an electric shock.

Figure 17.42 *Incorrect position for a switch — the switch should not be fitted to the neutral wire*


✓

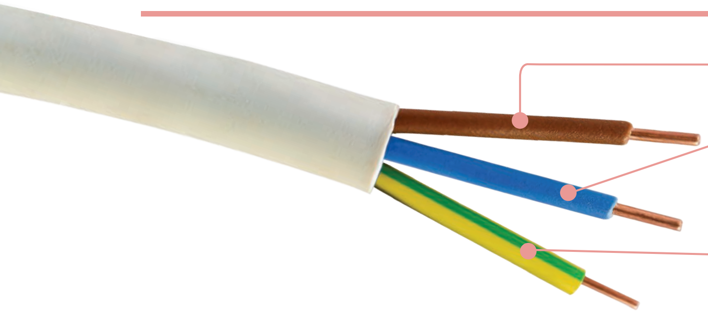
As the switch is fitted to the live wire, the metal casing is disconnected from the live wire when the switch is open. The metal casing is at low voltage (almost 0 V).

No current flows through the person touching the casing.

Figure 17.43 *Correct position for a switch — the switch should be fitted to the live wire*

Earthing

There are usually three wires in a home circuit — the live (L) wire, the neutral (N) wire and the earth (E) wire (Figure 17.44).



The **live wire** (brown) is connected to a high voltage and delivers current to the appliance. This is the wire to which trip switches, fuses and switches are fitted.

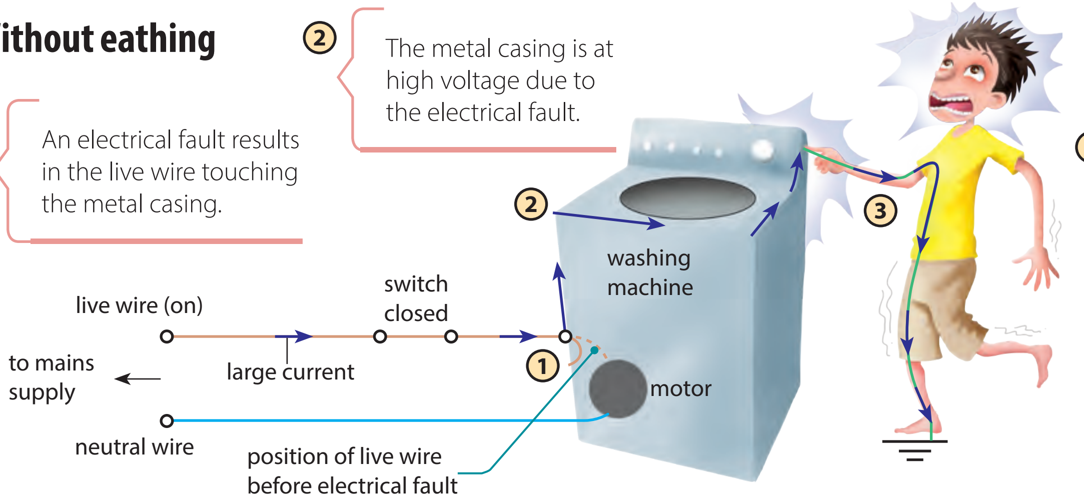
The **neutral wire** (blue) completes the circuit by providing a return path to the supply for the current. It is usually at 0 V.

The **earth wire** (green and yellow) is a low-resistance wire. It is usually connected to the metal casing of appliances.

Figure 17.44 The three wires in a home circuit

Figures 17.45 and 17.46 show how earthing prevents electric shocks when an electrical fault is present.

Without eathing



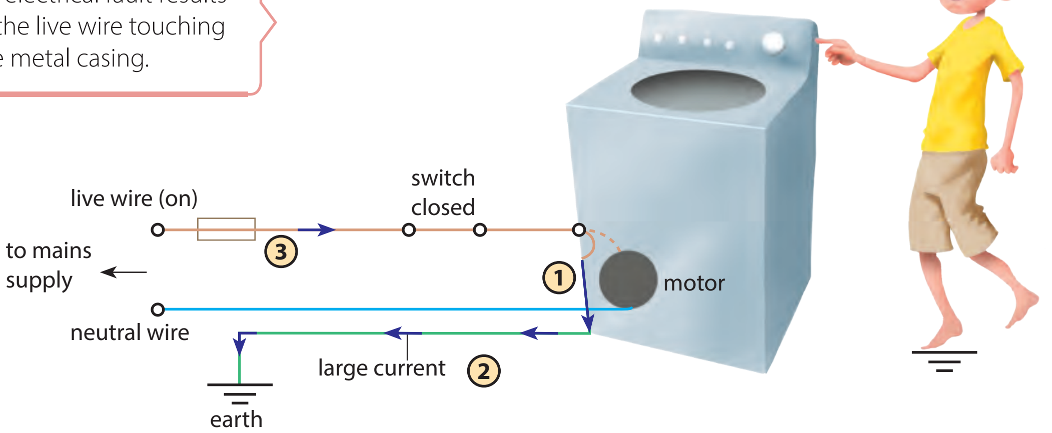
① An electrical fault results in the live wire touching the metal casing.

② The metal casing is at high voltage due to the electrical fault.

③ If a person touches the metal casing, a large current flows through the person — the person gets an electric shock.

Figure 17.45 The absence of earthing can cause electric shocks.

With earthing



② The large current flows to the ground through the earth wire, which has a much lower resistance than the person. Hence, the person does not suffer an electric shock.

③ An electrical fault results in the live wire touching the metal casing.

① The large current flows from the live wire. This through the metal casing, to the earth wire. This creates a short circuit. The sudden surge in current exceeds the rated value of the fuse. This causes the fuse to blow and the circuit is opened. The electricity supply to the appliance is cut off.

Figure 17.46 Earthing prevents electric shocks.

Three-pin plugs

A fused plug connects an electrical appliance to the mains supply via the power socket. The fused plug commonly used in some countries is the **three-pin plug** (Figures 17.47).

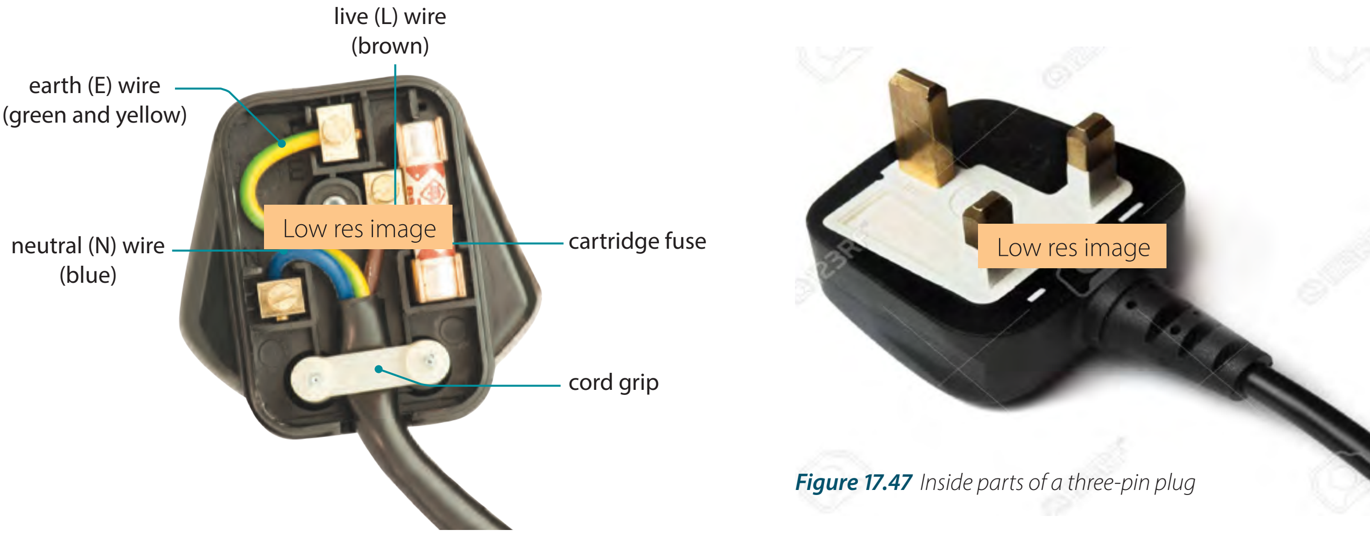


Figure 17.47 *Inside parts of a three-pin plug*

The fused plug is also known as a safety plug. The cartridge fuse inside the plug protects the appliance when there is an electrical fault. If excessive current flows in the appliance, the fuse blows. This breaks the circuit and isolates the appliance with the fault so that overheating does not damage it.

Double insulation

Some household appliances use two-pin plugs instead of three-pin plugs. For such appliances, there is no earth wire. These appliances use double insulation to protect users from electric shocks. Figure 17.48 shows such an appliance and the double insulation symbol.

Double insulation is a safety feature that can replace the earth wire. Appliances that have double insulation usually use a two-pin plug. This is because only the live and neutral wires are required.

Double insulation provides two levels of insulation:

1 The electric cables are insulated from the internal components of the appliance.
2 The internal components are insulated from the external casing.

Appliances with double insulation typically have non-metallic casings, such as plastic.

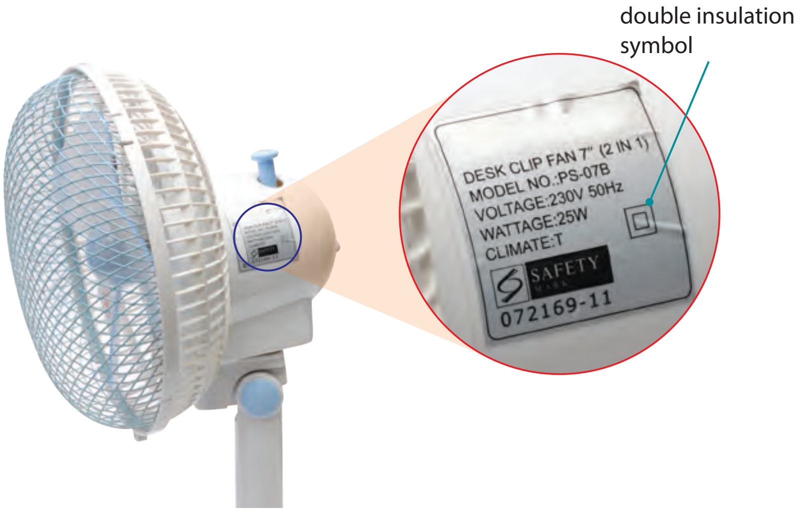


Figure 17.48 *Double-insulated appliances carry the double insulation symbol.*

Let's Practise 17.5

1 State **three** safety precautions that someone operating electrical devices should take to avoid an electric shock
2 State the function of the following safety features, and how they should be connected in a circuit:
   (a) Trip switch **(b)** Fuse **(c)** Earth wire
3 Explain why do some appliances use a three-pin plug, while others use a two-pin plug?
4 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

TWB **LINK**

Exercise 17D–17E, pp. XX–XX

Exercise 17F Let's Reflect, p. X

Let's Map It

ELECTRICAL CIRCUITS

can be represented by

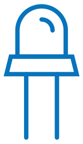
Circuit diagrams

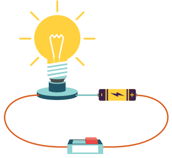
includes

Circuit components

examples

Cells, batteries, power supplies, generators, potential dividers, switches, resistors (fixed and variable), heaters, NTC thermistors, light-dependent resistors (LDRs), lamps, motors, ammeters, voltmeters, magnetising coils, transformers, fuses and relays, S diodes, S light-emitting diodes (LEDs)

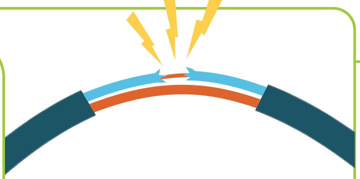




can cause

Electrical hazards

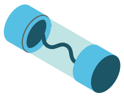
- Damaged insulation
- Overheating cables
- Damp conditions
- Excess current from overloading



can be avoided by using

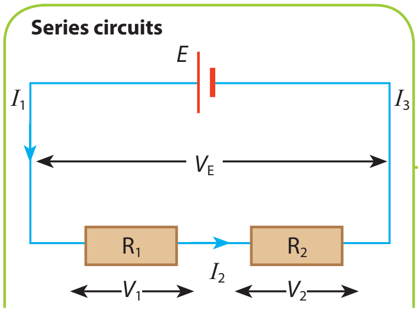
Safety features

- Trip switches
- Fuses
- Switches
- Earthing
- Three-pin plugs
- Double insulation



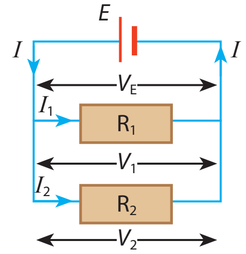
examples

Series circuits



- Current: $I_1 = I_2 = I_3$
- Potential difference: $V_E = V_1 + V_2$
- Combined resistance: $R = R_1 + R_2$

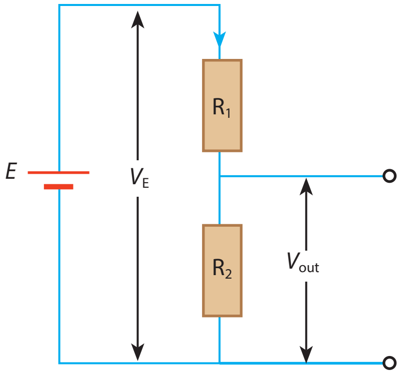
Parallel circuits



- Current: $I = I_1 + I_2$
- Potential difference: $V_E = V_1 = V_2$
- S Combined resistance: $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$

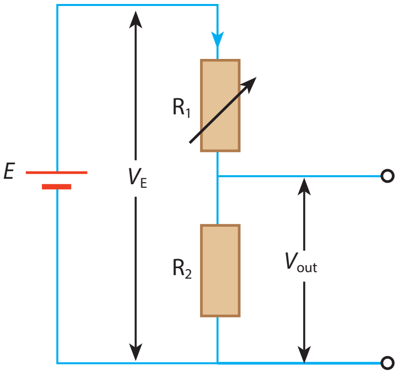
Potential divider circuit with fixed resistors

- Fixed R_1 and fixed R_2



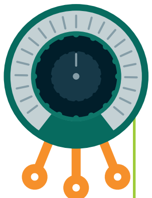
Variable potential divider circuit with rheostat

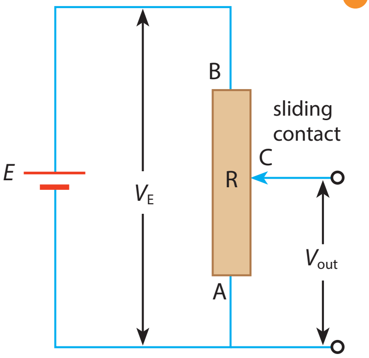
- Variable R_1 and fixed R_2



Variable potential divider circuit with potentiometer

- Variable R_1 and variable R_2





S $V_{out} = \frac{R_2}{R_1 + R_2} \times V_E$

S In general: $\frac{R_1}{R_2} = \frac{V_1}{V_2}$

S $V_{out} = \frac{R_{AC}}{R_{AB}} \times V_E$

Let's Review

Section A: Multiple-choice Questions

1 Figure 17.49 shows three identical resistors.

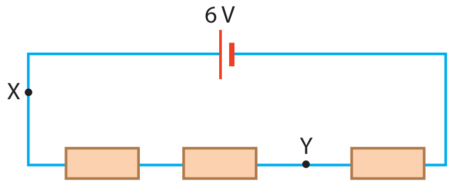


Figure 17.49

What is the voltage reading of a voltmeter connected across XY?

A 2 V **B** 3 V
C 4 V **D** 6 V

2 In Figure 17.50, the reading on ammeter A_2 is 1 A and that on ammeter A_4 is 3 A. What are the readings on ammeters A_1 and A_3?

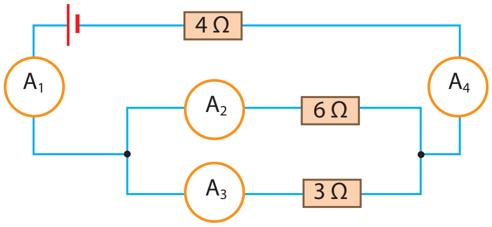


Figure 17.50

	A_1 reading/A	A_3 reading/A
A	1.5	0.5
B	2	1
C	3	1
D	3	2

3 In Figure 17.51, resistor R_1 is connected to an e.m.f. source. The ammeter reading is 2 A and the voltmeter reading is 6 V. In Figure 17.52, a new resistor R_2 is now connected in parallel with resistor R_1. The ammeter and voltmeter readings are now 3 A and 6 V respectively.

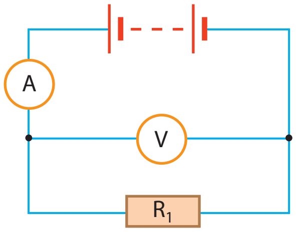


Figure 17.51

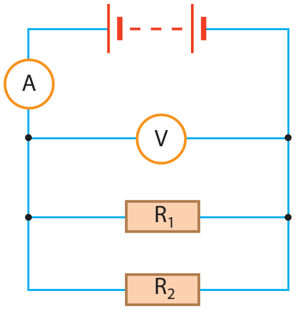


Figure 17.52

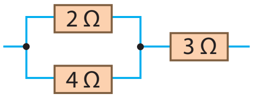
What is the resistance of resistor R_2?

A 2 Ω **B** 3 Ω
C 6 Ω **D** 9 Ω

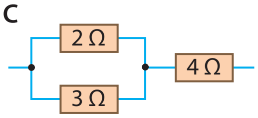
4 Which of the following combinations of resistors has the lowest resistance?

A

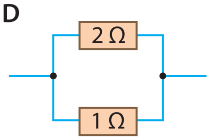
B



C



D



5 An appliance has a current of 7 A. Which fuse should be used to protect the appliance in the event of a fault?

A 1 A **B** 3 A
C 5 A **D** 13 A

6 Which safety precaution reduces the risk of an electrical fire if a device becomes faulty?

A Earth wire **B** Trip switch
C Insulation **D** Plug

For questions 7 and 8, refer to Figure 17.53. In the circuit shown, the resistors have equal resistance *R*.

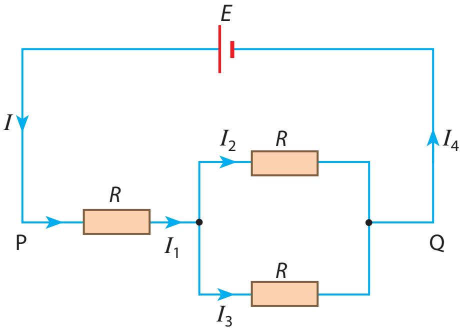


Figure 17.53

7 The combined resistance between PQ is

A $\frac{1}{3}R$. **B** $\frac{3}{2}R$.
C $2R$. **D** $3R$.

8 What can be deduced about I, I_1, I_2, I_3 and I_4?

A $I = I_1 = I_4 = I_2 + I_3$
B $I = I_1 = I_2 = I_3 + I_4$
C $I > I_1 > I_4$ and $I_2 = I_1$
D $I > I_1 > I_4$ and $I_4 = I_2 + I_3$

Let's Review

9 S In the potential divider in Figure 17.54, the variable resistor R_1 has a maximum resistance of 4 Ω. What are the minimum and maximum possible values of V_{out}?

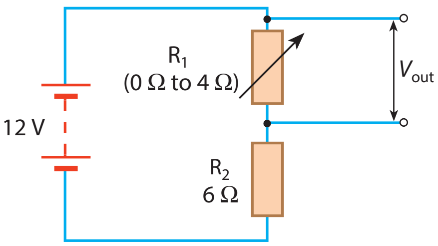


Figure 17.54

	Minimum V_{out}/V	Maximum V_{out}/V
A	0	4.8
B	0	6
C	2	4.8
D	6	12

10 S The circuit in Figure 17.55 is used to detect the level of sunlight. The resistance of the LDR is 1 MΩ in the dark and 100 Ω in bright sunlight. What is the voltmeter reading in dark and bright conditions?

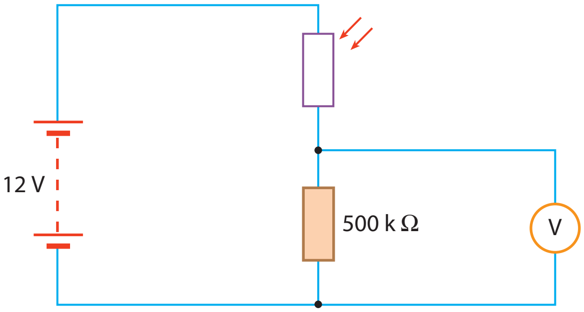


Figure 17.55

	Voltmeter reading in the dark/V	Voltmeter reading in bright sunlight/V
A	4	0
B	4	12
C	8	0
D	8	4

11 Figure 17.56 shows a thermistor connected in a potential divider circuit at room temperature. The resistance of this thermistor decreases with an increase in its temperature. Which of the following happens to the voltmeter reading when the thermistor is heated?

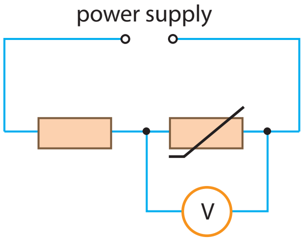


Figure 17.56

A Decreases
B Decreases and then increases
C Increases
D Stays the same

Section B: Short-answer and Structured Questions

1 S For the circuit in Figure 17.57, calculate the
(a) combined resistance across AB;
(b) combined resistance across CD;
(c) combined resistance of the whole circuit;
(d) current flowing through the 6 Ω resistor.

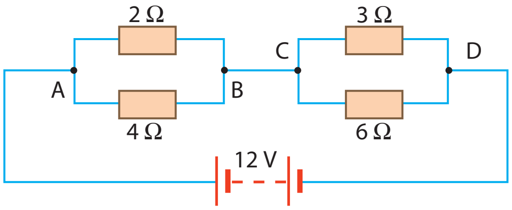


Figure 17.57

2 A 6 V cell is connected to three resistors in the circuit shown in Figure 17.58. The current flowing through the source is 0.8 A. Calculate the
(a) current I_1;
(b) current I_2;
(c) value of the resistance of resistor R.

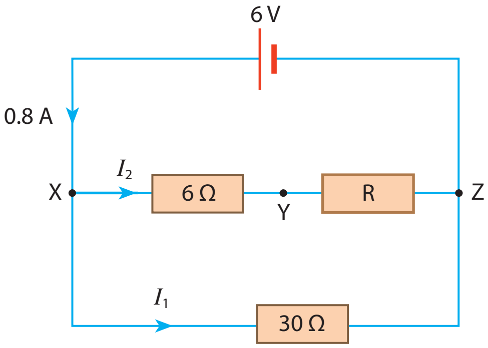


Figure 17.58

3 **(a)** Using four identical resistors, design a circuit in which the p.d. across

- **(i)** each resistor is one-fourth of the e.m.f.;
- **(ii)** each resistor is the same as the e.m.f.;
- **(iii)** each resistor is half of the e.m.f.;
- **(iv)** one resistor is the same as the e.m.f., and the p.d. across each of the other three resistors is less than the e.m.f.

(b) Compare the advantages and disadvantages of connecting lamps in series and in parallel. Explain your answer.

4 The electrical wiring in a house is complex. When an electrical failure occurs, it is hard to determine the cause of the failure. To determine the cause, an electrician uses a voltmeter to determine the p.d. across two points in a circuit. Table 17.8 shows the readings the electrician took for the circuit shown in Figure 17.59.

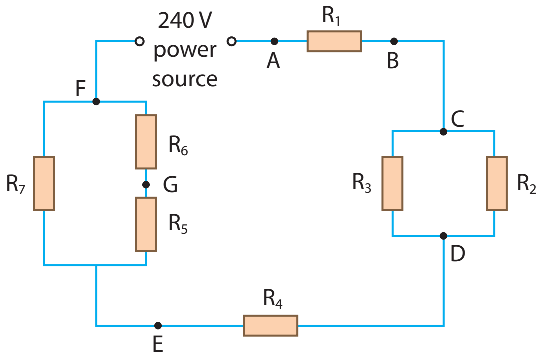


Figure 17.59

Table 17.8

Points	P.d. across the points
A and B	40 V
B and C	0 V
C and D	0 V
D and E	100 V
E and F	50 V
E and G	30 V
G and F	20 V

(a) Explain why there is no p.d. across BC.

(b) If the current flowing through R_4 is 0.50 A, determine the resistances of

(i) R_4; **(ii)** R_1.

(c) State the location of the fault in the circuit, and suggest a possible cause of the fault.

(d) If the current flowing through R_4 is 0.50 A, and the current flowing through R_7 is one-fourth of that flowing through R_5 and R_6, calculate the resistances of

(i) R_7; **(ii)** R_5; **(iii)** R_6.

(e) Calculate the combined resistance across EF.

5 S Variable resistors are used in circuits to produce variable output voltages.

(a) Using an e.m.f. of 9 V, a variable resistor with a range of 0 Ω to 12 Ω, and a fixed resistor of 24 Ω, design a circuit that can produce a variable output voltage of 0 V to 3 V.

(b) Perform calculations to show that your design produces the desired voltage output.

6 Figure 17.60 shows a circuit in which lamps 1 and 2 (of resistances R_1 and R_2) are connected in series. Figure 17.61 shows the same circuit after lamps 1 and 2 are replaced by a single lamp 3 of equivalent resistance R.

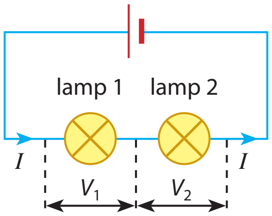


Figure 17.60

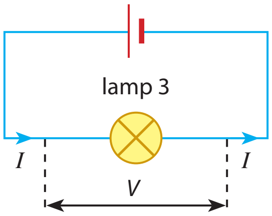


Figure 17.61

According to the principle of conservation of energy,

power dissipated by lamp 3 = power dissipated by lamp 1 + power dissipated by lamp 2

(a) Given that power P dissipated by a lamp is $P = IV$,
where I = current flowing through the lamp,
V = p.d. across the lamp,
use the principle of conservation of energy to derive the formula for the combined resistance R of lamps 1 and 2.

(b) Using a similar method as in **(a)**, derive the formula for the combined resistance of lamps 1 and 2 when they are arranged in parallel.

CHAPTER

18

Electromagnetic Effects

PHYSICS WATCH

Scan this page to watch a clip about the uses of electromagnetic effects.

QUESTIONS

- Look at the photo. What is the drone used for?
- What does d.c. stand for?
- Which parts of the drones make use of d.c. motors?
- Why do the motors have permanent magnets?

Farms in the rural areas of Japan are facing a problem. They are left in the hands of aging farmers who may no longer have the strength to do the work. Many of the young people prefer to find jobs in the city. This aging of the agricultural industry is also happening in countries such as Thailand.

One answer to the problem is to use drones. Drones are unmanned aerial vehicles that can operate using small d.c. motors. The motors have permanent magnets that are made of alloys. These magnets need to be small and light so that the motors can provide enough thrust for a lift off.

Perhaps, using drone technology in agriculture could lure the young people back to the rural farms.

18.1 Electromagnetic Induction

In this section, you will learn the following:

- Know that a conductor moving across a magnetic field or a changing magnetic field linking with a conductor can induce an e.m.f. in the conductor.
- Describe an experiment to demonstrate electromagnetic induction.
- State the factors affecting the magnitude of an induced e.m.f.
- S Know that the direction of an induced e.m.f. opposes the change causing it.
- S State and use the relative directions of force, field and induced current.

In chapter 15, you have learnt that a current flowing through a conductor produces a magnetic field around it. In 1831, an English scientist named Michael Faraday discovered that the converse is true — a changing magnetic field produces an induced current. This effect is known as *electromagnetic induction*.

Electromagnetic induction is the process through which an induced e.m.f. is produced in a conductor due to a *changing magnetic field.*

LINK

Recall the magnetic field pattern around a current-carrying conductor.

Refer to Chapter 15.

What did Faraday discover?

Figure 18.1 shows the apparatus that Faraday used to test whether a moving magnet could induce a current.

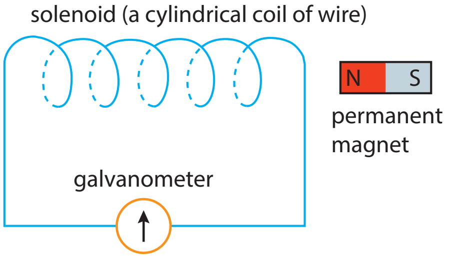


Figure 18.1 *Faraday's solenoid experimentremains constant.*

These were Faraday's observations:

- When a magnet was inserted into a solenoid, the galvanometer needle was deflected in one direction.
- When the magnet was withdrawn from the solenoid, the galvanometer needle was deflected in the other direction.
- When the magnet was stationary in the solenoid, the galvanometer needle was not deflected.

From his observations, Faraday concluded that a relative movement between the solenoid and the magnet induced an electromotive force (e.m.f.) in the circuit. The induced e.m.f. drove an induced current which was then detected by the galvanometer.

Faraday also found that the magnitude of this induced e.m.f. could be increased by increasing the

1. number of turns in the solenoid;
2. strength of the magnet;
3. speed at which the magnet moves with respect to the solenoid.

WORD ALERT

Deflected: caused to move

Flux: the rate of flow of something across an area; magnetic flux is a measure of the quantity of magnetic field surrounding a magnetic object.

The laws of electromagnetic induction

There are two laws of electromagnetic induction.

Faraday's Law of electromagnetic induction states that the magnitude of the induced e.m.f. in a circuit is directly proportional to the rate of change of magnetic flux in the circuit.

S **Lenz's Law** states that the direction of the induced e.m.f., and hence the induced current in a closed circuit, is always such that its magnetic effect opposes the motion or change producing it.

We can carry out Let's Investigate 18A to demonstrate the laws of electromagnetic induction.

PHYSICS WATCH

Scan this page to explore a simulation on electromagnetic induction.

Let's Investigate 18A

Objective

To demonstrate the laws of electromagnetic induction

Apparatus

Bar magnet, solenoid of wire, connecting wires, centre-zero galvanometer or other sensitive ammeter

Procedure

1. Connect the ends of a solenoid to a sensitive centre-zero galvanometer with connecting wires.
2. Move the S pole of a permanent bar magnet into the solenoid, and note any deflection on the galvanometer (Figure 18.2).
3. Once the bar magnet is inside the solenoid, hold it stationary and note any deflection on the galvanometer.
4. Next, move the S pole of the magnet out of the solenoid, and note any deflection on the galvanometer.
5. Repeat steps 2 to 4, using the N pole of the same bar magnet.

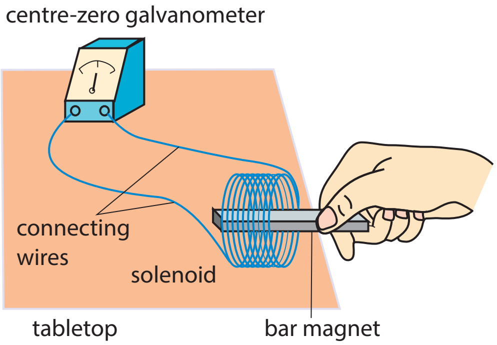


Figure 18.2

Observation and discussion

Tables 18.1 and 18.2 summarise the observations and discussion of this investigation.

LINK PWB

Practical 18A, pp. XX–XX

Table 18.1 *S pole of bar magnet moved into and out of the solenoid*

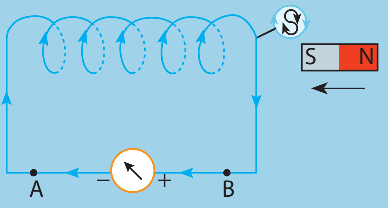
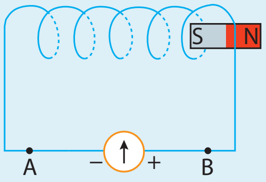
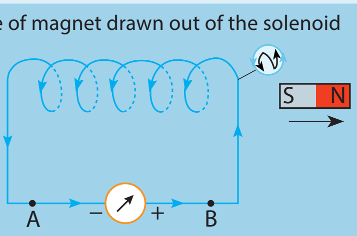
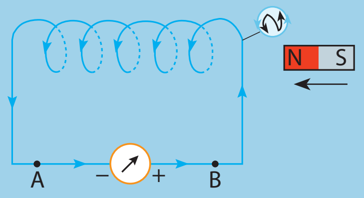
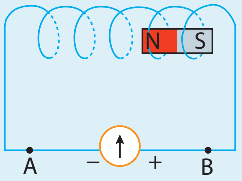
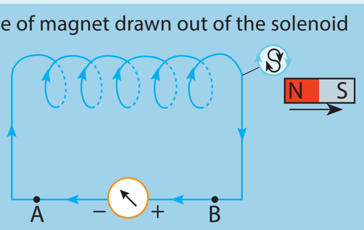
Observation	Discussion
(a) S pole of magnet moved towards the solenoid  The galvanometer needle was deflected momentarily to one side.	• When the S pole of the bar magnet was moved towards the solenoid, the galvanometer needle was deflected momentarily to one side. • This shows that an e.m.f. was induced in the coil and a current flowed through the galvanometer. • The induced current produced an S pole at the end of the solenoid to repel the S pole of the bar magnet moving towards it.
(b) S pole of magnet held stationary in the solenoid  The galvanometer needle was not deflected.	• No current was induced in the circuit.
(c) S pole of magnet drawn out of the solenoid  The galvanometer needle was deflected momentarily to the other side.	• When the S pole of the bar magnet was moved away from the solenoid, the galvanometer needle was deflected momentarily to the other side. • This shows that an e.m.f. was induced in the coil and a current flowed through the galvanometer. • The induced current produced an N pole at the end of the solenoid to attract the S pole of the barmagnet moving away from it.

Table 18.2 *N pole of bar magnet moved into and out of the solenoid*

Observation	Discussion
(a) N pole of magnet moved towards the solenoid  The galvanometer needle was deflected momentarily to one side.	• When the N pole of the bar magnet was moved towards the solenoid, the galvanometer needle was deflected momentarily to one side. • This shows that an e.m.f. was induced in the coil and a current flowed through the galvanometer. • The induced current produced an N pole at the end of the solenoid to repel the N pole of the bar magnet moving towards it.
(b) N pole of magnet held stationary in the solenoid  The galvanometer needle was not deflected.	• No current was induced in the circuit.
(c) N pole of magnet drawn out of the solenoid  The galvanometer needle was deflected momentarily to the other side.	• When the N pole of the bar magnet was moved away from the solenoid, the galvanometer needle was deflected momentarily to the other side. • This shows that an e.m.f. was induced in the coil and a current flowed through the galvanometer. • The induced current produced an S pole at the end of the solenoid to attract the N pole of the bar magnet moving away from it.

Worked Example 18A

In Figure 18.4, a short bar magnet passes through a long solenoid. A galvanometer is connected across the solenoid.

(a) Sketch a graph of the galvanometer needle deflection θ against time t, starting from the instant shown in Figure 18.4 to the time the magnet emerges from the solenoid.

(b) Using the principles of electromagnetic induction, explain the shape of the graph you sketched in **(a)**.

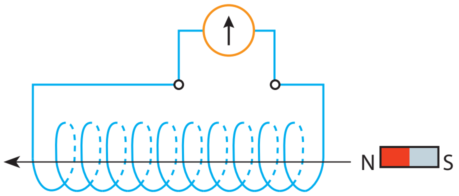


Figure 18.4

ENRICHMENT *INFO*

Conservation of Energy and Lenz's Law

There is a link between the conservation of energy we have seen in other chapters and Lenz's Law. This is used in electromagnetic braking.

A current is induced in a spinning aluminium disc because of the presence of a magnetic field. The induced current produces a force on the disc. This force will either accelerate or decelerate the disc, depending on the direction of the current. In one direction the disc would continue to accelerate and would never slow down — impossible. Hence, the current must be in the direction predicted by Fleming's right-hand rule (see page 335).

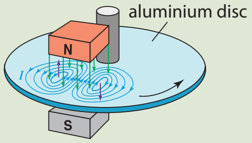


Figure 18.3

Solution

(a) Figure 18.5 shows the graph of galvanometer needle deflection θ against time t.

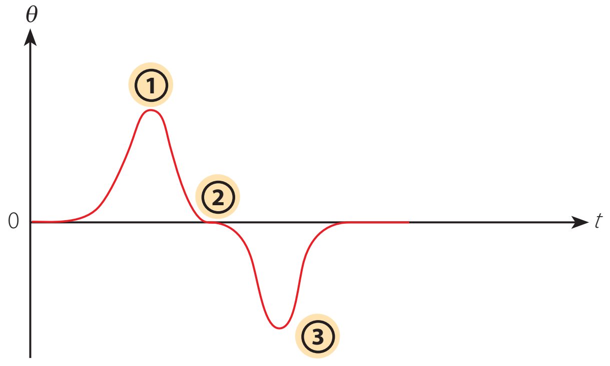


Figure 18.5

(b) At 1:

- At the instant when the bar magnet travels past the midlength point of the solenoid, there is no change in the magnetic flux in the solenoid.
- There is no induced e.m.f., and hence no induced current to cause the galvanometer needle to be deflected.

At 2:

- As the N pole of the bar magnet enters the solenoid, there is a change in the number of magnetic field lines linking the solenoid (i.e. magnetic flux in the solenoid changes).
- By Faraday's Law, the change of the magnetic flux in the solenoid results in an induced e.m.f. in the circuit. This e.m.f. drives an induced current through the closed circuit. The induced current produces a galvanometer needle deflection θ.
- By Lenz's Law, the induced current creates an N pole at the right end of the solenoid to oppose the incoming N pole. Thus, the galvanometer needle is deflected momentarily to one side.

At 3:

- As the S pole of the bar magnet exits the solenoid, there is again a change in the magnetic flux in the solenoid.
- By Faraday's Law, this produces an induced e.m.f. and hence an induced current.
- By Lenz's Law, the induced current creates an N pole at the left end of the solenoid to oppose the outgoing S pole. Thus, the galvanometer needle is deflected momentarily to the other side.

Let's Practise 18.1

1 A bar magnet is pushed towards one end of a solenoid, as shown in Figure 18.6.

(a) Explain what happens to the galvanometer needle.

(b) Describe how you would increase the angle of deflection of the galvanometer needle.

(c) S Explain which pole is induced at end A of the solenoid.

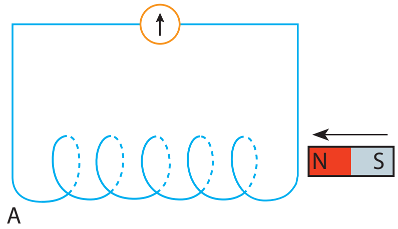


Figure 18.6

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

LINK TWB

Exercise 18A, pp. XX–XX

18.2 The A.c. Generator

In this section, you will learn the following:

- Describe a simple form of a.c. generator and the use of slip rings and brushes.
- Sketch and interpret graphs of e.m.f. against time for simple a.c. generators and relate the position of the generator coil to the peaks, troughs and zeros of the e.m.f.

One important use of electromagnetic induction is in the generation of electricity. The **alternating current (a.c.) generator** uses alternating current to transform mechanical energy into electrical energy.

HELPFUL NOTES

An e.m.f. is induced in a conductor only when there is a change in magnetic flux. If the conductor is at rest in a constant magnetic field or moving in the same direction as the magnetic field lines are pointing, no e.m.f. is induced.

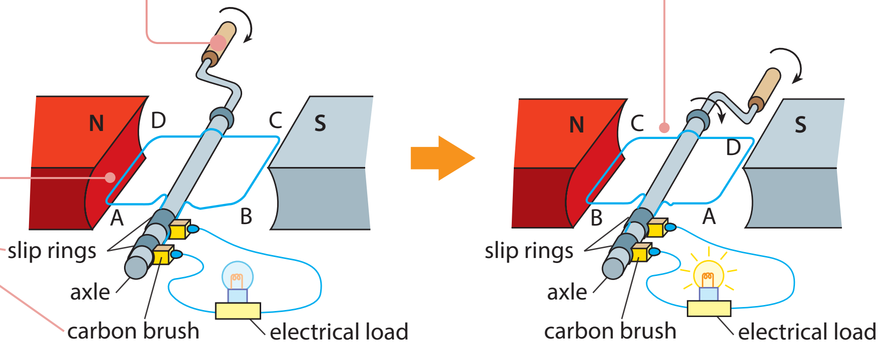
How can we generate a.c. from motion?

Figure 18.7 shows how a simple a.c. generator works. Note that the direction of the induced current flowing in the coil can be found using **Fleming's right-hand rule**.

① A rectangular coil of wire ABCD (the armature) is mounted on an axle.

② By turning the handle, the coil rotates between the poles of two permanent magnets.

③ As the coil rotates in the magnetic field, the change in magnetic flux creates an induced e.m.f., and hence an induced current in the coil.



④ The **slip rings** are always in contact with the carbon brushes as the axle rotates. The slip rings ensure that the induced current in the coil is transferred to the external circuit.

⑤ The induced current powers the electrical load connected to the external circuit, so the lamp lights up.

Figure 18.7 *Simple a.c. generator*

Fleming's right-hand rule

The British physicist John Ambrose Fleming came out with a simple hand rule to find the direction of induced current when a conductor moves in a magnetic field (Figure 18.8).

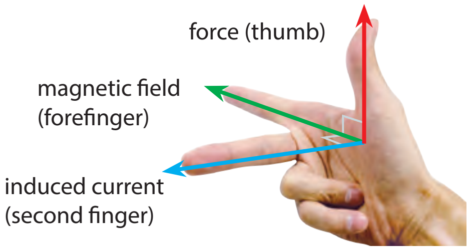


Figure 18.8 *Fleming's right-hand rule*

① Point your thumb, forefinger and second finger at right angles to one another using your right hand.

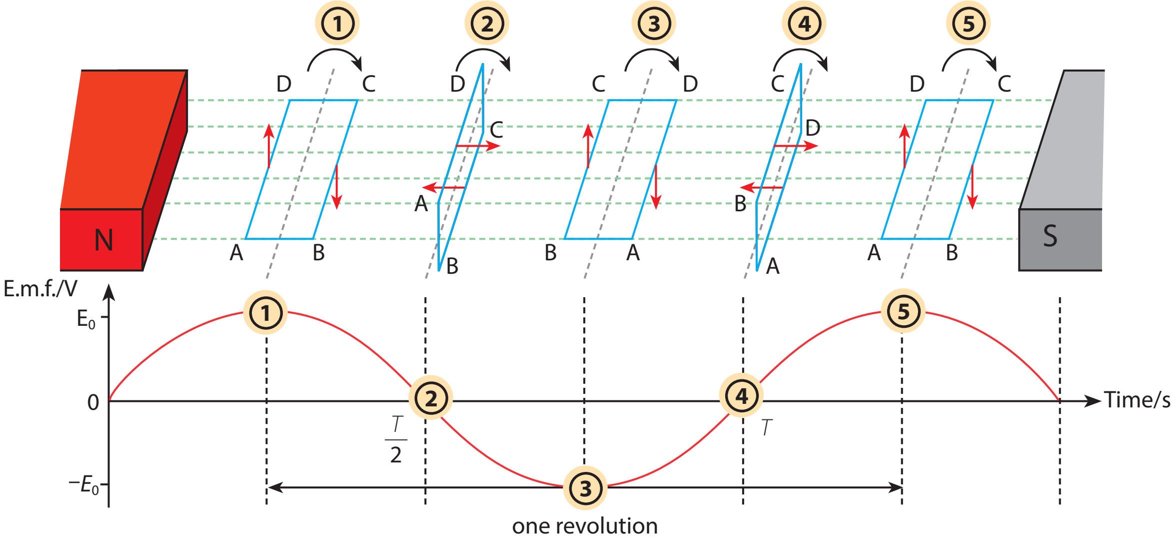
② Point your forefinger in the direction of the magnetic field (N-to-S direction) and your second finger in the direction of the induced current.

③ Your thumb then gives the direction of the motion of the wire, i.e., the direction of the force. In fact, given any two of the directions, we can deduce the remaining one.

What does the voltage-time graph look like for an a.c. generator?

At different positions, the rate at which the coil cuts across the magnetic field differs. Figure 18.9 shows how the magnitude of the output voltage (induced e.m.f.) changes as the coil rotates. Note that the alternating voltage in turn produces an alternating current (hence the name *alternating current* generator).

The horizontal and vertical red arrows in the diagram shows the direction of the forces produced. These forces cause the coil to turn.



① When the plane of the coil is parallel to the magnetic field, the arms AD and BC cut across the magnetic field lines at the greatest rate. Since the rate of change of magnetic flux is maximum, the magnitude of the induced e.m.f. is maximum.

② When the plane of the coil is perpendicular to the magnetic field, the arms AD and BC do not cut across the magnetic field lines. Since the rate of change of the magnetic flux is zero, the magnitude of the induced e.m.f. is zero.

③ After the coil rotates half a cycle, it is parallel to the magnetic field again. The magnitude of the induced e.m.f. is maximum. Note that since the arms AD and CB are moving in directions opposite to those in step 1, the direction of the induced e.m.f. is opposite to that in step 1.

④ The arms AD and BC of the coil do not cut across the magnetic field lines. The magnitude of the induced e.m.f. is zero.

⑤ The coil has rotated one complete cycle. It is parallel to the magnetic field again, and hence the maximum induced e.m.f. is produced.

Figure 18.9 *The induced e.m.f. varies with the position of the coil.*

QUICK CHECK

Look at the coil in step 1 of Figure 18.9. The induced current is flowing from D to A.

True or false?

We can increase the magnitude of the induced e.m.f. of an a.c. generator by

1. increasing the number of turns in the coil (Figure 18.10);
2. using stronger permanent magnets;
3. increasing the frequency of rotation of the coil (Figure 18.11);
4. winding the coil around a soft iron core to strengthen the magnetic flux linking the coil.

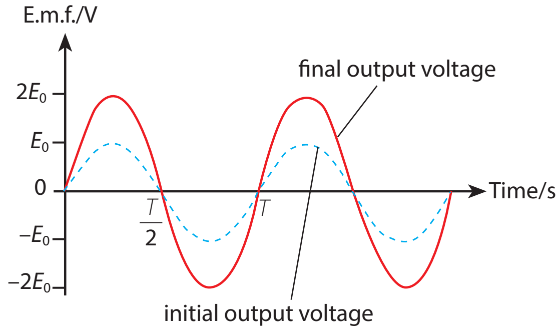


Figure 18.10 Doubling the number of turns of the coil doubles the maximum output voltage

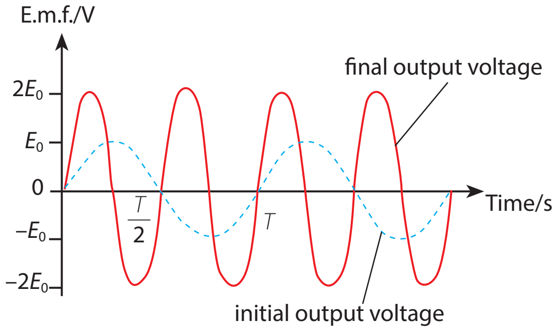


Figure 18.11 Doubling the frequency f doubles the maximum output voltage.

Worked Example 18B

(a) Explain why rotating a coil between two magnets generates an induced e.m.f.

(b) On the same axes, sketch the graphs of induced e.m.f. against time for a time interval of 0.6 s for the coil when it rotates

- 5.0 times per second, and the induced e.m.f. generated has a maximum value of 40 mV;
- 2.5 times per second. Note that the maximum value of the e.m.f. changes when the frequency of rotation changes.

Assume that the plane of the coil is parallel to the magnetic field at t = 0 s.

Solution

(a) When the coil rotates, it cuts across the magnetic field lines, and there is a change in the magnetic flux in the coil. By Faraday's Law, this change induces an e.m.f. in the coil.

(b) Period $T_1 = \frac{1}{f_1} = \frac{1}{5.0 \text{ Hz}} = 0.2 \text{ s}$

Period $T_2 = \frac{1}{f_2} = \frac{1}{2.5 \text{ Hz}} = 0.4 \text{ s}$

The maximum value of the induced e.m.f. (i.e. the amplitude of the graph) is halved when the frequency of rotation is halved (Figure 18.12).

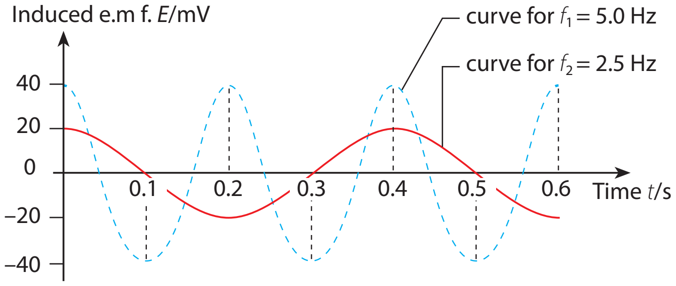


Figure 18.12

HELPFUL NOTES

1 Hz means 1 cycle per second.

So $\frac{1}{5.0 \text{ Hz}} = \frac{1}{5.0 \frac{1}{s}}$

$= 0.2 \text{ s}$

The practical design of an a.c. generator

In a simple a.c. generator, it is the coil that rotates between fixed magnets. However, we can also have an a.c. generator in which magnets rotate with respect to fixed coils. This type of a.c. generator is called a **fixed coil generator**. An example of a fixed coil generator is the bicycle dynamo (Figure 18.13).

① A magnet is attached to an axle and a wheel. As the wheel rotates, the magnet rotates too.

② The magnetic field rotates with respect to a fixed coil. This changes the magnetic flux in the coil. An induced e.m.f. is generated, and this in turn creates an induced current.

③ The induced current is channelled directly to the external circuit through the output terminals. Slip rings and carbon brushes are not needed.

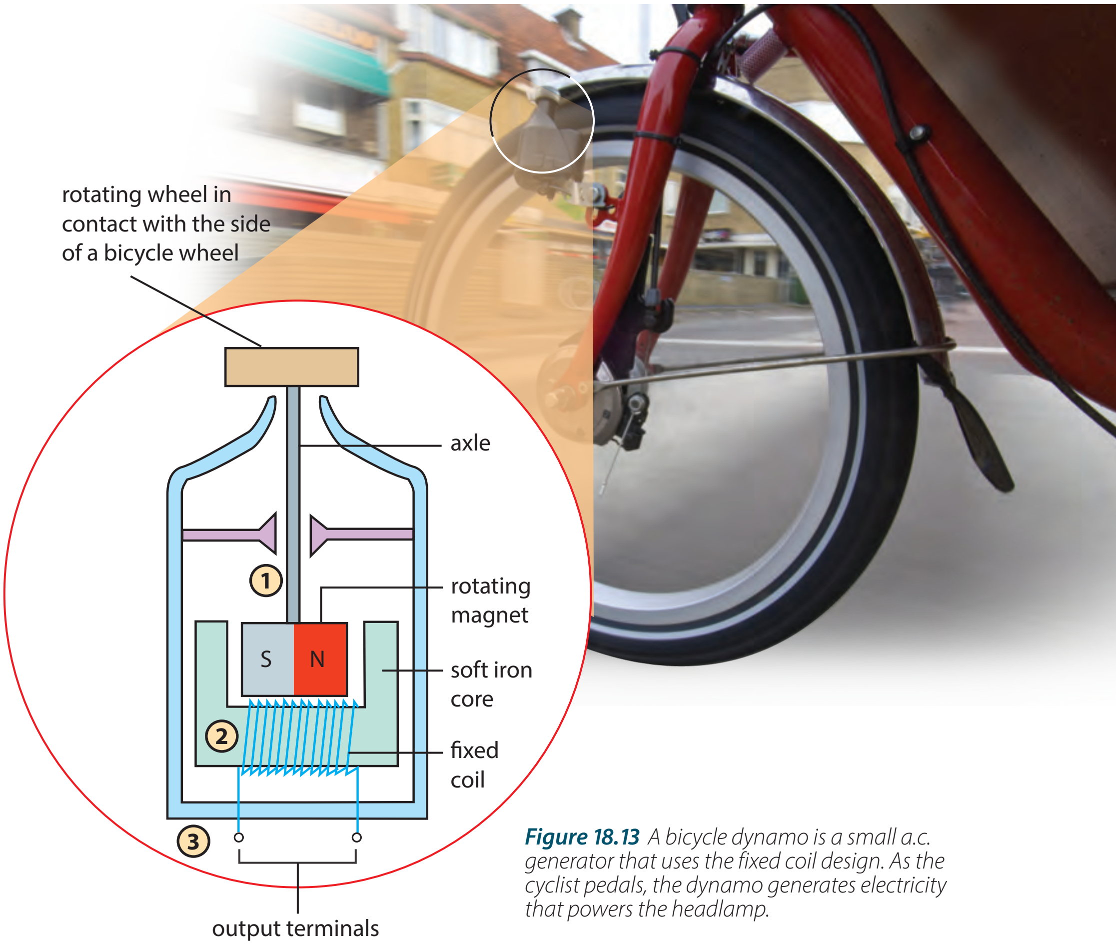


Figure 18.13 *A bicycle dynamo is a small a.c. generator that uses the fixed coil design. As the cyclist pedals, the dynamo generates electricity that powers the headlamp.*

In practical applications, a fixed coil a.c. generator is favoured for the following reasons:

1 It does not require carbon brushes, which wear out easily and need to be replaced frequently.
2 It is less likely to break down from overheating. This is because it does not use slip rings and carbon brushes. An eroded connection between slip rings and carbon brushes has increased resistance, which can generate large quantities of heat.
3 It is more compact.

Let's Practise 18.2

1 Name the components of an a.c. generator that allow the transfer of the induced alternating current to an external circuit.
2 Sketch a graph of output voltage against time of an a.c. generator for two complete rotations of the coil.
3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 18B, pp. XX–XX

18.3 Magnetic Effect of a Current

In this section, you will learn the following:

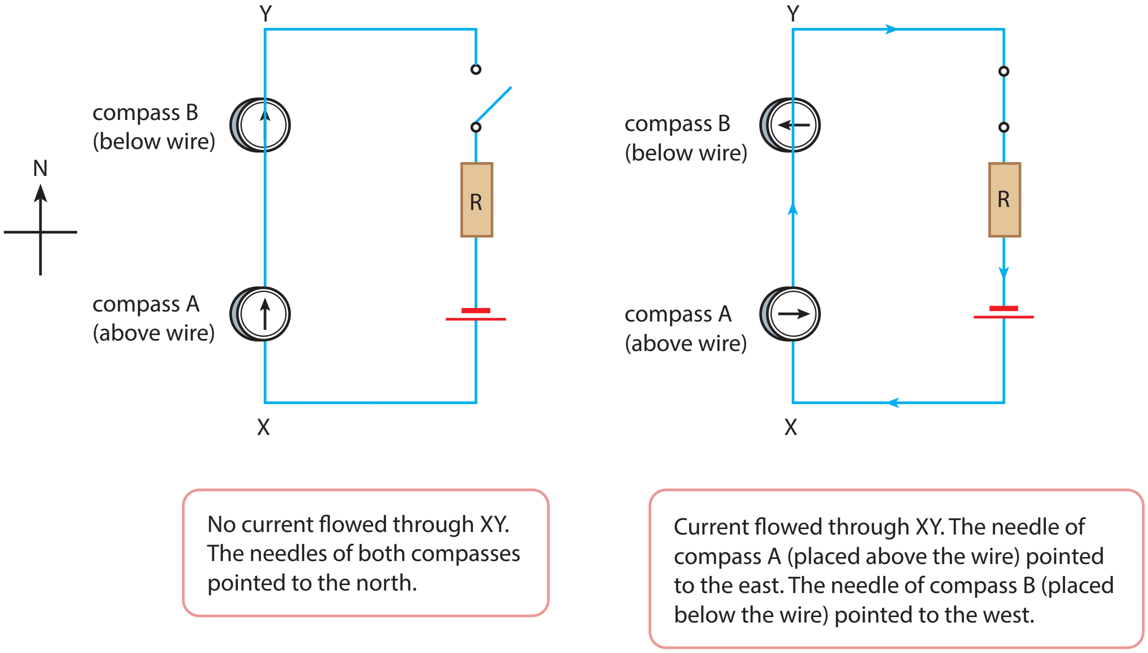
- Describe the pattern and direction of the magnetic field due to currents in straight wires and in solenoids.
- Describe an experiment to identify the pattern of the magnetic field (including direction) due to currents in straight wires and in solenoids.
- Describe how the magnetic effect of a current is used in relays and loudspeakers and give examples of their application.
- Ⓢ State the qualitative variation of the strength of the magnetic field around straight wires and solenoids.
- Ⓢ Describe the effect on the magnetic field around straight wires and solenoids of changing the magnitude and direction of the current.

How did Oersted discover electromagnetism?

In 1820, Hans Christian Oersted, a Danish professor, discovered the magnetic effect of an electric current by accident. During a class demonstration, he noticed that when a current was flowing through a wire, it caused the needle of a compass nearby to be deflected. This indicated the presence of a magnetic field. Oersted's observation eventually led to the discovery of **electromagnetism** — the relationship between electricity and magnetism.

Figure 18.14 shows the result of Oersted's experiment. Note that wire XY was placed in the north–south direction. Oersted's experiment showed that a magnetic field was present when a current flowed through wire XY.

A current-carrying conductor produces a magnetic field around it.



No current flowed through XY. The needles of both compasses pointed to the north.

Current flowed through XY. The needle of compass A (placed above the wire) pointed to the east. The needle of compass B (placed below the wire) pointed to the west.

(a) Open circuit

(b) Closed circuit

Figure 18.14 *The positions of the needles of compasses A and B in Oersted's experiment*

What are the shapes and directions of magnetic field lines?

Magnetic field pattern around a straight wire

Let's Investigate 18B describes an experiment that can be conducted to plot the magnetic field pattern around a straight current-carrying wire.

Let's Investigate 18B

Objective

To plot magnetic field lines around a straight current-carrying wire with a compass

Apparatus

Straight wire, plotting compass, cardboard, pencil, e.m.f. source

Procedure

1. Thread a wire through a small hole in a sheet of cardboard. The wire should be perpendicular to the cardboard sheet (Figure 18.15). Connect the wire to an e.m.f. source such that the current flows up the wire.
2. Place a compass on the cardboard sheet.
3. On the cardboard sheet, mark the positions of the S and N ends of the compass needle with pencil dots X and Y respectively.
4. Move the compass so that the S end of the needle is now at Y (Figure 18.16).
5. Mark the new position of the N end of the needle with a third dot Z.
6. Repeat steps 2 to 5, placing the compass at different distance from the wire until several field lines are drawn.

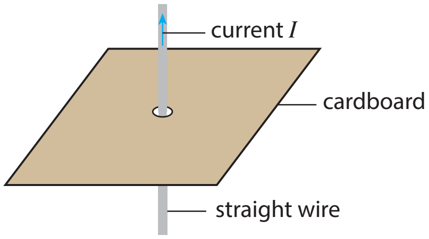


Figure 18.15 A wire threaded through a cardboard sheet

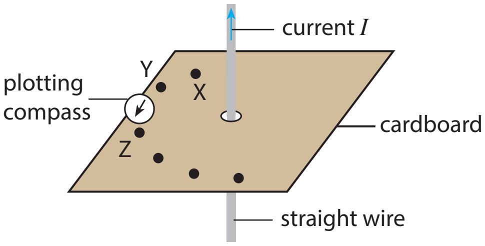


Figure 18.16 The positions of the S and N ends of the compass needle are marked with pencil dots.

Observation and discussion

- The magnetic field plot obtained consisted of concentric circles (Figure 18.17).
- The circles nearer the wire were closer to one another. This implies that the magnetic field was stronger at regions nearer the wire.

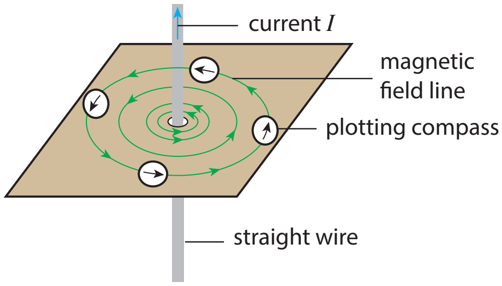


Figure 18.17 The magnetic field pattern of a straight wire

We can determine the direction of the magnetic field around the wire using the **right-hand grip rule** (Figure 18.18).

PHYSICS WATCH

Scan this page to explore a simulation on magnetic field patterns.

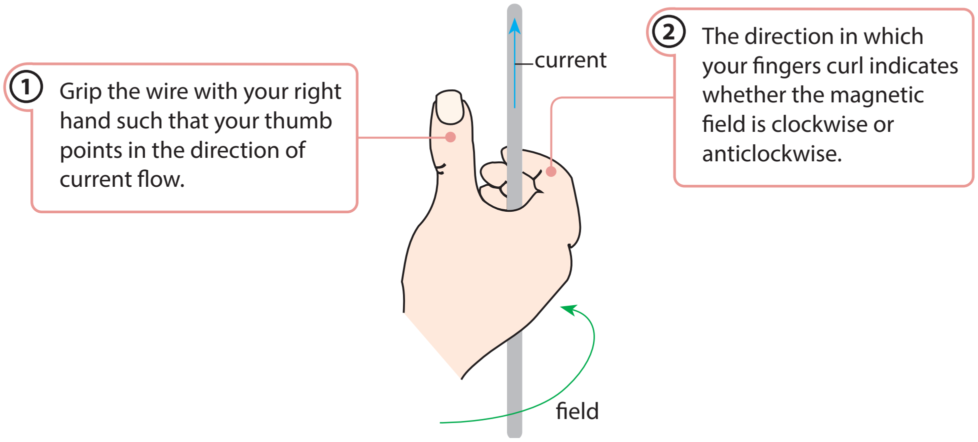


Figure 18.18 *The right-hand grip rule*

The factors that affect the direction and strength of a magnetic field around a current-carrying straight wire are shown in Figures 18.19 and 18.20.

(a) Direction of current reversed

The direction of the magnetic field of a current-carrying wire is reversed when the direction of the current is reversed.

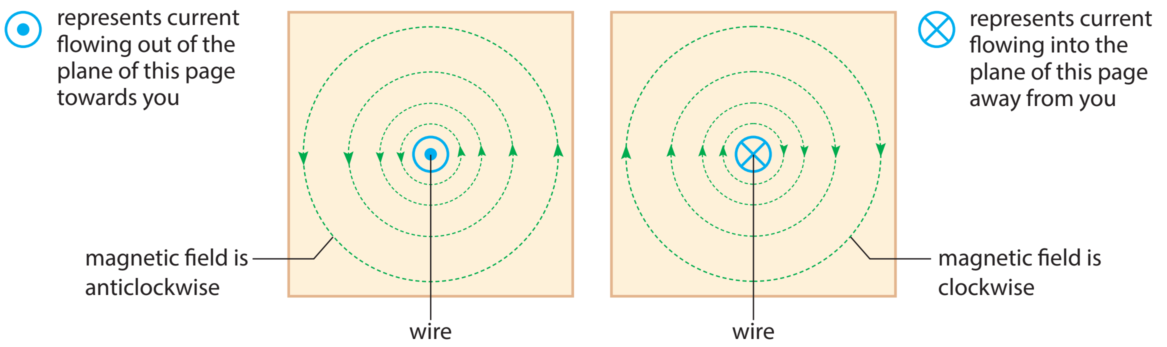


Figure 18.19 *When the direction of the current is reversed, the direction of the magnetic field is reversed.*

(b) Magnitude of current increased

HELPFUL NOTES

When drawing the magnetic field around a straight current-carrying wire, remember that the magnetic field lines should be further apart with increasing distance from the wire.

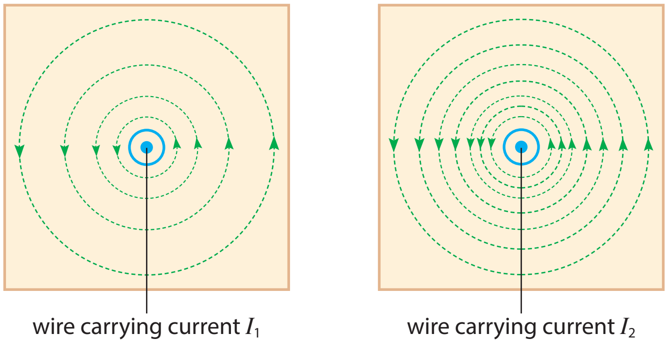


Figure 18.20 *When the current is increased from I_1 to I_2, the strength of the magnetic field increases.*

The strength of the magnetic field of a current-carrying wire increases when the current is increased. Note that the strength of the magnetic field around the wire is not uniform. It depends on the distance from the wire. The magnetic field is stronger closer to the wire. This is represented by drawing the magnetic field lines closer together near the wire.

HELPFUL NOTES

You can use the right-hand grip rule (Figure 18.22) to deduce which end of a solenoid the north pole is.

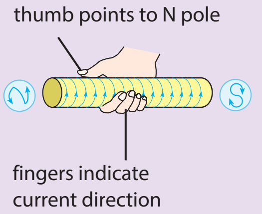


Figure 18.22

QUICK CHECK

The right-hand end of the solenoid in Figure 18.21 is a North pole.

True or false?

LINK

Practical 18B, pp. XX–XX

Magnetic field pattern of a solenoid

We can do a similar experiment to the one in Let's Investigate 18B using a solenoid.

Figure 18.21 shows the magnetic field pattern of a solenoid.

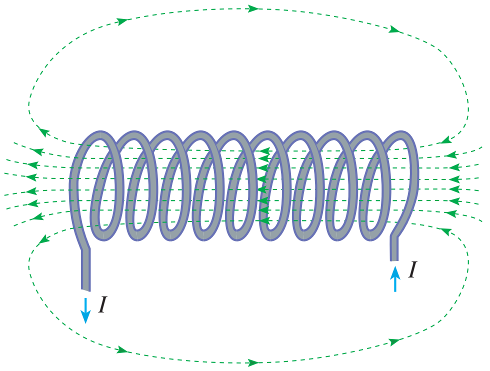


Figure 18.21 *Diagram of the magnetic field lines of a solenoid*

From the diagram, we observe the following:

- The magnetic field pattern of a solenoid resembles that of a bar magnet. Thus, the solenoid acts like a bar magnet. It has two poles and can be used as an electromagnet.
- The magnetic field lines inside the solenoid are closer together than the field lines outside. This means that the magnetic field inside the solenoid is stronger. The magnetic field inside the solenoid can be taken to be uniform.

In addition, if a soft iron core is placed within the solenoid, it will concentrate the magnetic field lines and increase the magnetic field strength of the solenoid.

The magnetic field strength in a solenoid can be increased by

- increasing the current flowing through the solenoid;
- increasing the number of turns per unit length of the solenoid;
- placing a soft iron core within the solenoid.

What devices make use of electromagnetism?

Relay

A relay is a device that consists of two circuits (Figure 18.22). The primary circuit, controlled by a switch, is designed to work at a low, safe current. When the primary circuit is complete, the electromagnet is energised. The iron lever is attracted to the electromagnet and in moving, it pushes the moveable contact. This causes the moveable contact to touch the fixed contact, making the secondary circuit complete. The secondary circuit could contain a very much higher voltage supply and a high power device such as a motor.

The advantage of using a relay is that there is no electrical connection between the user activating the switch and the secondary circuit. The user can activate the device in the secondary circuit remotely. This is especially helpful if the device is somewhere that is otherwise unsafe for the user or is a large distance away.

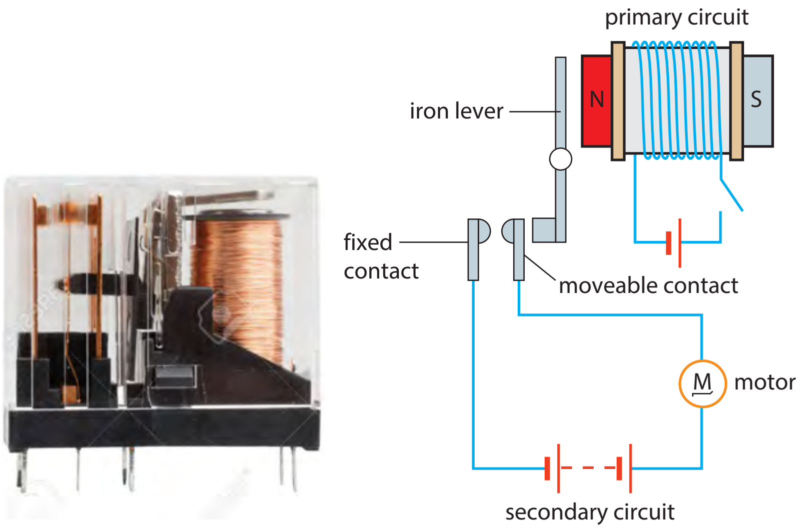


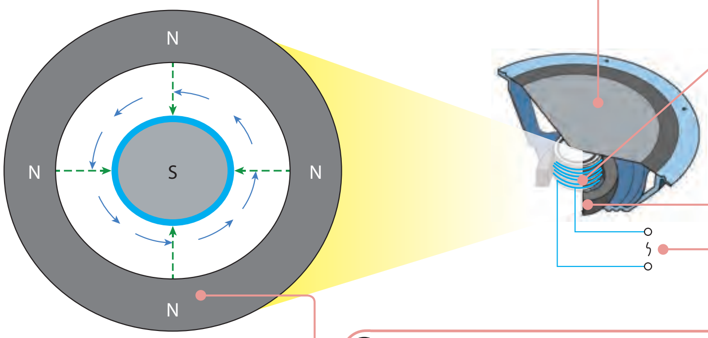
Photo of an electrical relay

Diagram of a relay circuit

Figure 18.22 *Can you identify some parts of a relay in the photo.*

Moving-coil loudspeaker

Figure 18.23 shows how electromagnetism is used in a loudspeaker.



⑤ The loudspeaker diaphragm vibrates due to the alternating attraction and repulsion between the temporary and permanent magnets.

If the frequency of the a.c. supply is 200 Hz, then the coil will vibrate at a frequency of 200 Hz.

③ The coil of wire becomes a temporary magnet when current flows through the coil. Each time the current reverses direction, the poles of the temporary magnet reverses and the force on the coil will also reverse direction.

② A strong permanent magnet is used to provide a constant static magnetic field.

④ S The current is shown flowing counter-clockwise around the coil. Using Fleming's left-hand rule (see page 314), the force on the coil will be outwards (towards you the reader). When the current changes direction, the force on the coil will be inwards, away from you.

① A moving coil is connected to a circuit that provides a.c. (alternating current). A pure wave a.c. supply will give a pure, single-toned note from a loudspeaker.

Figure 18.23 *Use of electromagnet in a moving-coil loudspeaker*

The magnetic component in the loudspeaker is designed so that the magnetic field lines are always at right angles to the current direction. This makes this design very much more efficient.

Let's Practise 18.3

1 Figure 18.24 shows a current flowing in a long straight wire. In the diagram, draw the pattern and direction of the magnetic field produced.

2 **(a)** Draw the magnetic field lines around a current-carrying solenoid.

(b) Name **three** ways to increase the magnetic field strength of a solenoid.

3 Explain what would happen if the iron core of the solenoid in a circuit breaker were replaced with a steel one.

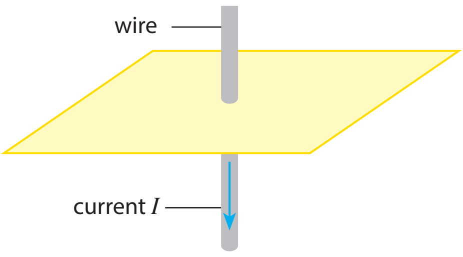


Figure 18.24

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

TWB **LINK**

Exercise 18C, pp. XX–XX

18.4 Force on a Current-carrying Conductor

In this section, you will learn the following:

- Describe an experiment to show that a force acts on a current-carrying conductor in a magnetic field.
- Ⓢ Recall and use the relative directions of force, magnetic field and current.
- Ⓢ Determine the direction of the force on beams of charged particles in a magnetic field.

Do current-carrying conductors affect each other?

In the previous section, you have learnt that a current-carrying wire produces a magnetic field around it. What happens if the current-carrying conductor is placed in another magnetic field?

Let's Investigate 18C describes an experiment to demonstrate the motor effect.

Let's Investigate 18B

Objective

To demonstrate that a force acts on a current-carrying conductor when it is placed in a magnetic field (i.e. the motor effect)

Apparatus

Stiff wire, strong permanent U-shaped magnet, 9 V dry cell, switch, connecting wires

Procedure

1 Bend a stiff wire into the shape of a swing ABCD (Figure 18.25).

2 Set up the apparatus as shown in Figure 18.25. The wire swing is connected to a dry cell and a switch by copper wires.

3 Close the switch. Observe the direction in which the wire swings.

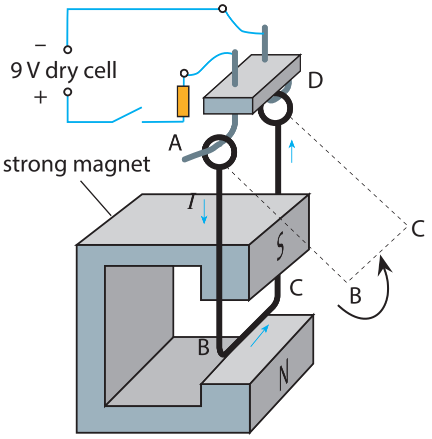


Figure 18.25 *A current-carrying wire swing placed in a magnetic field*

4 Reverse the polarity of the dry cell to reverse the direction of the current and repeat step 3. In which direction does the swing move now?

5 Invert the magnet so that the N pole is now above the wire section BC. Repeat step 3.

Observation

1 When current flowed in the direction A to B to C to D, the wire swung outwards, away from the magnet.

2 When the direction of the current was reversed, the wire swung in the opposite direction, i.e., it swung inwards, towards the magnet.

3 When the magnetic field was reversed, the wire swung outwards again.

In all three scenarios, we observe that the wire moved when current flowed through it. This shows that *a force acts on a current-carrying wire when it is placed in a magnetic field*.

LINK PWB

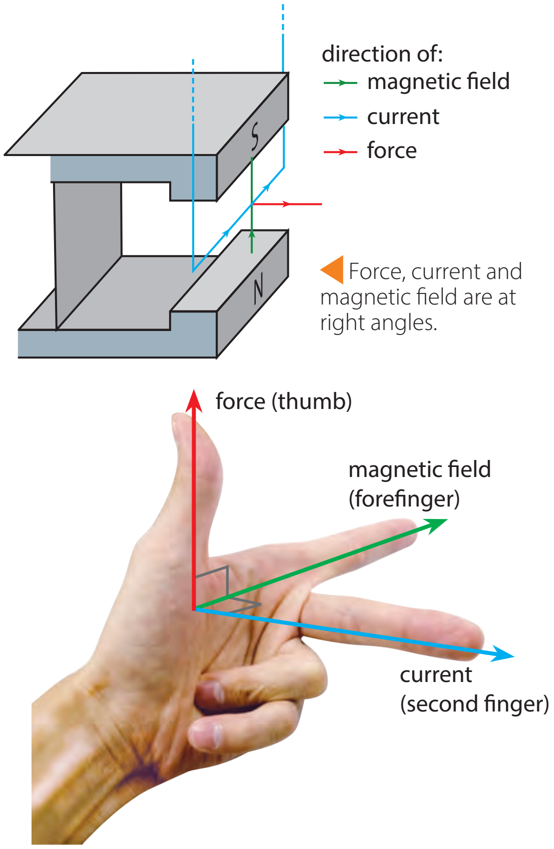
Practical 18C, pp. XX–XX

From Let's Investigate 18C, the following conclusions can be made:

- The direction of the force on a current-carrying conductor is reversed when we reverse the direction of the current or the magnetic field.
- The force, current and magnetic field are at right angles to one another.

Fleming's left-hand rule

We can deduce the direction of the force acting on a current-carrying conductor in a magnetic field using **Fleming's left-hand rule** (Figure 18.26).



① Point your thumb, forefinger and second finger at right angles to one another.

② Point your forefinger in the direction of the magnetic field (N-to-S direction) and your second finger in the direction of the current.

③ Your thumb then gives the direction of the motion of the wire, i.e., the direction of the force. In fact, given any two of the directions, we can deduce the remaining one.

Figure 18.26 *Fleming's left-hand rule*

Worked Example 18C

Figure 18.27 shows a wire placed between two magnetic poles. State what happens when the current in the wire flows from

(a) A to B;

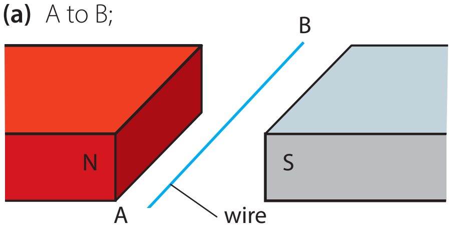


Figure 18.27

(b) B to A.

Solution

(a) When a current-carrying wire is placed in a magnetic field, a force acts on it. Using Fleming's left-hand rule, we find that the force acts vertically downwards on the wire (Figure 18.28).

(b) Using Fleming's left-hand rule, we find that the force acts vertically upwards on the wire.

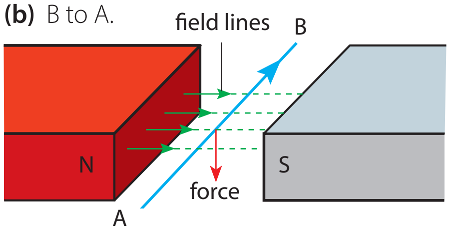


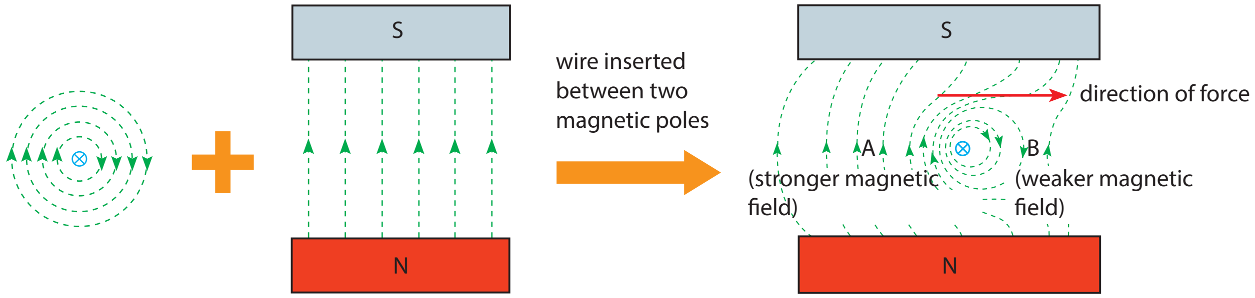
Figure 18.28 *The force acts vertically downwards when current flows from A to B.*

PHYSICS WATCH

Scan this page to explore a simulation on force on a current-carrying conductor.

What causes the motor effect?

Examine what happens when the magnetic field due to the current in a wire is combined with the magnetic field of a magnet (Figure 18.29).



(a) Magnetic field due to current in wire

(b) Magnetic field between two magnetic poles

(c) Combined magnetic field of wire and magnetic poles

Figure 18.29 *How magnetic fields combine when a current-carrying wire is placed between the poles of a magnet*

From Figure 18.29(c), we can see that at point A, the magnetic fields produced by the current-carrying wire and by the magnetic poles act in the same direction. They reinforce each other and so the magnetic field at point A is stronger. At point B, the magnetic field of the current-carrying wire is in the opposite direction to the magnetic field of the magnetic poles. Thus, the combined magnetic field at point B is weaker.

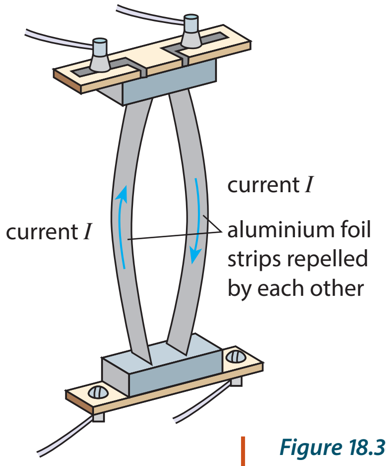
The *difference between the magnetic field strength* at A and at B results in a net force acting on the wire. The force acts towards the weaker field.

Forces between two parallel current-carrying conductors

When we place two current-carrying conductors parallel to each other, the magnetic fields of both wires *combine*. The combined magnetic field results in forces acting on each conductor.

Currents in opposite directions

Figure 18.30 shows the forces that act on two parallel strips of aluminium foil carrying currents in opposite directions.



Explanation: To understand the repulsion of the aluminium foil strips, consider the cross-section (top view) of a pair of parallel current-carrying wires.

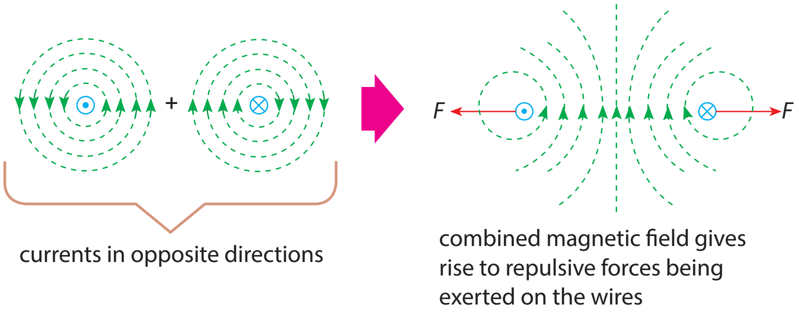
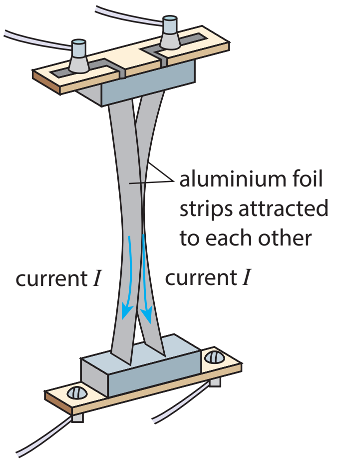


Figure 18.30 *Parallel aluminium foil strips carrying current in opposite directions repel each other.*

Conductors carrying currents in opposite directions repel.

Currents in same direction

Figure 18.31 shows the forces that act on two parallel strips of aluminium foil carrying currents in the same direction.



Explanation: To understand the attraction of the aluminium foil strips, consider the cross-section (top view) of a pair of parallel current-carrying wires.

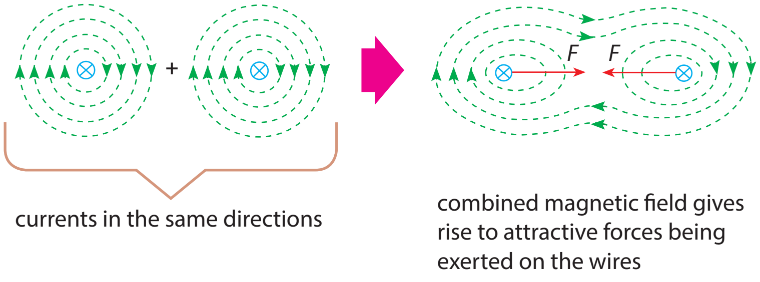


Figure 18.31 *Parallel aluminium foil strips carrying currents in the same direction attract each other.*

Conductors carrying currents in the same direction attract.

Force on a beam of charged particles in a magnetic field

In Chapter 17, you have learnt that current consists of moving charges. A current-carrying conductor experiences a force when placed in a magnetic field. Since a beam of charged particles is essentially a line of charged particles, we can examine the effects of a magnetic field on a beam of charged particles by examining the effect of a magnetic field on a single moving charge.

Positive charge moving in a magnetic field

Figure 18.32 shows the force acting on a positively charged particle moving through a magnetic field.

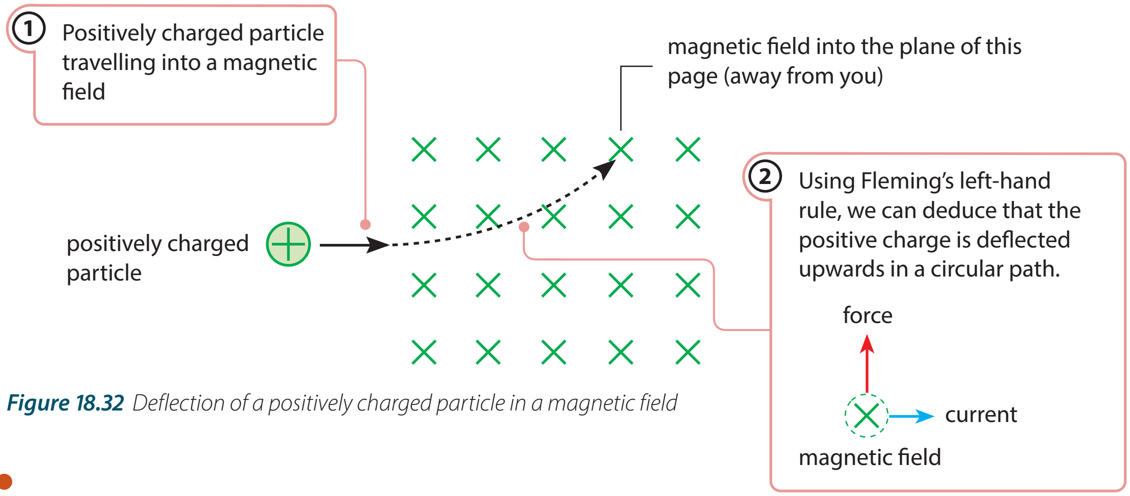


Figure 18.32 *Deflection of a positively charged particle in a magnetic field*

QUICK CHECK

A magnetic field can exert a force on a stationary charge.

True or false?

ENRICHMENT *ACTIVITY*

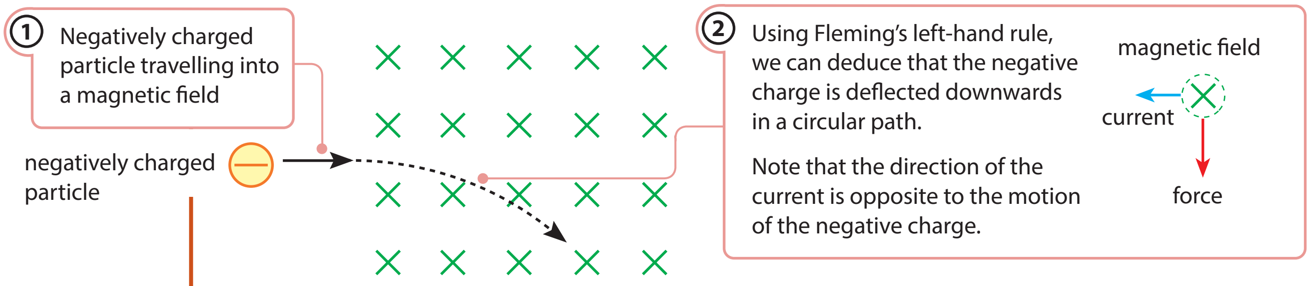
A mass spectrometer is a device that can work out the chemical composition of unknown substances.

Find out how a mass spectrometer uses a magnetic field to distinguish between chemical elements.

Share your findings with the class.

Negative charge moving in a magnetic field

Figure 18.33 shows what would happen to the force if the positive charge in Figure 18.32 were replaced with a negative charge (e.g. an electron).



① Negatively charged particle travelling into a magnetic field

② Using Fleming's left-hand rule, we can deduce that the negative charge is deflected downwards in a circular path.

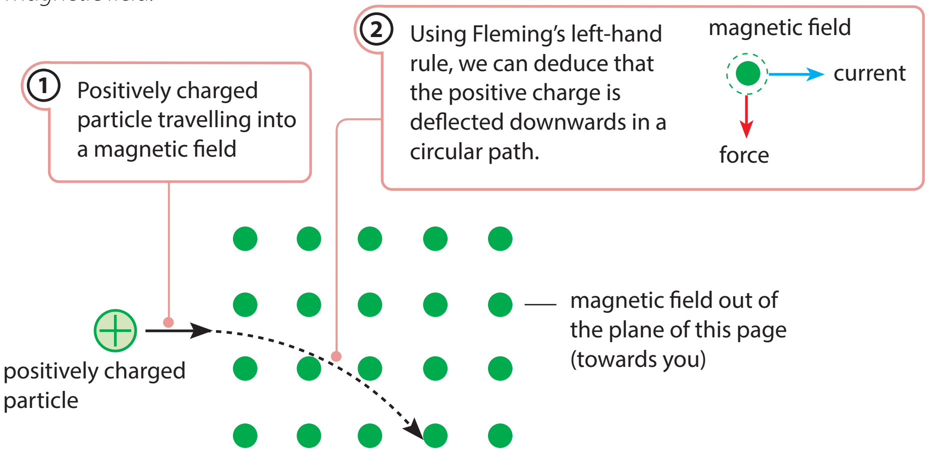
Note that the direction of the current is opposite to the motion of the negative charge.

Figure 18.33 Deflection of a negatively charged particle in the same magnetic field

Reversing the magnetic field

Other than the charge of the particles, what do you think affects the direction of the force acting on the particles? Figure 18.34 shows what happens to the force acting on the positively charged particle (in Figure 18.33) if the magnetic field is reversed.

The direction of the force on a beam of charged particles is reversed when we reverse the direction of the magnetic field.



② Using Fleming's left-hand rule, we can deduce that the positive charge is deflected downwards in a circular path.

① Positively charged particle travelling into a magnetic field

Figure 18.34 The positively charged particle is deflected downwards when the magnetic field is reversed.

Let's Practise 18.4

1 Figure 18.35 shows a current-carrying wire placed between the poles of a magnet.

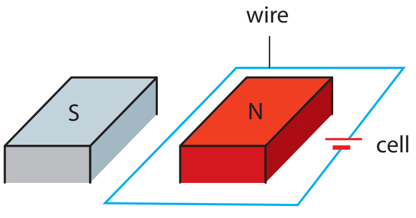


Figure 18.35

(a) On the diagram, mark the direction of the force acting on the wire AB.

(b) Describe what happens to the motion of the wire AB if the poles of the magnets are reversed.

2 S Consider two parallel wires with currents flowing in the same direction.

(a) Draw a diagram showing the forces acting on each wire.

(b) State the change(s) that can be made to increase the magnitude of each force.

(c) Explain what will be observed if two current carrying wires are placed perpendicular to each other.

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

LINK TWB

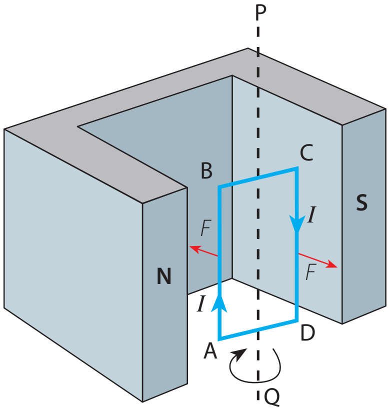
Exercise 18D, pp. XX–XX

18.5 The D.c. Motor

In this section, you will learn the following:

- Know that a current-carrying coil in a magnetic field experiences a turning effect and the factors that can increase the turning effect.
- S Describe the operation of an electric motor, including the action of a split-ring commutator and brushes.

In Section 18.4, you have learnt that a straight current-carrying wire placed between the poles of a magnet experiences a force. Figure 18.36 shows what happens if the straight current-carrying wire is replaced with a current-carrying wire coil.

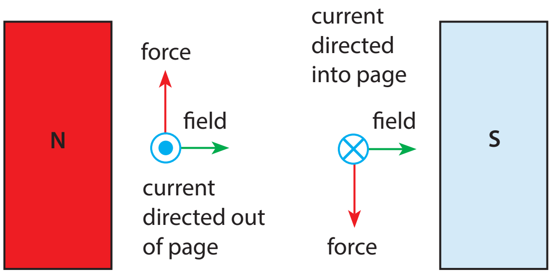


① A stiff wire coil ABCD is placed between the poles of a strong magnet. A current is passed through the coil.

② The coil experiences a **turning effect** about the axis PQ.

Figure 18.36 *Current-carrying wire coil placed between two magnetic poles*

What causes the turning effect of coil ABCD in the set-up in Figure 18.36? To understand this turning effect, we consider the top view of the cross-section of the set-up (Figure 18.37).



The two forces produce a turning effect.

Note: Fleming's left-hand rule was used to deduce the directions of the forces on wire sections AB (current out of page) and CD (current into page).

Figure 18.37 *Top view of cross-section of set-up in Figure 18.36*

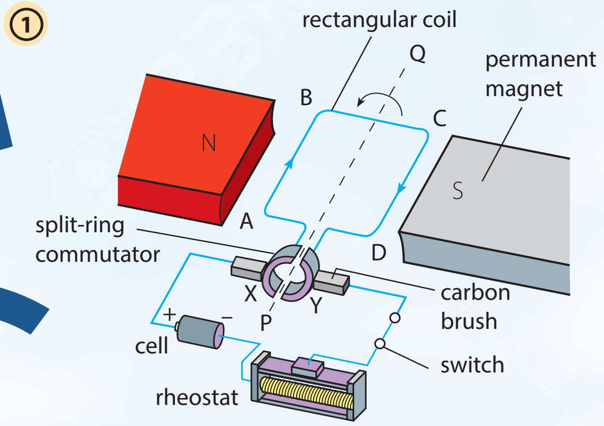
The turning effect on a current-carrying wire coil can be increased by increasing

- the number of turns in the wire coil;
- current in the wire coil;
- the strength of the magnetic field.

The d.c. motor

An important application of the turning effect on a current-carrying coil in a magnetic field is the **direct current (d.c.) motor**. A d.c. motor is used to convert electrical energy to mechanical energy. It is commonly used in battery-operated toys, DVD players and hard disk drives. Figure 18.38 shows how a d.c. motor works.

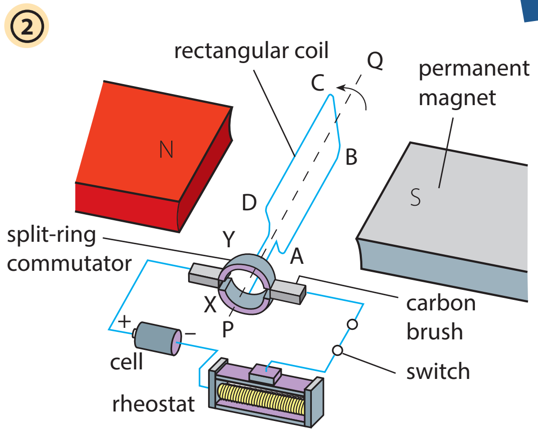
a d.c. motor



Structure of a d.c. motor:

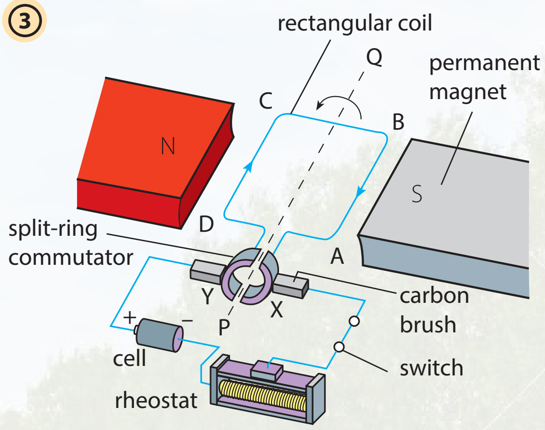
1. A rectangular wire coil ABCD is mounted on an axle (represented by the dotted line PQ) that allows it to rotate about PQ.
2. The coil and the axle are positioned in between the poles of a permanent magnet.
3. The ends of coil ABCD are connected to a split-ring commutator XY. The commutator rotates with the coil.
4. Two carbon brushes press lightly against the commutator.

Using Fleming's left-hand rule, we know that a downward force acts on wire section AB, and an upward force on wire section CD. The coil thus rotates anticlockwise about PQ until it reaches a vertical position.



- When the coil is in the vertical position, the current is cut off because the split ring commutator XY is not in contact with the carbon brushes.
- The momentum of the coil, however, carries it past the vertical position.

it is common to find d.c. motors in small devices.



- The direction of the currents flowing through wire sections AB and CD is now reversed. An upward force now acts on AB, and a downward force acts on CD.
- Hence, the coil continues to rotate in the anticlockwise direction.

Figure 18.38 *How a d.c motor works*

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

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

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

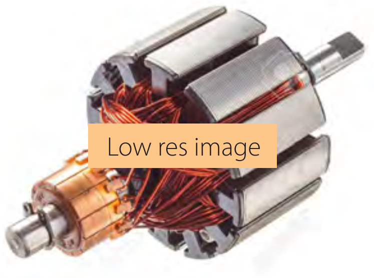


Figure 18.39 *Practical d.c. motors, like the one shown above, have hundreds of turns of wire with a soft iron core at the centre.*

ENRICHMENT ***THINK***

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

Let's Practise 18.5

1 The coil in a particular d.c. motor rotates in an anticlockwise direction. State the change(s) that must be made in order for the coil to rotate in a clockwise direction.

2 Explain the purpose of the rheostat in the d.c. motor.

3 State the energy conversion that takes place in the d.c. motor.

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

LINK

Exercise 18E, pp. XX–XX

18.6 The Transformer

In this section, you will learn the following:

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

LINK

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

Refer to Chapter 15.

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

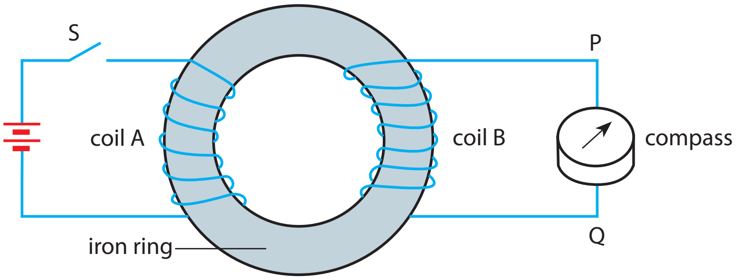


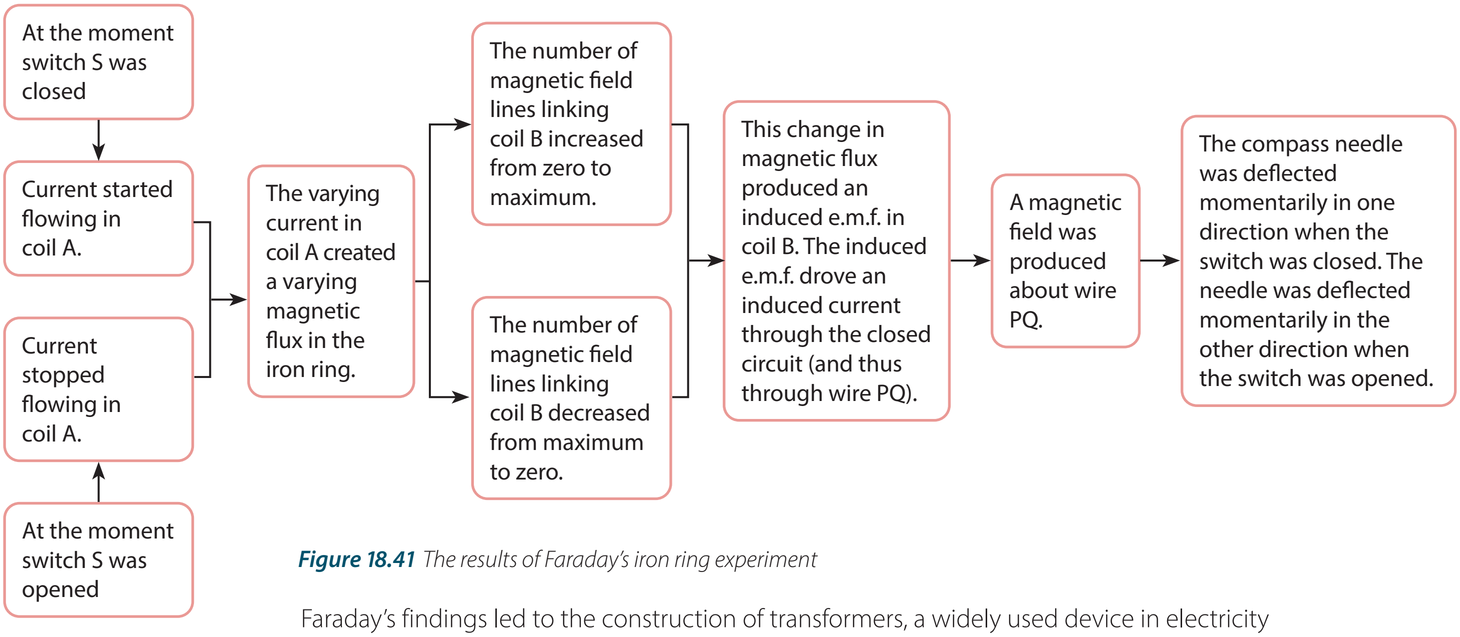
Figure 18.40 *Faraday's iron ring experiment*

QUICK CHECK

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

True or false?

Figure 18.41 summarises the results of Faraday's experiment.


At the moment switch S was closed

Current started flowing in coil A.

Current stopped flowing in coil A.

At the moment switch S was opened

The varying current in coil A created a varying magnetic flux in the iron ring.

The number of magnetic field lines linking coil B increased from zero to maximum.

The number of magnetic field lines linking coil B decreased from maximum to zero.

This change in magnetic flux produced an induced e.m.f. in coil B. The induced e.m.f. drove an induced current through the closed circuit (and thus through wire PQ).

A magnetic field was produced about wire PQ.

The compass needle was deflected momentarily in one direction when the switch was closed. The needle was deflected momentarily in the other direction when the switch was opened.

Figure 18.41 *The results of Faraday's iron ring experiment*

Faraday's findings led to the construction of transformers, a widely used device in electricity transmission. In the following sections, you will learn what transformers are and how they work.

What is a transformer?

The mains supply voltage for homes in many Asian countries such as Singapore is between 220 V and 240 V. However, different electrical appliances operate at different voltages. For example, a typical mobile phone only needs about 5 V. To convert the mains supply voltage to a suitable voltage for different appliances, transformers are used.

A **transformer** is a device that can change a high alternating voltage (at low current) to a low alternating voltage (at high current), or vice versa.

Transformers are used in

1. electrical power transmission from power stations to households and industries;
2. regulating voltages for the proper operation of electrical appliances.

Structure and operation of a transformer

The structure (Figure 18.42) and workings of a transformer are based on Faraday's findings in the iron ring experiment.

- Two coils, the **primary** coil and the **secondary** coil, are wound around a laminated soft iron core.
- Each coil has a certain number of turns.

- The laminated soft iron core comprises thin sheets of soft iron. These sheets are insulated from one another by coats of lacquer.
- Soft iron is used because it is easily magnetised and demagnetised. This ensures better magnetic flux linkage between the two coils.
- The lamination reduces heat loss.

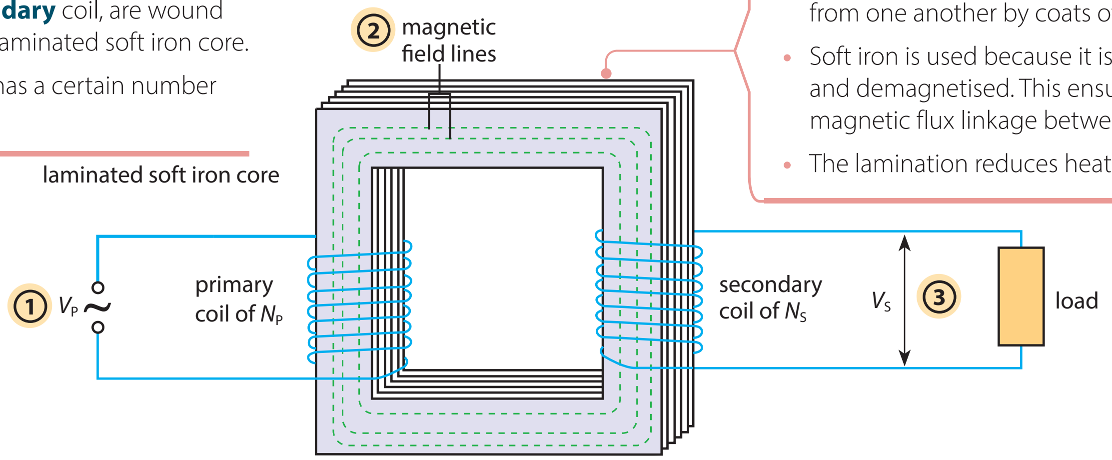


Figure 18.42 *Structure of a transformer*

S The workings of a transformer are as follows (refer to Figure 18.42):

① The primary coil is connected to an alternating voltage — the **input voltage** V_P.

→

② A varying magnetic field is set up in the laminated soft iron core.

→

③ An e.m.f. V_S is induced in the secondary coil. This voltage is called the **output voltage**. Since the circuit is closed, a current is also induced in the coil.

Electrical energy is transferred from the primary coil to the secondary coil in a transformer. The voltages and the number of turns in the primary and secondary coils are related by this formula:

$$\frac{V_P}{V_S} = \frac{N_P}{N_S}$$

where V_S = secondary (output) voltage (in V)
V_P = primary (input) voltage (in V)
N_S = number of turns in secondary coil
N_P = number of turns in primary coil

In a **step-up** transformer, the number of turns in the secondary coil is greater than that in the primary coil. This results in an output voltage that is higher than the input voltage.

In a **step-down** transformer, the converse is true. The number of turns in the secondary coil is less than that in the primary coil, so that the output voltage produced is lower than the input voltage.

QUICK CHECK

$\frac{N_P}{N_S}$ for a step-up transformer is less than 1.

True or false?

S Power transmission in a transformer

In an ideal transformer, there is no power loss (i.e. the efficiency is 100%). The power supplied to the primary coil is fully transferred to the secondary coil. Hence, from the principle of conservation of energy, power in the primary coil = power in the secondary coil.

$$I_P V_P = I_S V_S$$

where V_S = secondary (output) voltage (in V)
V_P = primary (input) voltage (in V)
I_S = current in secondary coil (in A)
I_P = current in primary coil (in A)

LINK

Recall the equation $P = IV$ which you have learnt in Chapter 16.

From the equations $\frac{V_P}{V_S} = \frac{N_P}{N_S}$ and $I_P V_P = I_S V_S$,

we can obtain the equation $\frac{V_P}{V_S} = \frac{N_P}{N_S} = \frac{I_S}{I_P}$.

Therefore, $V_S = \left(\frac{N_S}{N_P}\right) V_P$ and $I_P = \left(\frac{N_S}{N_P}\right) I_S$.

We can see that for a step-up transformer:

1 $V_S > V_P$ by the fraction $\frac{N_S}{N_P}$;

2 $I_S < I_P$ by the same fraction $\frac{N_S}{N_P}$.

Figure 18.43 *A transformer — the coils and laminated soft iron core can be seen. The design of this transformer differs from the one shown in Figure 18.42. What other designs are there, and why?*

The converse is true for a step-down transformer (Table 18.3).

Table 18.3 *Comparing step-up and step-down transformers*

Step-up transformer	Step-down transformer
$N_s > N_p$	$N_s < N_p$
$V_s > V_p$	$V_s < V_p$
$I_s < I_p$	$I_s > I_p$

LINK

Recall about mechanical efficiency which you have learnt in Chapter 6.

In reality, transformers are not ideal. There is power loss, and therefore the efficiency is less than 100%. The efficiency of a transformer can be calculated using the following equation:

$$\textbf{Efficiency} = \frac{\textbf{output power}}{\textbf{input power}} \times 100\%$$

Worked Example 18D

The circuit shown in Figure 18.44 is set up.

(a) Explain briefly how a transformer works.

(b) Assuming the transformer in Figure 18.44 is 100% efficient, complete Table 18.4.

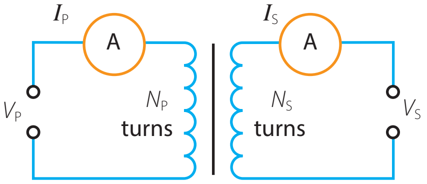


Figure 18.44

Table 18.34

V_p/V	I_p/mA	N_P turns	V_S/V	I_s/mA	N_s turns
240	2			40	50

(c) Is the transformer a step-up or step-down transformer?

(d) The transformer used in the experiment is actually non-ideal. It is found that when the primary current is 2 mA, the secondary current is 30 mA instead of 40 mA. Assuming that the secondary voltage V_S is the same as that calculated in **(b)**, calculate the efficiency of this practical transformer.

Solution

(a) The operation of a transformer is based on electromagnetic induction. An alternating current in the primary coil induces a varying magnetic field in the soft iron core. This varying magnetic field creates an alternating induced e.m.f. in the secondary coil, which generates an induced current.

(b) At 100% efficiency,

input power of primary coil = output power of secondary coil

$I_P V_P = I_S V_S$

$$V_S = \frac{I_P V_P}{I_S} = \frac{2\text{ mA} \times 240\text{ V}}{40\text{ mA}} = 12\text{ V}$$

$$\text{Using } \frac{V_P}{V_S} = \frac{N_P}{N_S},\ N_P = \frac{V_P N_S}{V_S} = \frac{240\text{ V} \times 50\text{ turns}}{12\text{ V}} = 1000\text{ turns}$$

(c) Since the number of turns in the secondary coil is less than the number of turns in the primary coil (i.e. $N_s = 50 < N_P = 1000$), the transformer is a step-down transformer.

(d) By definition,

$$\text{efficiency} = \frac{\text{output power in secondary coil}}{\text{input power in primary coil}} \times 100\%$$

$$= \frac{I_S V_S}{I_P V_P} \times 100\% = \frac{30\text{ mA} \times 12\text{ V}}{2\text{ mA} \times 240\text{ V}} \times 100\% = 75\%$$

Transformers and the transmission of electricity

There are problems in the transmission and distribution of electricity from power stations to households and industries. One of them is the *loss of power due to Joule heating* ($P = I^2R$) in the cables. This loss should be minimised for efficiency and economy.

Possible solutions:

- Use very thick cables, so that the resistance R is low. In this way, the power lost as heat in the cables is reduced. However, thicker cables increase the cable and construction costs.
- Reduce the magnitude of the current I flowing in the cables. This can be done with a step-up transformer. When the transmission voltage V is stepped up, the current I in the cables is stepped down.

HELPFUL NOTES

Voltage does not contribute to the power loss due to Joule heating. However, the output voltage affects the output current. So, we can adjust the output voltage (by adjusting the number of turns in the secondary coil of a transformer) to adjust the output current.

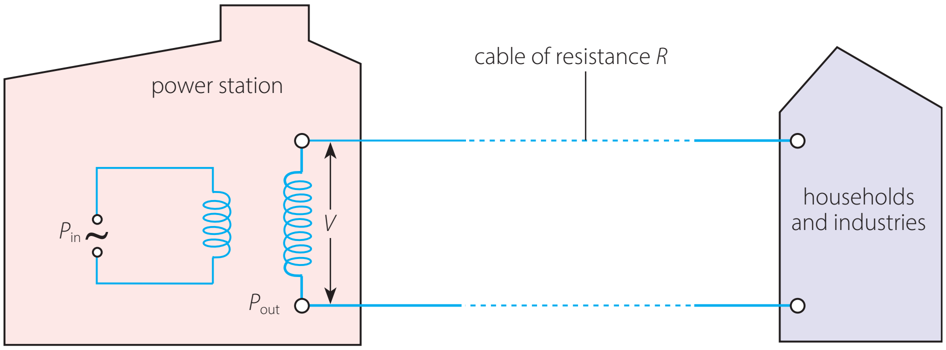


Figure 18.45 *Power transmission*

Suppose the electrical power output P_{out} of a power station is to be transmitted at a voltage V by transmission cables of total resistance R (Figure 18.45). The current I in the transmission cables is

$$I = \frac{P_{out}}{V}.$$

Hence, the power lost as thermal energy, P_{loss}, is

$$P_{loss} = I^2R = \left(\frac{P_{out}}{V}\right)^2 R.$$

Thus, the greater the value of V, the lower the power loss.

As electricity is transmitted more efficiently at high voltages, electricity produced in power stations has its voltage stepped up by step-up transformers. The high-voltage electricity is then transmitted to households and industries through transmission cables. Step-down transformers then reduce the voltage to suitable values so that households and industries can use the electricity safely.

Figure 18.46 *Step-down transformers help distribute electricity to households and industries.*

ENRICHMENT THINK

Overhead transmission cables are supported by electricity pylons. In some countries, most transmission cables are underground. Why?

Worked Example 18E

A power station with an output power of 100 kW at 20 000 V is connected by cables to a factory.

(a) If the resistance of the cables is 5.0 Ω, calculate the

  (i) current flowing in the cables;

  (ii) power loss in the cables.

(b) Account for the power loss.

Solution

Given: Output power $P_{\text{out}} = 100 \times 10^3$ W

Voltage $V = 20\ 000$ V

Resistance R of cables = 5.0 Ω

(a) **(i)** Since $P_{\text{out}} = VI$, where I is the current in the cables,

$$I = \frac{P_{\text{out}}}{V} = \frac{100 \times 10^3\ \text{W}}{20\ 000\ \text{V}} = 5\ \text{A}$$

(ii) Power loss in the cables

$$P_{\text{loss}} = I^2R = (5\ \text{A})^2 \times 5.0\ \Omega = 125\ \text{W}$$

(b) Power is lost as thermal energy. This is due to Joule heating, caused by the resistance of the cables and the current flowing through the cables.

Let's Practise 18.6

Figure 18.47 shows a simple transformer.

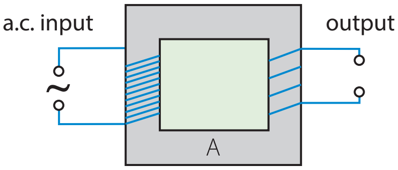


Figure 18.47

1 **(a)** Explain

  (i) the material used to make the item labelled A;

  (ii) whether the output voltage is greater or smaller than the input voltage.

(b) S This transformer supplies a voltage of 12 V to a model train, which draws a current of 0.8 A. If the voltage of the a.c. source is 240 V, calculate the current in the primary coil.

2 Power is lost as thermal energy during the transmission of electricity from power stations to homes. State **two** ways through which this power loss can be minimised.

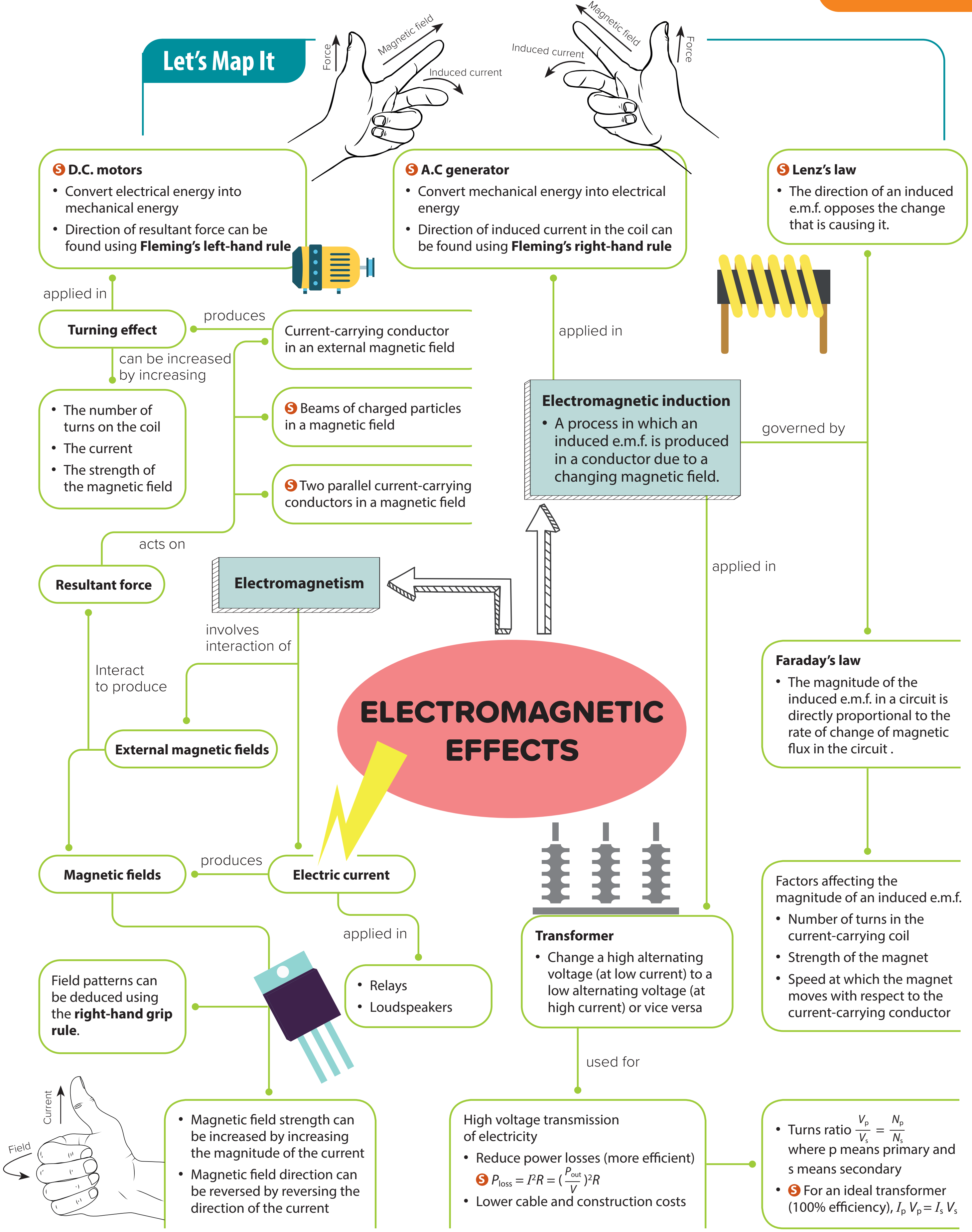
3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 18F–18G, pp. XX–XX

Exercise 18H Let's Reflect

Let's Map It



ELECTROMAGNETIC EFFECTS

Electromagnetism

involves interaction of

External magnetic fields

Electric current

Interact to produce

Magnetic fields

produces

Resultant force

acts on

Current-carrying conductor in an external magnetic field

S Beams of charged particles in a magnetic field

S Two parallel current-carrying conductors in a magnetic field

produces

Turning effect

can be increased by increasing

- The number of turns on the coil
- The current
- The strength of the magnetic field

applied in

S D.C. motors

- Convert electrical energy into mechanical energy
- Direction of resultant force can be found using **Fleming's left-hand rule**

Field patterns can be deduced using the **right-hand grip rule**.

- Magnetic field strength can be increased by increasing the magnitude of the current
- Magnetic field direction can be reversed by reversing the direction of the current

applied in

- Relays
- Loudspeakers

Electromagnetic induction

- A process in which an induced e.m.f. is produced in a conductor due to a changing magnetic field.

applied in

S A.C generator

- Convert mechanical energy into electrical energy
- Direction of induced current in the coil can be found using **Fleming's right-hand rule**

governed by

S Lenz's law

- The direction of an induced e.m.f. opposes the change that is causing it.

Faraday's law

- The magnitude of the induced e.m.f. in a circuit is directly proportional to the rate of change of magnetic flux in the circuit .

Factors affecting the magnitude of an induced e.m.f.

- Number of turns in the current-carrying coil
- Strength of the magnet
- Speed at which the magnet moves with respect to the current-carrying conductor

applied in

Transformer

- Change a high alternating voltage (at low current) to a low alternating voltage (at high current) or vice versa

used for

High voltage transmission of electricity

- Reduce power losses (more efficient)

  S $P_{\text{loss}} = I^2R = (\frac{P_{\text{out}}}{V})^2R$
- Lower cable and construction costs

- Turns ratio $\frac{V_p}{V_s} = \frac{N_p}{N_s}$ where p means primary and s means secondary
- S For an ideal transformer (100% efficiency), $I_p\,V_p = I_s\,V_s$

Let's Review

Section A: Multiple-choice Questions

1 Figure 18.48 shows a current-carrying wire passing through the centre of a sheet of cardboard. How do the strengths of the magnetic field at points X, Y, and Z compare?

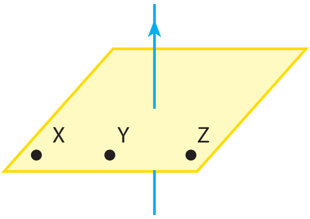


Figure 18.48

A Different at X, Y, and Z
B Equal at X and Z, but stronger at Y
C Equal at X and Z, but weaker at Y
D Stronger at X than Y, and stronger at Y than Z

2 Ⓢ In Figure 18.49, a current-carrying wire is placed between two magnetic poles. In which direction does the wire move?

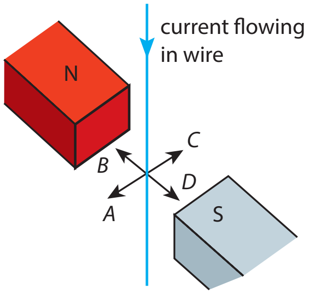


Figure 18.49

3 Ⓢ Figure 18.50 shows a current-carrying coil placed within a magnetic field. The coil experiences forces that make it move. How does the coil move?

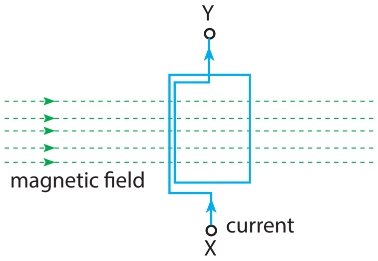


Figure 18.50

A From X to Y
B Out of page
C Along the magnetic field
D About the axis XY

4 Ⓢ Figure 18.51 shows a beam of electrons entering a magnetic field.

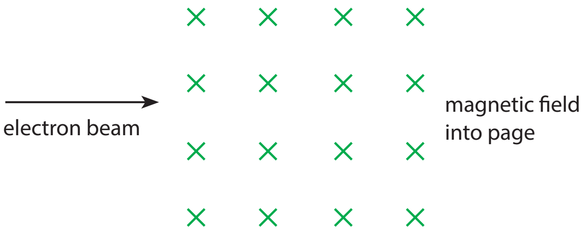


Figure 18.51

What is the initial direction of the deflection of the electrons as the beam passes through the field?

A Into page
B Out of page
C Towards the bottom of page
D Towards the top of page

5 Ⓢ In a simple d.c. motor, the direction of current in the motor coil is reversed every half-revolution. This is to keep the coil turning in the same direction. Which part of the motor enables this?

A Brushes
B Coil
C Split-ring commutator
D Permanent magnets

6 Which of the following procedures does not generate an e.m.f.?

A Holding a magnet stationary inside a coil
B Rotating a coil in a magnetic field
C Rotating a magnet around a stationary coil
D Moving a bar magnet across a flat piece of metal

7 In electromagnetic induction, which of the following does not affect the magnitude of the induced e.m.f.?

A The strength of the magnetic field linking the coil
B The resistance of the coil cutting across the magnetic field
C The speed with which the coil cuts across the magnetic field
D The number of turns in the coil

8 Ⓢ Figure 18.52 shows the coil of a generator with slip rings.

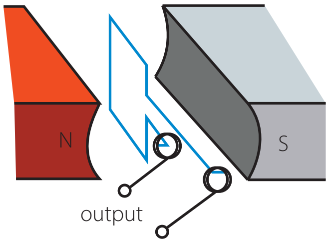
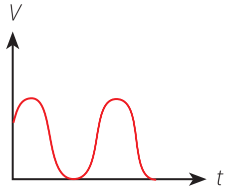
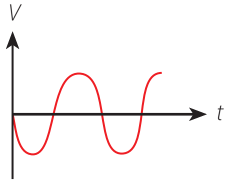
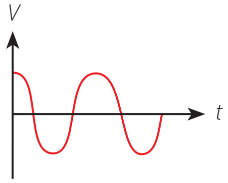


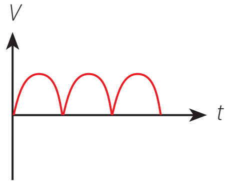
Figure 18.52

Which of the following graphs gives the correct output voltage against time when the coil begins to turn from the position shown?

A


B


C


D


9 Ⓢ Why is soft iron used in the core of a transformer?

A It has a low electrical resistance.

B It conducts the induced current well.

C It does not melt easily when the induced current is too large.

D It ensures better magnetic flux linkage between the two coils.

Section B: Short-answer and Structured Questions

1 **(a)** Using suitable diagrams, describe the pattern of the magnetic field due to the current in a

(i) long straight wire;

(ii) solenoid.

(b) Ⓢ State a factor that affects the strength of the magnetic field of a current-carrying conductor, and describe how it affects the magnetic field strength.

(c) Ⓢ State a factor that affects the direction of the magnetic field of a current-carrying conductor, and describe how it affects the magnetic field direction.

2 **(a)** What is electromagnetic induction?

(b) State the factors that affect the magnitude of the induced e.m.f.

3 Referring to Figure 18.53, state what is observed in the galvanometer when the

(a) magnet is moved into the solenoid;

(b) magnet is pulled out of the solenoid;

(c) number of turns in the solenoid is increased and **(a)** is repeated.

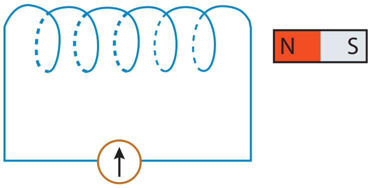


Figure 18.53

4 Ⓢ

(a) State Lenz's Law of electromagnetic induction.

(b) Explain how Lenz's Law illustrates the principle of conservation of energy.

5 Ⓢ

(a) Draw a labelled diagram of a simple a.c. generator and describe the use of the slip rings.

(b) Sketch the graph of the output voltage against time for a simple a.c. generator.

6 Figure 18.54 shows a solenoid connected to a galvanometer.

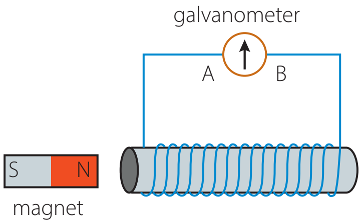


Figure 18.54

Explain the following observations:

(a) When the magnet is held stationary at the end of the coil, the galvanometer needle is not deflected.

(b) When the magnet is moved towards the solenoid, the galvanometer needle is deflected towards A.

(c) The faster the motion of the magnet towards the solenoid, the larger the deflection of the galvanometer needle.

(d) When the magnet is moved away from the solenoid, the galvanometer needle is deflected towards B.

Let's Review

7 Ⓢ A transformer has 400 turns in the primary coil and 10 turns in the secondary coil. The primary voltage is 250 V and the primary current is 2.0 A.

(a) Calculate the

(i) secondary voltage;

(ii) secondary current, assuming the transformer is ideal.

(b) Several measures are taken to increase the efficiency of transformers. Explain why, and describe **two** features in transformer design that improve efficiency.

8 A battery charger draws electricity from the 240 V mains supply. The charger contains a transformer, which provides an output of 15 V.

(a) There are 6400 turns on the primary coil of the transformer. Calculate the number of turns on the secondary coil.

(b) Ⓢ Assuming that the transformer is 100% efficient, calculate the current flowing in the primary coil if the output current of the transformer is 2.0 A.

9 Figure 18.55 shows part of a power transmission system. Electricity from the power station is transmitted to end users via transmission cables. The power station has a capacity of 200 MW and produces a voltage of 2 kV. The transmission cable is at 400 kV. The end users receive a voltage of 250 V.

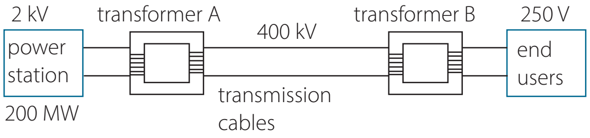


Figure 18.55

(a) Is transformer A a step-up or a step-down transformer? Explain your answer.

(b) Ⓢ Assuming that transformers A and B are ideal, and that no energy is lost during transmission, calculate the

(i) current flowing through the transmission cables;

(ii) total current supplied to the end users;

(iii) total energy generated by the power station each day.

(c) Ⓢ Why is electricity transmitted at high voltage?

10 Ⓢ

(a) What is Fleming's left-hand rule used for?

(b) On Figure 18.56, label the following parts:

(i) Split-ring commutator

(ii) Carbon brushes

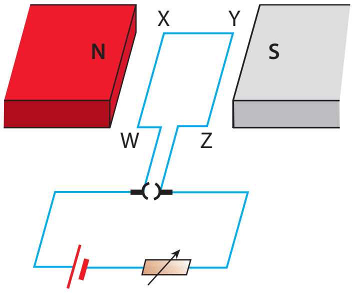


Figure 18.56

(c) What are the functions of the parts in **(b)(i)** and **(ii)**?

(d) Using Fleming's left-hand rule, state whether the rectangular coil will rotate clockwise or anticlockwise. Draw the forces that cause the rotation on the diagram.

(e) How would you change the direction of rotation of the coil?

11 A wire is wound 30 times around a soft iron C-core (Figure 18.57).

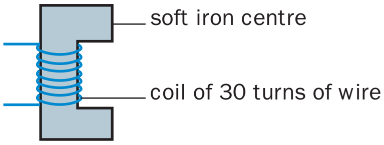


Figure 18.57

You are provided with two such C-cores.

(a) Without the use of a magnet, describe how you would use the C-cores to show that a current can be induced in a coil of wire through electromagnetic induction.

(b) Should the wires that are wound around the soft iron C-cores be insulated? Why?

12 **(a)** Describe an experiment to demonstrate electromagnetic induction. Explain how you would demonstrate the factors that affect the magnitude and the direction of the induced e.m.f.

(b) Ⓢ Describe briefly how electromagnetic induction is applied in the operation of a transformer.