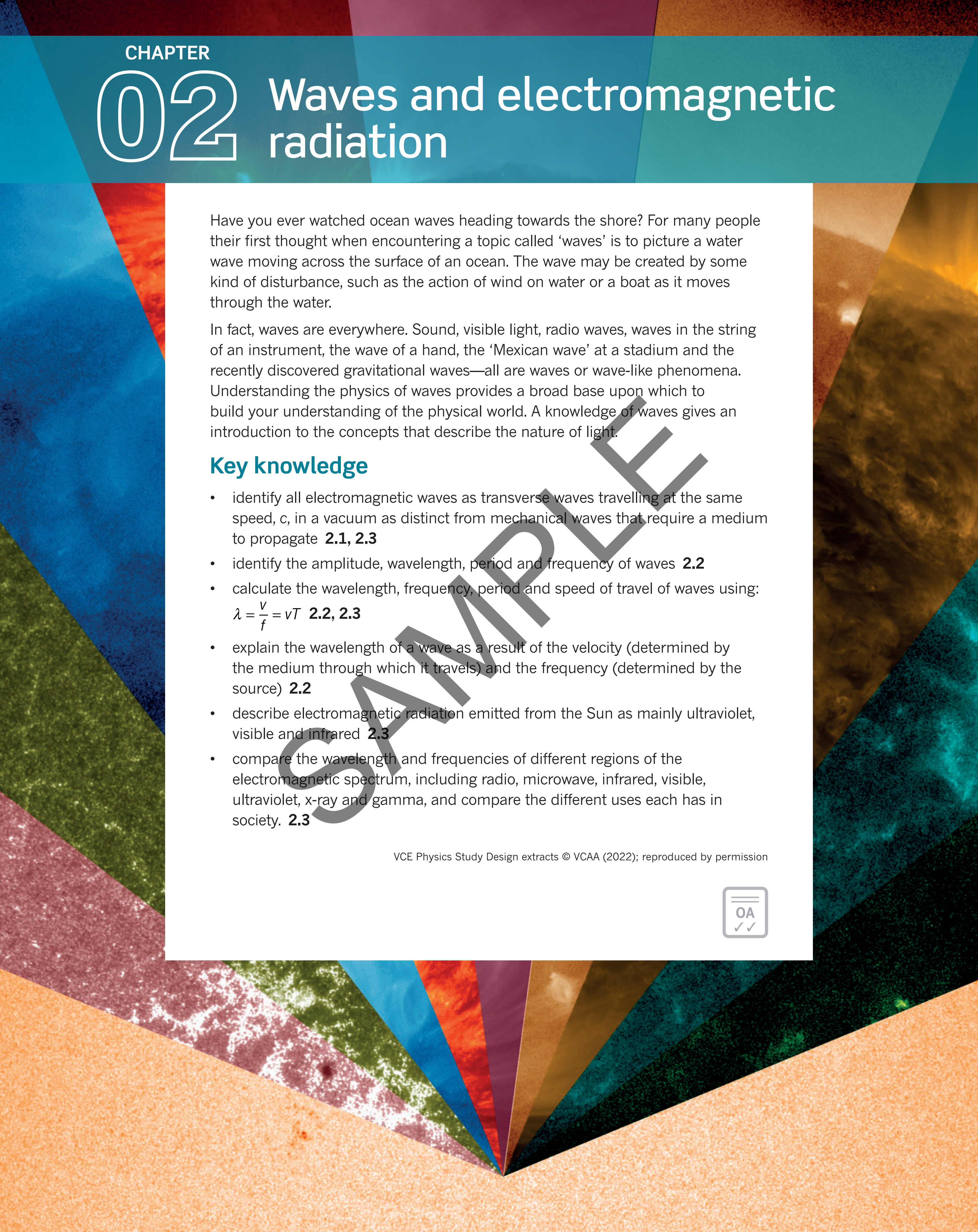

CHAPTER 02

Waves and electromagnetic radiation

Have you ever watched ocean waves heading towards the shore? For many people their first thought when encountering a topic called ‘waves’ is to picture a water wave moving across the surface of an ocean. The wave may be created by some kind of disturbance, such as the action of wind on water or a boat as it moves through the water.

In fact, waves are everywhere. Sound, visible light, radio waves, waves in the string of an instrument, the wave of a hand, the ‘Mexican wave’ at a stadium and the recently discovered gravitational waves—all are waves or wave-like phenomena. Understanding the physics of waves provides a broad base upon which to build your understanding of the physical world. A knowledge of waves gives an introduction to the concepts that describe the nature of light.

Key knowledge

- identify all electromagnetic waves as transverse waves travelling at the same speed, *c*, in a vacuum as distinct from mechanical waves that require a medium to propagate **2.1, 2.3**
- identify the amplitude, wavelength, period and frequency of waves **2.2**
- calculate the wavelength, frequency, period and speed of travel of waves using: $\lambda = \frac{v}{f} = vT$ **2.2, 2.3**
- explain the wavelength of a wave as a result of the velocity (determined by the medium through which it travels) and the frequency (determined by the source) **2.2**
- describe electromagnetic radiation emitted from the Sun as mainly ultraviolet, visible and infrared **2.3**
- compare the wavelength and frequencies of different regions of the electromagnetic spectrum, including radio, microwave, infrared, visible, ultraviolet, x-ray and gamma, and compare the different uses each has in society. **2.3**

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2.1 Longitudinal and transverse waves

Throw a stone into a pool or lake, and you will see circular waves form and move outwards from the source as ripples. Stretch a cord out on a table and wriggle one end back and forth across the table surface and another type of wave can be observed. Water waves, sound waves and waves in strings are all examples of **mechanical waves**. These waves require a **medium** (a physical substance) to **transmit** (carry or transfer) energy: water waves use water molecules, sound waves use air and the wave on a string uses the string (Figure 2.1.1).

FIGURE 2.1.1 In this tin can phone, sound waves vibrate the string. The vibrating string transfers the sound between the children.

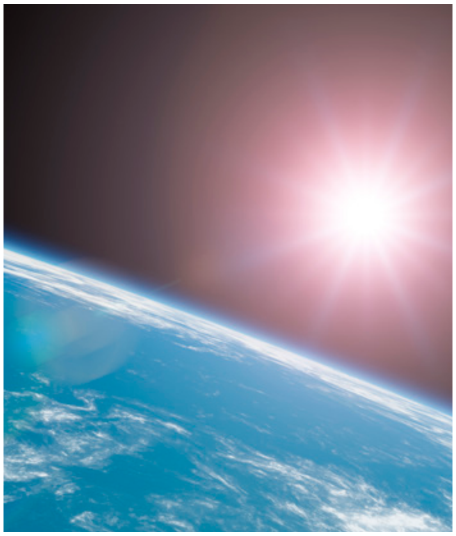


FIGURE 2.1.2. Light travels from the Sun through the vacuum of space and does not need a medium.

Electromagnetic waves, which include visible light, do not require a medium to transfer energy. Thus, light from the Sun can transmit across the vacuum of space (Figure 2.1.2).

MECHANICAL WAVES

Watch a piece of driftwood, a leaf, or even a surfer resting in the water as a smooth wave goes past. The object moves up and down but doesn't move forwards with the wave. The movement of the object on the water reveals how the particles in the water move as the wave passes; that is, the particles in the water move up and down from an average position.

Any wave that needs a medium (such as water) through which to travel is called a mechanical wave. Mechanical waves can move over very large distances, but the particles of the medium only have very limited movement.

Mechanical waves transfer energy from one place to another through a medium. The particles of the matter vibrate back and forth or up and down about an average position, which transfers the energy from one place to another. For example, energy is given to an ocean wave by the action of the wind far out at sea. The energy is transported by waves to the shore, but (except in the case of a tsunami event) most of the ocean water itself does not travel to the shore.

A wave involves the transfer of energy without the net transfer of matter.

Pulses versus periodic waves

A single wave **pulse** can be formed by giving a slinky spring or a rope a single up-and-down motion, as shown in Figure 2.1.3(a). As the hand pulls upwards, the adjacent parts of the slinky will also feel an upwards force and begin to move upwards. The source of the wave energy is the movement of the hand.

If the up-and-down motion is repeated, each successive section of the slinky will move up and down, moving the wave forwards along the slinky, as shown in Figure 2.1.3(b). Connections between each loop of the slinky cause the wave to travel away from the source, carrying with it the energy from the source.

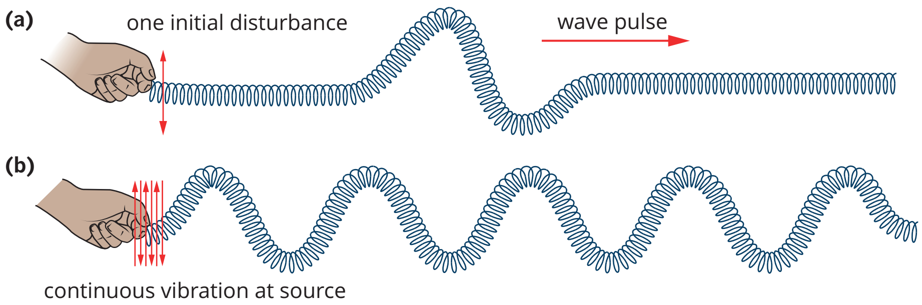


FIGURE 2.1.3 (a) A single wave pulse can be sent along a slinky by a single up and down motion. (b) A continuous or periodic wave is created by a regular, repeated movement of the hand.

In a continuous or periodic wave, continuous vibration of the source, such as that shown in Figure 2.1.3(b), will cause the particles within the medium to **oscillate** (move about their average position in a regular, repetitive or periodic pattern). The source of any mechanical wave is this repeated motion or vibration. The energy from the vibration moves through the medium and constitutes a mechanical wave.

Transverse waves

When waves travel on water, or through a rope, spring or string, the particles within the medium vibrate up and down in a direction perpendicular, or **transverse**, to the direction of motion of the wave energy, as can be seen from the position of the cork in Figure 2.1.4. Such a wave is called a transverse wave. When the particles are displaced upwards from the average position, or resting position, they reach a maximum positive displacement called a **crest**. Particles below the average position fall to a maximum negative position called a **trough**.

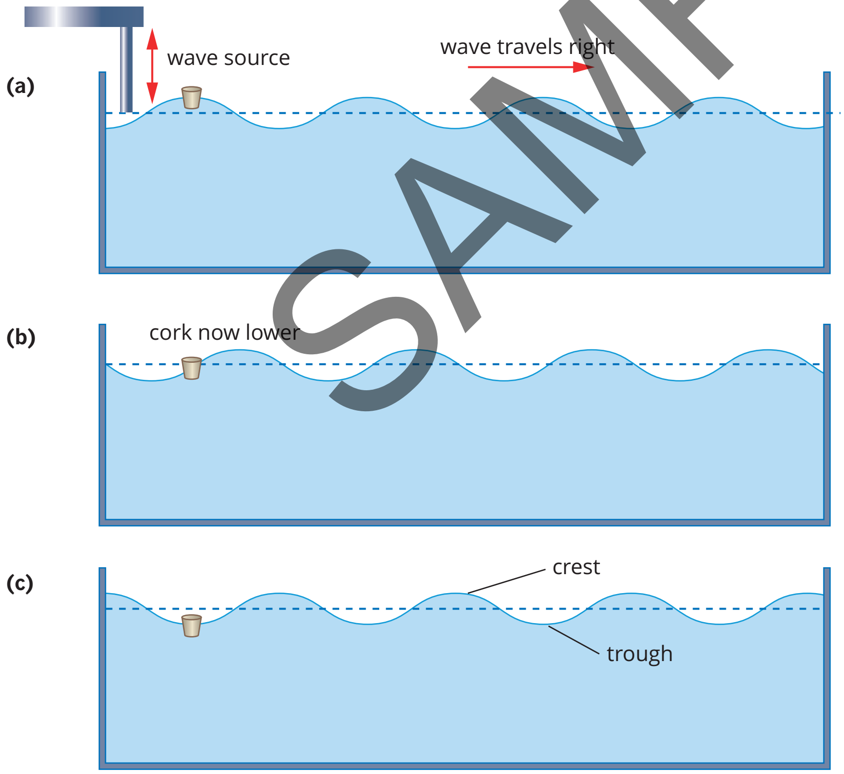


FIGURE 2.1.4 A continuous water wave moves to the right. As it does so, the up-and-down displacement of the particles transverse to the wave motion can be monitored using a cork. The cork simply moves up and down as the wave passes through it.

Longitudinal waves

In a **longitudinal** mechanical wave, the vibration of the particles within the medium is in the same direction, or parallel to, the direction of the energy flow of the wave.

You can demonstrate this type of wave with a slinky by moving your hand backwards and forwards in a line parallel to the length of the slinky, as shown in Figure 2.1.5.

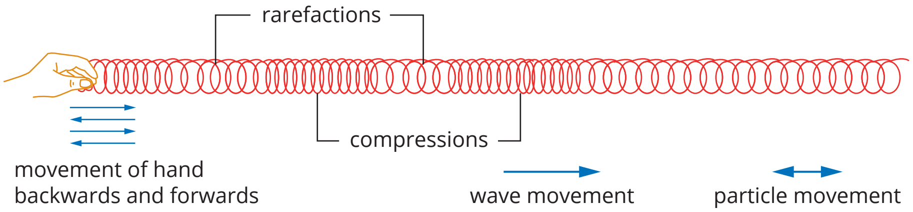


FIGURE 2.1.5 When the direction of the vibrations of the medium and the direction of travel of the wave energy are parallel, a longitudinal wave is created. This can be demonstrated with a slinky.

As you move your hand, a series of compressed and expanded areas form along the slinky (Figure 2.1.5). **Compressions** are those areas where the coils of the slinky come together. Expansions are regions where the coils are spread apart. Areas of expansion are termed **rarefactions**. The compressions and rarefactions in a longitudinal wave correspond to the crests and troughs of a transverse wave.

An important example of a longitudinal wave is a sound wave. As the cone of a loudspeaker vibrates, the layer of air next to it is alternately pushed away and drawn back, creating a series of compressions and rarefactions in the air (Figure 2.1.6). This vibration is transmitted through the air as a sound wave. As in transverse waves, the individual molecules vibrate over a very small distance while the wave itself can carry energy over very long distances. If the vibration was from a single point, then the waves would tend to spread out spherically.

FIGURE 2.1.6 The motion of a flame in front of a loudspeaker is clear evidence of the continuous movement of air backwards and forwards as the loudspeaker creates a sound wave.

When measuring a sound wave, an oscilloscope device (or an oscilloscope app on a phone) converts the sound waves to an electrical signal and represents it as a transverse wave. The transverse waveform is produced by plotting the pressure variation in the medium against distance from the source. Figure 2.1.7 shows that the sound wave compression corresponds to a peak or crest in the transverse wave representation. This is because the compression is an area of high pressure—the particles are close together. The rarefaction corresponds to a trough in the transverse wave. This is because the particles are spread out and so the pressure is lower.

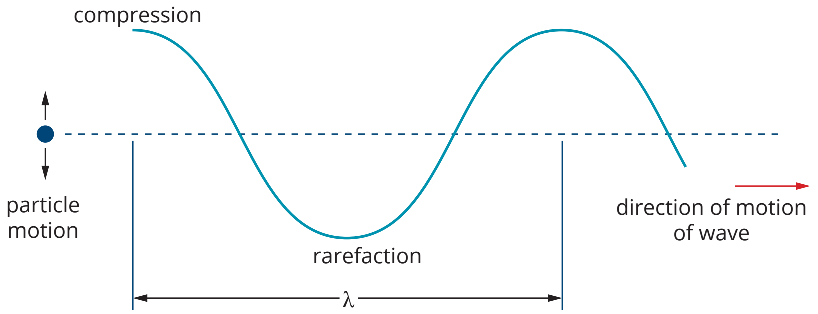


FIGURE 2.1.7 The compression of a longitudinal wave coincides with the peak of the transverse wave representation, while the rarefaction coincides with the trough.

PHYSICSFILE

Water waves

Water waves are often classified as transverse waves, but this is an approximation. In practical situations, transverse and longitudinal waves don't always occur in isolation. The breaking of waves on a beach produces complex wave forms that are a combination of transverse and longitudinal waves (see below).

If you looked carefully at a cork bobbing about in gentle water waves you would notice that it doesn't move straight up and down but that it has a more elliptical motion. It moves up and down, and very slightly forwards and backwards as each wave passes. However, since this second aspect of the motion is so subtle, in most circumstances it is adequate to treat water waves as if they were purely transverse waves.

Although this surfer rides forwards on the wave, the water itself only moves in an elliptical motion as the wave passes.

2.1 Review

SUMMARY

- Vibrating objects transfer energy through waves, travelling outwards from the source.
- A wave may be a single pulse, or it may be continuous or periodic (successive crests and troughs or compressions and rarefactions).
- A wave only transfers energy from one point to another. There is no net transfer of matter or material.
- Mechanical waves require a medium to transmit energy. Waves on water or on a string, and sound waves in air are examples of mechanical waves.
- Mechanical waves can be either transverse or longitudinal.
  - In a transverse wave, the oscillations are perpendicular to the direction in which the wave energy is travelling. A wave in a string is an example of a transverse wave.
  - In a longitudinal wave, the oscillations are parallel to the direction the wave energy is travelling. Sound is an example of a longitudinal wave.
- Electromagnetic radiation includes visible light and does not require a medium to transmit energy.

KEY QUESTIONS

Knowledge and understanding

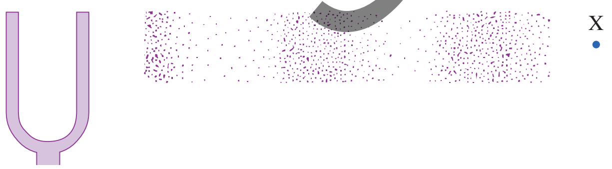
1 Describe the motion of particles within a medium and the transmission of energy as a mechanical wave passes through the medium.

2 Which of the following are examples of mechanical waves?
light, sound, ripples on a pond, vibrations in a rope

3 Classify the waves described below as either longitudinal or transverse.

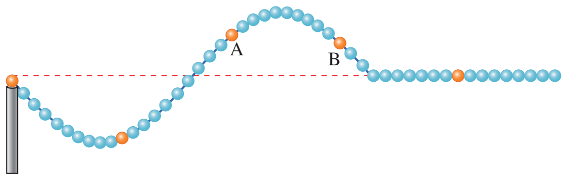
a sound waves
b a vibrating violin string
c slinky moved with an upwards pulse
d slinky pushed forwards and backwards

4 For the wave shown below, describe the direction of energy transfer of the sound between the tuning fork and point X. Justify your answer.

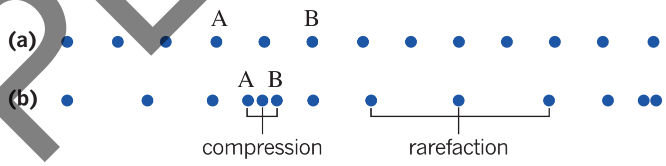


Analysis

5 A mechanical arm moves to produce a pulse that transfers energy to a piece of string. The pulse travels from the left to the right of the string, as shown below. The dots represent the particles on the string. Describe the movement of particles A and B for one complete oscillation, as the particle moves to the right.



6 The diagrams below shows dots representing the average displacement of air particles at one moment in time as a sound wave travels to the right.



Initially the particles, including A and B, are equally spaced as shown in (a). A wave passes through, forming compressions and rarefactions as shown in (b). Describe how particles A and B have moved from their initial positions to form the compression.

7 Compare similarities and differences between the properties of longitudinal and transverse waves and give an example of each.

8 Why can't sound waves travel through the vacuum of space?

9 Compare the similarities and differences between a wave on a guitar string and light.

2.2 Measuring waves

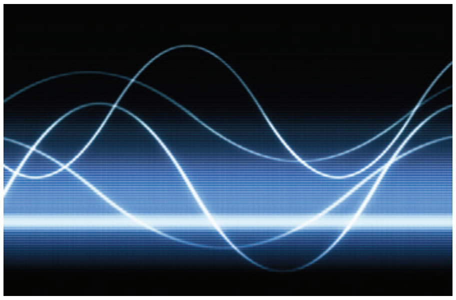


FIGURE 2.2.1 Waves can have different wavelengths, amplitudes, frequencies, periods and speeds, which can all be represented on a graph.

The features of a mechanical wave can be represented using a graph. In this section you will explore how the displacement of particles within the wave can be represented using graphs. From these graphs several key features of a wave can be identified:

- amplitude
- wavelength
- frequency
- period
- speed.

Waves of different amplitudes and wavelengths can be seen in Figure 2.2.1.

DISPLACEMENT–DISTANCE GRAPHS

The displacement–distance graph in Figure 2.2.2 shows the displacement of all particles along the length of a transverse wave at a particular point in time.

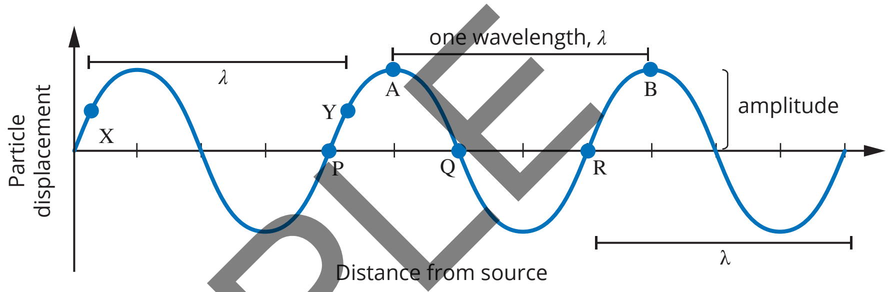


FIGURE 2.2.2 A sine wave represents the particle displacements along a wave.

Have a look back at Figure 2.1.3(b) (page XX) of a continuous wave in a slinky on page XXX. This 'snapshot' in time shows the particles moving up and down sinusoidally about a central rest position. As a wave passes a given point, the particle at that point will go through a complete cycle before returning to its starting point. The wave spread along the length of the slinky has the shape of a sine or cosine function, which you will recognise from mathematics. A displacement–distance graph shows the position (displacement) of the particles at any moment in time along the slinky about a central position.

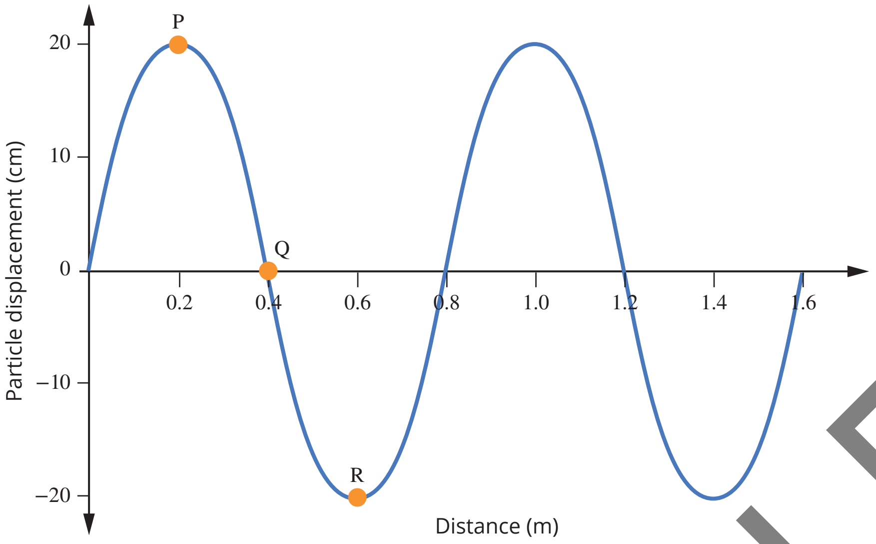
From a displacement–distance graph, the amplitude and wavelength of a wave are easily recognisable.

- The **amplitude** of a wave is the maximum displacement of a particle from the average or rest position. That is, the amplitude is distance from the middle of a wave to the top of a crest or to the bottom of a trough. The total distance a particle will move through in one cycle is twice the amplitude.
- The **wavelength** of a wave is the distance between any two successive points in phase (e.g. points A and B or X and Y in Figure 2.2.2). Wavelength is denoted by the Greek letter λ (lambda) and is measured in metres. Two particles on the wave are said to be in phase if they have the same displacement from the average position and are moving in the same direction. Points P and R in Figure 2.2.2 are two such particles that are in phase, as are points A and B and X and Y, but not P and Q.
- The **frequency**, f, is the number of complete cycles that pass a given point per second and is measured in hertz (Hz). By drawing a series of displacement–distance graphs at various times, you can see the motion of the wave. By comparing the changes in these graphs, the travelling speed and direction of the wave can be found, as well as the direction of motion of the vibrating particles.

Worked example 2.2.1

DISPLACEMENT–DISTANCE GRAPH

The displacement–distance graph below shows a snapshot of a transverse wave as it travels along a spring towards the right. Use the graph to determine the amplitude and the wavelength of this wave.

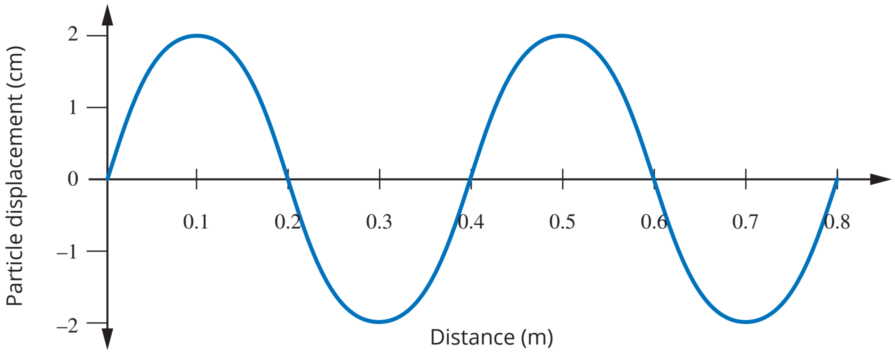


Thinking	**Working**
Amplitude on a displacement–distance graph is the distance from the average position to a crest (P) or a trough (R). Read the displacement of a crest or a trough from the vertical axis. Convert to SI units where necessary.	Amplitude is 20 cm = 0.2 m.
Wavelength is the distance for one complete cycle. Any two consecutive points in phase and at the same position on the wave could be used.	The first cycle runs from the origin through P, Q, and R to intersect the horizontal axis at 0.8 m. This intersection is the wavelength. Wavelength λ is 0.8 m.

Worked example: Try yourself 2.2.1

DISPLACEMENT–DISTANCE GRAPH

The displacement–distance graph below shows a snapshot of a transverse wave as it travels along a spring towards the right. Use the graph to determine the wavelength and the amplitude of this wave.



The displacement–time graph looks very similar to a displacement–distance graph of a transverse wave, so be careful to check the horizontal axis label.

DISPLACEMENT–TIME GRAPHS

A displacement–time graph, such as the one shown in Figure 2.2.3, tracks the position of one point over time as the wave moves through that point.

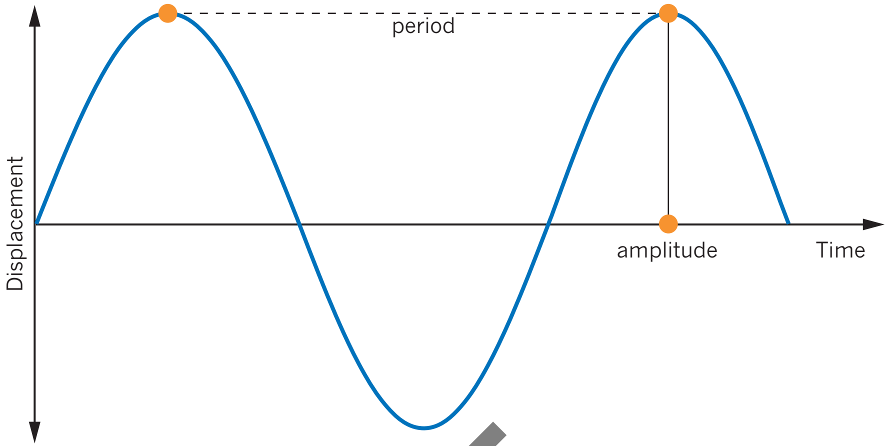


FIGURE 2.2.3 The graph of displacement versus time from the source of a transverse wave shows the movement of a single point on a wave over time as the wave passes through that point.

Crests and troughs are shown in the same way in both graphs. The amplitude is still the maximum displacement from the average or rest position of either a crest or a trough, but the distance between two successive points in phase in a displacement–time graph represents the period of the wave, T, measured in seconds.

The **period** is the time it takes for any point on the wave to go through one complete cycle (e.g. from crest to successive crest). The period of a wave is inversely related to its frequency.

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

where T is the period of the wave (s)

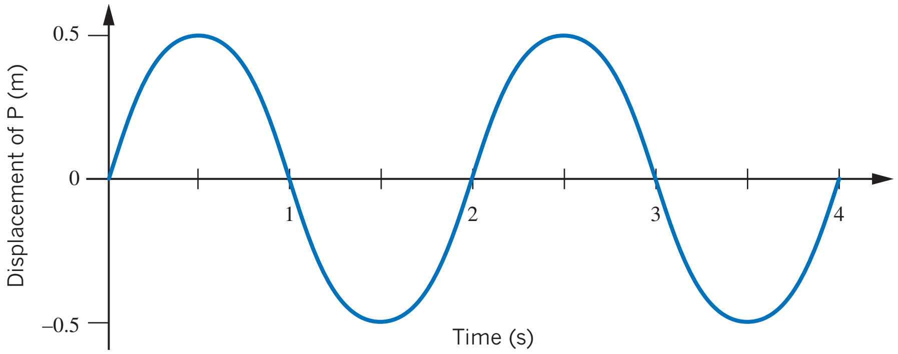
f is the frequency of the wave (Hz).

The amplitude and period of a wave, and the direction of motion of a particular particle, can be determined from a displacement–time graph.

Worked example 2.2.2

DISPLACEMENT–TIME GRAPHS

The displacement–time graph below shows the motion of a single part of a rope (point P) as a wave passes by travelling to the right. Use the graph to find the amplitude, period and frequency of the wave.

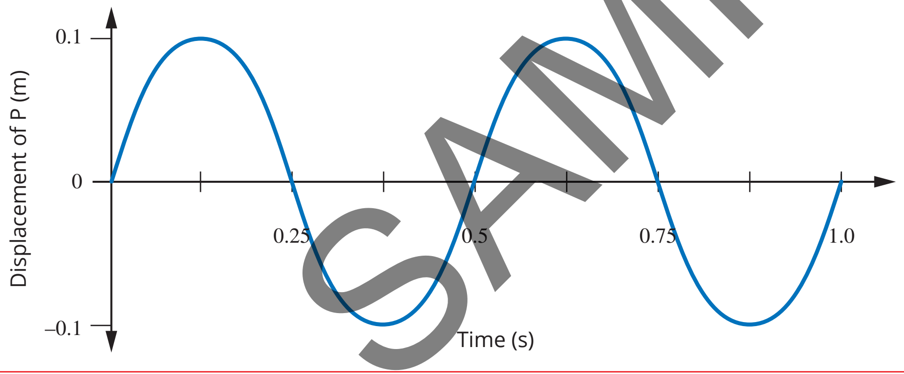


Thinking	**Working**
The amplitude on a displacement–time graph is the displacement from the average position to a crest or trough. Note the displacement of successive crests and/or troughs on the wave and carefully note units on the vertical axis.	Maximum displacement is 0.5 m. Therefore amplitude is 0.5 m.
Period is the time it takes to complete one cycle and can be identified on a displacement–time graph as the time between two successive points on the graph that are in phase. Identify two points on the graph at the same position in the wave cycle, e.g. the origin and $t = 2$ s. Confirm by checking two other points, e.g. two crests or two troughs.	Period T is 2 s.
Frequency can be calculated using $f = \frac{1}{T}$, measured in hertz (Hz).	$f = \frac{1}{T} = \frac{1}{2} = 0.5$ The frequency is 0.5 Hz.

Worked example: Try yourself 2.2.2

DISPLACEMENT–TIME GRAPHS

The displacement–time graph below shows the motion of a single part of a rope as a wave passes travelling to the right. Use the graph to find the amplitude, period and frequency of the wave.



THE WAVE EQUATION

Although the speed of a wave can vary, there is a relationship between the speed of a wave and other significant wave characteristics.

In general, the speed (v) of an object is given by:

$$v = \frac{\text{distance travelled}}{\text{time taken}} = \frac{d}{\Delta t}$$

For a wave, the distance between any two successive points in phase is one wavelength ($d = \lambda$). This occurs in the time of one period ($t = T$). Therefore, the equation becomes:

$$v = \frac{\lambda}{T}$$

As $f = \frac{1}{T}$, we can substitute $T = \frac{1}{f}$ into the expression for v.

This gives

$$v = \lambda f$$

Rearrange this expression to make wavelength the subject, and you can see that wavelength depends on both the speed of the wave and the frequency.

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

where λ is the wavelength (m)
v is the speed (m s^{-1})
f is the frequency (Hz).

This is known as the wave equation and applies to both longitudinal and transverse mechanical waves.

Worked example 2.2.3

THE WAVE EQUATION

A longitudinal wave has a wavelength of 2.00 m and a speed of 340 m s^{-1}. What is the frequency, f, of the wave?

Thinking	Working
The wave equation states that $\lambda = \frac{v}{f}$. Both v and λ are known, so the frequency, f, can be found. Rewrite the wave equation in terms of f.	$\lambda = \frac{v}{f}$ $f = \frac{v}{\lambda}$
Substitute the known values and solve.	$f = \frac{v}{\lambda}$ $= \frac{340}{2.00} = 170$ The frequency is 170 Hz.

Worked example: Try yourself 2.2.3

THE WAVE EQUATION

A transverse wave has a wavelength of 4.0×10^{-7} m and a speed of 3.0×10^{8} m s^{-1}. What is the frequency, f, of the wave?

Worked example 2.2.4

THE WAVE EQUATION

A longitudinal wave has a wavelength of 2.00 m and a speed of 340 m s^{-1}.
What is the period, T, of the wave?

Thinking	**Working**
Rewrite the wave equation in terms of T.	$\lambda = \frac{v}{f}$ and $f = \frac{1}{T}$ Substitute $f = \frac{v}{\lambda}$ into $T = \frac{1}{f}$. $T = \frac{1}{\frac{v}{\lambda}}$ $T = \frac{\lambda}{v}$
Substitute the known values and solve.	$T = \frac{\lambda}{v}$ $= \frac{2.00}{340}$ $= 5.90 \times 10^{-3}$ Period T is 5.90×10^{-3} s.

Worked example: Try yourself 2.2.4

THE WAVE EQUATION

A transverse wave has a wavelength of 4.0×10^{-7} m and a speed of 3.0×10^{8} m s^{-1}.
What is the period, T, of the wave?

CASE STUDY ANALYSIS

Seismic waves and the composition of Earth

On 28 December 1989, an earthquake devastated the region in and around Newcastle, New South Wales. The earthquake was rated 5.6 on the Richter Scale. It was not the most powerful earthquake recorded in Australia; however, it did cause the most damage. Contributing factors were that the epicentre was close to the city centre, it occurred at a shallow depth, soft sediments in the ground amplified the vibrations, and buildings were not designed to adequately withstand earthquakes.

Three main types of seismic waves are produced in an earthquake: two types of body waves (P- and S-waves) and surface waves. These waves can have different wavelengths. The difference in speed between the S and P waves can give a measure of the location of the epicentre, the source of the waves.

Body waves travel through the Earth. The primary (P) waves are longitudinal waves (Figure 2.2.4(a) on page XX) and they travel through both liquids, such as molten rocks in Earth's mantle, and solids, such as rocks that comprise most of the Earth's crust. They have speeds between 1.5 and 8.0 km s^{-1}, with a typical speed of about 6.0 km s^{-1}. The blue grid shows the compressions and rarefactions as the wave oscillates in the direction of the motion.

The secondary (S) waves are transverse waves (Figure 2.2.4(b) on page XX). They do not travel through liquids and their speed is slower than that of P-waves. The blue grid shows the displacement of the wave perpendicular to the direction of travel. The difference in speed between these two waves allows scientists to determine the location of the epicentre of the earthquake.

The third type of wave, the surface wave (Figure 2.2.4 (c) on page XX), has a rolling motion and travels along Earth's surface. The blue grid shows it is a transverse wave, but the perpendicular displacement is only at the surface. This type of wave typically causes the most damage.

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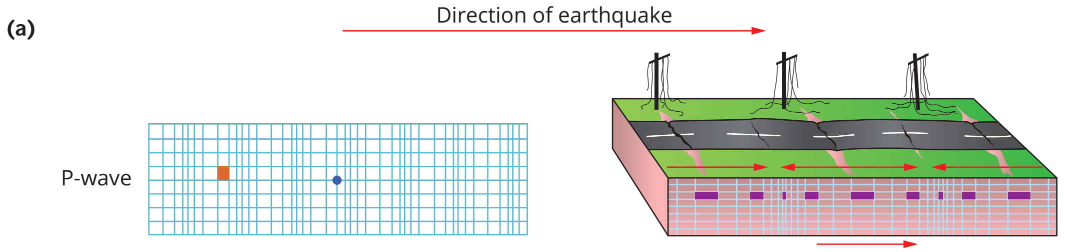
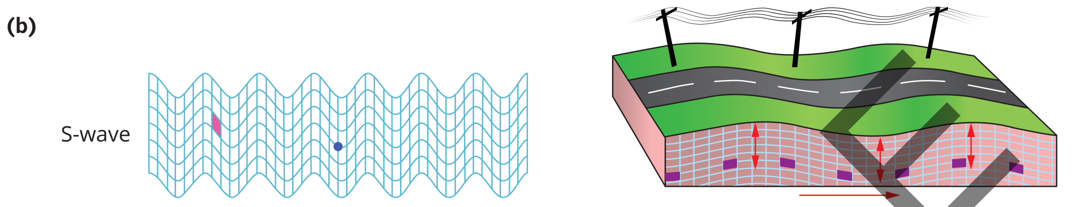
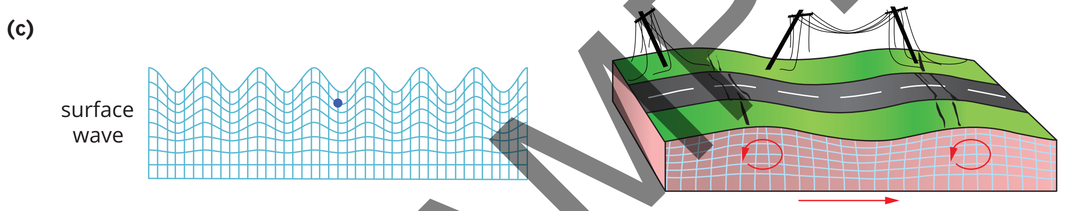
CASE STUDY ANALYSIS *continued*



The back and forth motion produced as P-waves travel along the surface can cause the ground to buckle and fracture.



S-waves cause the ground to shake up-and-down and sideways.



A surface wave travels horizontally, much like rolling ocean waves. The arrows show the movement of rock as the wave passes. The wave follows the shape of an ellipse.

FIGURE 2.2.4 The three different wave types have different effects on the Earth's crust.

Analysis

Scientists can measure the seismic waves using seismometers. From the information collected, they can determine the composition of Earth.

1 If a large earthquake occurred in Melbourne, the P-waves would travel through the centre of Earth and be detected on the other side of the world in England. However, the S-waves would not be detected. From the information above, determine the likely state of the material comprising the centre of Earth.

2 An average P-wave has a speed of 6.0 km s^{-1}. If it has a period of 0.20 seconds, calculate the requency and the wavelength of the P-wave.

The difference in arrival time at a seismometer between a P-wave (t_P) and an S-wave (t_S) is given by $\Delta t = t_P - t_S$. Each wave travels the same distance.

3 Derive an expression for Δt in terms of the distance travelled, the speed of the P-wave (v_P) and the speed of the S-wave (v_S).

4 Use your answer to question 3 to calculate the distance from the seismometer to the epicentre of the earthquake, if $v_S = 3.45$ km s^{-1} and $v_P = 8.00$ km s^{-1}, and the difference in the time for arrival of the waves is 9.00 seconds.

2.2 Review

SUMMARY

- Waves can be represented by displacement–distance graphs and displacement–time graphs.
- From a displacement–time graph, you can determine amplitude, frequency and period.
- The period of a wave has an inverse relationship to the frequency, according to the relationship:

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

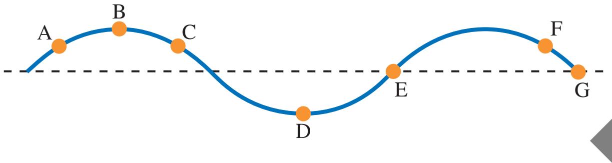
- The speed of a wave can be calculated using the wave equation:

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

KEY QUESTIONS

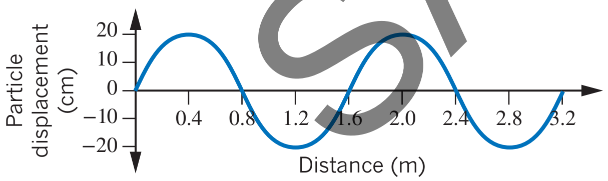
Knowledge and understanding

1 From the displacement–distance graph below, give the correct term or letters for the following:

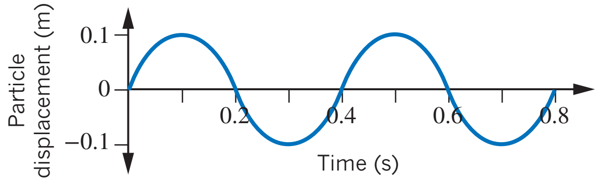


a two points on the wave that are in phase
b the name for the distance between these two points
c two particles with maximum displacement from their rest position
d the term for this maximum displacement.

2 Use the graph below to determine the wavelength and the amplitude of this wave.



3 This is the displacement–time graph for a particle.



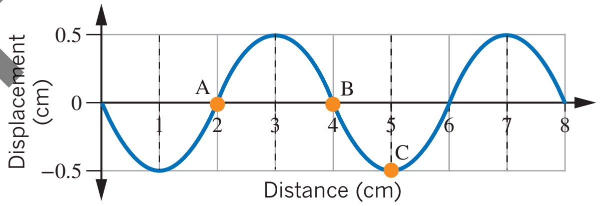
a Determine the period of the wave.
b Calculate frequency of the wave.

4 Calculate the period of a wave with frequency 2×10^5 Hz.

5 Five wavelengths of a wave pass a point each second. The amplitude is 0.3 m and the distance between successive crests of the waves is 1.3 m. What is the speed of the wave?

Analysis

6 Consider the displacement–distance graph below.



a State the wavelength and amplitude of the wave.
b If the wave moves through one wavelength in 2 s, what is the speed of the wave?
c If the wave is moving to the right, which of the particles is moving down?

7 Five complete waves pass a point in 8.0 s. The amplitude of the wave is 0.70 m and distance between successive troughs is 1.20 m. Calculate the speed of the wave.

2.3 The electromagnetic spectrum

Light, like all electromagnetic radiation (EMR), is a transverse wave that does not need a medium in order to travel from its source. As will be explored more fully in Year 12, light consists of two transverse waves perpendicular to each other: one is an electric field wave and the other is the magnetic field wave, as shown in Figure 2.3.1.

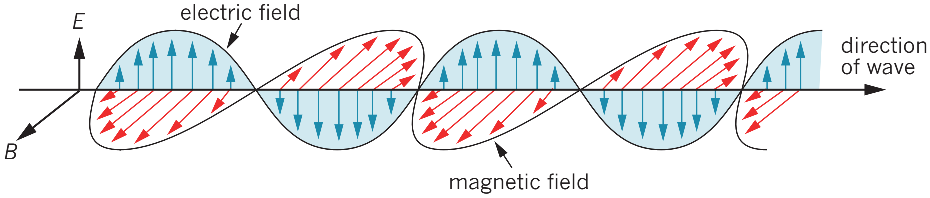


FIGURE 2.3.1 The electric field (E) and magnetic field (B) in electromagnetic radiation are perpendicular to each other and both are perpendicular to the direction of propagation of the radiation.

Our eyes are receptive to the visible spectrum. The wavelengths of all the different colours of visible light fall between 390 nm (violet) and 780 nm (red), Naturally, physicists were bound to inquire about other wavelengths of electromagnetic radiation. It is now understood that the visible spectrum is just one small part of a much broader set of possible wavelengths known as the **electromagnetic spectrum** (Figure 2.3.2).

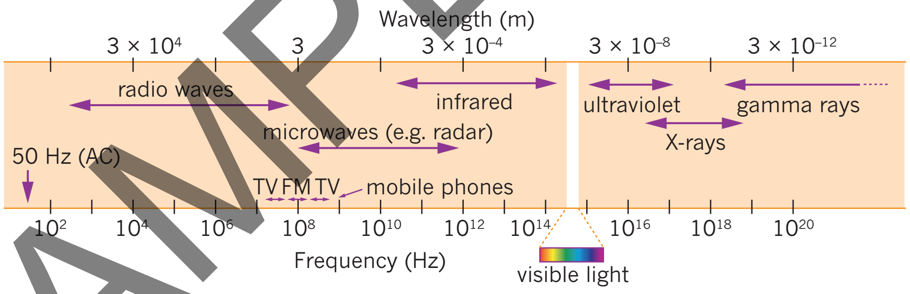


FIGURE 2.3.2 The electromagnetic spectrum

THE WAVE EQUATION AND ELECTROMAGNETIC RADIATION

The wave equation, introduced in Section 2.2, also applies to EMR. However, the speed of light is always constant in a vacuum regardless of the speed of the source or the observer, so it is given its own constant, *c*.

The wave equation for light is:

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

where c is the speed of light ($\mathrm{m\,s^{-1}}$) = $3.0 \times 10^{8}\,\mathrm{m\,s^{-1}}$ in a vacuum.

λ is the wavelength (m)

f is the frequency (Hz).

You will note that Worked example 2.3.1 and Worked example: Try yourself 2.3.1 are examples of an electromagnetic wave travelling through a vacuum or air. The speed of light in air is not significantly different from its speed in a vacuum. However, the speed of light in a medium such as glass is lower than in a vacuum. This is discussed further in Chapter 3.

Worked example 2.3.1

THE WAVE EQUATION AND ELECTROMAGNETIC RADIATION

A laser of blue light travelling through a vacuum has a frequency of 6.7×10^{14} Hz. What is the wavelength, λ, of the light?

Thinking	**Working**
State your variables and the wave equation.	$f = 6.7 \times 10^{14}\,\text{Hz}$ $v = c = 3.0 \times 10^{8}\,\text{m s}^{-1}$ $\lambda = ?$ $\lambda = \frac{v}{f}$ $\lambda = \frac{c}{f}$
Substitute the known values and solve.	$\lambda = \frac{c}{f}$ $= \frac{3.0 \times 10^{8}}{6.7 \times 10^{14}}$ $= 4.5 \times 10^{-7}\,\text{m}$

Worked example: Try yourself 2.3.1

THE WAVE EQUATION AND ELECTROMAGNETIC RADIATION

A beam of red light travelling through air has a frequency of 4.3×10^{14} Hz. What is the wavelength, λ, of the light?

CASE STUDY

Why do we see the wavelengths we do?

Earth's atmosphere blocks many types of EMR (Figure 2.3.3). The highest level of the atmosphere, the ionosphere, contains charged particles and effectively blocks the high-energy ionising EMR (gamma rays, X-rays). Lower down, molecular ozone, O_3, and nitrogen, N_2, absorb and block about 70% of the ultraviolet EMR. Visible light is transmitted well, as it is not energetic enough to be absorbed. The atmosphere becomes increasingly opaque in the infrared and microwave bands, due mainly to absorption by water vapour.

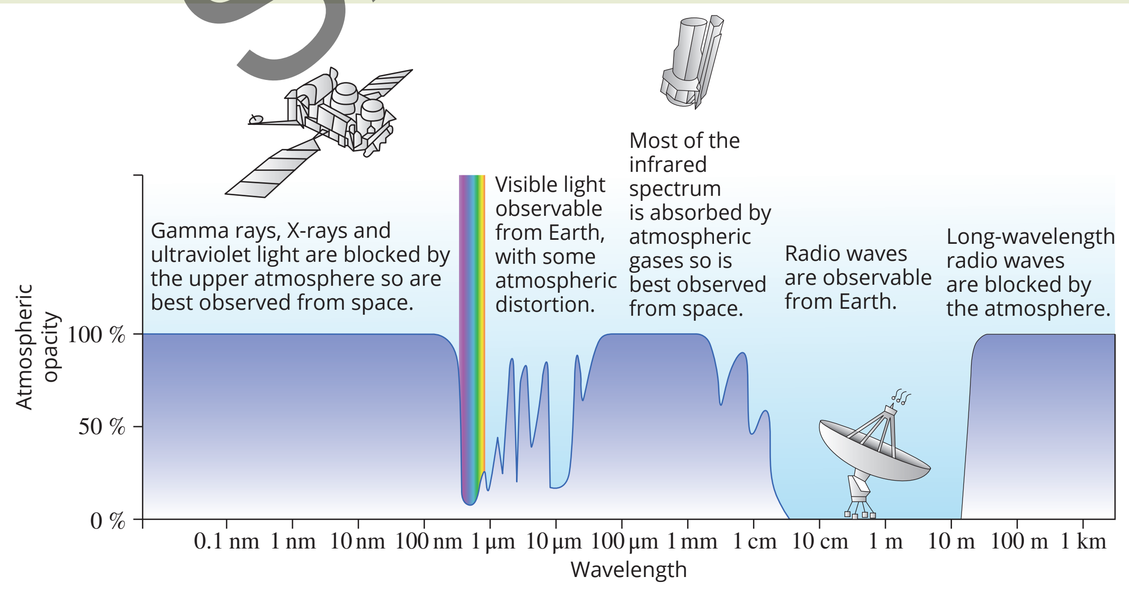


FIGURE 2.3.3 Depending on the wavelength of the EMR, Earth's atmosphere is transparent, translucent or opaque.

continued over page

CASE STUDY *continued*

At still lower energies, the atmosphere becomes transparent again to shorter wavelength radio waves, until the lowest energy longer wavelength EMR cannot penetrate the atmosphere.

During our evolution, our eyes have developed photoreceptors (‘cones’) that respond to the visible spectrum. It is not the only option, however. Dogs have two types of photoreceptors, green and blue, which enable them to see blue, green and yellow. Humans have three types, which are sensitive to red, green and blue, and allow us to see colours derived from red, such as orange and purple, which are invisible to dogs. Honeybees also have three types of photoreceptors, but the evolution of bees led to their photoreceptors being sensitive to ultraviolet, blue and green, which makes the pollen of flowers stand out more strongly. Butterflies have five types, and the mantis shrimp (Figure 2.3.4) has sixteen types of photoreceptor. We see an entire rainbow with just three photoreceptors. What must a mantis shrimp see?

FIGURE 2.3.4 The magnificent mantis shrimp

TYPES OF ELECTROMAGNETIC RADIATION

Changing the frequency and wavelength of the waves changes the properties of the EMR, and so the electromagnetic spectrum is divided into ‘bands’ according to its properties and how the particular types of EMR are used. The shorter the wavelength of the electromagnetic wave, the greater its penetrating power. This means that waves with extremely short wavelengths, such as X-rays, can pass through some materials (e.g. skin), revealing the structures inside (e.g. bone).

Long wavelength waves, such as AM radio waves, have such low penetrating power that they cannot even escape Earth’s atmosphere, and can be used to ‘bounce’ radio signals around to the other side of the world. Table 2.3.1 compares the characteristics of different waves in the electromagnetic spectrum.

TABLE 2.3.1 Comparison of the different waves in the electromagnetic spectrum.

Type of wave	Typical wavelength (m)	Typical frequency (Hz)	Comparable object	Effect on matter
AM radio wave	100	3×10^{6}	sports oval	causes movement of free electrons in a conductor
FM radio or TV wave	3	1×10^{8}	small car	causes movement of free electrons in a conductor
microwaves	0.03	1×10^{10}	50c coin	causes molecular rotation
infrared	10^{-5}	3×10^{13}	white blood cell	makes chemical bonds vibrate
visible light	10^{-7}	3×10^{15}	small cell	affects electronic states in atoms or molecules
ultraviolet	10^{-8}	3×10^{16}	large molecule	affects electronic states in atoms or molecules
X-ray	10^{-10}	3×10^{18}	atom	excites electrons in atomic orbitals
gamma ray	10^{-15}	3×10^{23}	atomic nucleus	causes disintegration of atomic nuclei

Our Sun emits electromagnetic radiation mainly in the infrared, visible and ultraviolet bands. Some high-energy radiations such as X-rays and gamma rays are also emitted, but we are protected from these by Earth's magnetic field and atmosphere.

Radio waves

One of the most revolutionary applications of electromagnetic radiation is the use of radio waves to transmit information from one point to another over long distances. Radio waves are the longest type of electromagnetic radiation, with wavelengths ranging from 1 mm to hundreds of kilometres, as shown in Figure 2.3.2. The principle of radio transmission is relatively simple, and neatly illustrates the nature of electromagnetic waves.

The radio transmitter converts the signal (e.g. radio announcer's voice, music or stream of data) into an alternating current. When this alternating current flows in the transmission antenna, the electrons in the antenna oscillate backwards and forwards. This oscillation of charges in the antenna produces a corresponding electromagnetic wave that radiates outwards in all directions from the antenna.

When the radio wave hits the antenna of a radio receiver, the electrons in the receiver's antenna start to oscillate in exactly the same way as in the transmitting antenna. The radio receiver then reverses the process of the transmitter, converting the alternating current from the reception antenna back into the original signal, as seen in Figure 2.3.5.

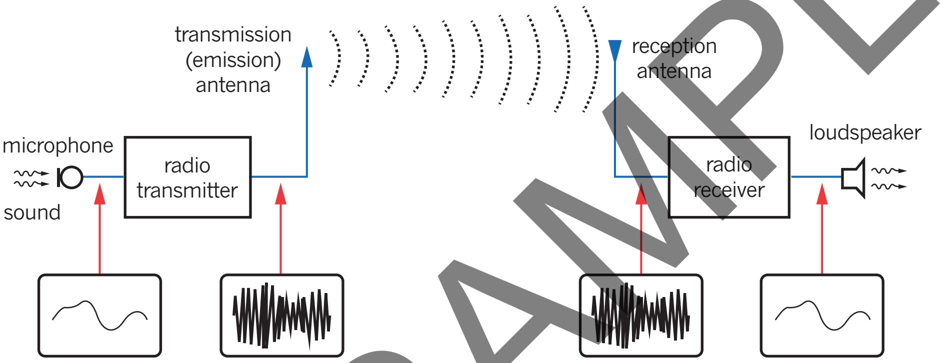


FIGURE 2.3.5 A typical radio transmission system

Microwaves

Microwaves have wavelengths between those of radio waves and visible light, as shown in Figure 2.3.2 on page XX. The most familiar example of microwaves is the microwave oven, used in heating and cooking food. A microwave oven is 'tuned' to produce a particular frequency of electromagnetic radiation: 2.45 GHz (i.e. 2.45×10^9 Hz). This is the resonant or natural vibration frequency of water molecules. The energy from the microwaves is transferred to the water molecules, causing the water molecules to vibrate more strongly, thus heating up the food.

Microwaves are also particularly useful in personal communication devices such as mobile phones, and for wireless internet transmission (WiFi), something we are incredibly reliant on and take for granted, as well as many other applications. Microwaves have shorter wavelengths and therefore greater penetrating power than radio waves, and so can be produced by devices with short antennas.

CASE STUDY

Australia invents WiFi

In 1990 there were no wireless devices. If people attempted to send complex signals at radio frequencies wirelessly across a room, the signals would reflect, interfere with each other and cause reverberations (delayed echoes). The solution to this problem came from a small team of Australian scientists, mathematicians and engineers at the CSIRO Department of Radiophysics. The team was led by physicist and radio-astronomer John O'Sullivan and included Terry Percival, Diet Ostry, Graham Daniels and John Deane.

Using a solution from Dr O'Sullivan's work in radio-astronomy, the team developed the Fast Fourier Transform (FFT) chip. A complex wave can be modelled as the superposition of individual waves. In WiFi, the original signal undergoes an FFT process through a computer chip, and is transmitted on a carrier signal to the receiver. There, the wave undergoes a reverse FFT and other signal processing, which results in the original waveform or signal.

Two common bands are used for the WiFi carrier signal, depending on the amount of data being sent: 2.4 GHz and 5 GHz. The two frequencies are split into multiple channels so as to prevent high traffic and interference

FIGURE 2.3.6 A common symbol for wireless communication (WiFi).

FIGURE 2.3.7 The coals of a fire emit red light as well as infrared radiation, which you experience as heat.

Infrared

The infrared section of the electromagnetic spectrum lies between microwaves and visible light (Figure 2.3.2 on page XX). Infrared waves are longer than the red waves of the visible spectrum, hence their name.

Infrared waves become useful because they are emitted by objects, to varying degrees, due to their temperature. The warmth that you feel standing next to an electric bar heater or a fire is due to infrared radiation (Figure 2.3.7). The radiant heat Earth receives from the Sun is transmitted in the form of infrared waves; life on Earth would not be possible without this important form of electromagnetic radiation.

Carbon dioxide is an important greenhouse gas that **absorbs** (takes in) and re-emits infrared radiation. This cycle is part of an important energy balance that keeps Earth warm enough for life.

Ultraviolet light

As the name suggests, ultraviolet (UV) waves have wavelengths that are shorter than those of violet light (Figure 2.3.2 on page XX), and therefore cannot be detected by the human eye. The shorter wavelengths means that UV rays have a stronger penetrating power than visible light. In fact, UV rays can actually penetrate human skin and overexposure can cause skin cancers. It should be noted that some exposure to UV radiation is essential for the production of vitamin D, which helps absorb calcium and potassium from food.

PHYSICSFILE

Night vision

Infrared radiation can be detected by sensors in night-vision goggles and cameras, and can be used to form images at night. For example, researchers can record the movement of many native Australian animals that are mostly active at night. Infrared radiation is also used in your television remote control.

UV radiation is divided into three bands: UVA, UVB and UVC. As shown in Table 2.3.2, UVA is not blocked by the atmosphere, while only 10% of UVB reaches Earth. Both bands can be blocked by a good sunscreen. UVC is blocked by the ozone layer. As exposure to UVC increases the risk of cancer to 10 000 times more than for UVA and UVB, scientists became concerned in the 1980s when a depletion in the ozone layer over the poles was measured. This was caused by chlorofluorocarbons, used in refrigeration. International efforts to reduce their use and use alternatives has resulted in a reduction in the size of the ozone hole.

TABLE 2.3.2 The UV radiation band is divided into three wavelength ranges according to how much reaches Earth.

UV band	Wavelength range	Penetrating power
UVA	315–400 nm	not blocked by Earth's atmosphere
UVB	280–315 nm	10% reaches Earth
UVC	100–280 nm	blocked by the ozone layer

Scientists can make use of UV light to take images. Figure 2.3.8 is a UV image of the surface of the Sun taken after a solar flare has occurred. The image has been re-coloured so that it highlights areas of different temperature. Here, areas that are coloured white are the hottest. Images like this help scientists learn about the temperatures of very hot objects. Taking an image of the Sun using visible light would not allow this same distinction.

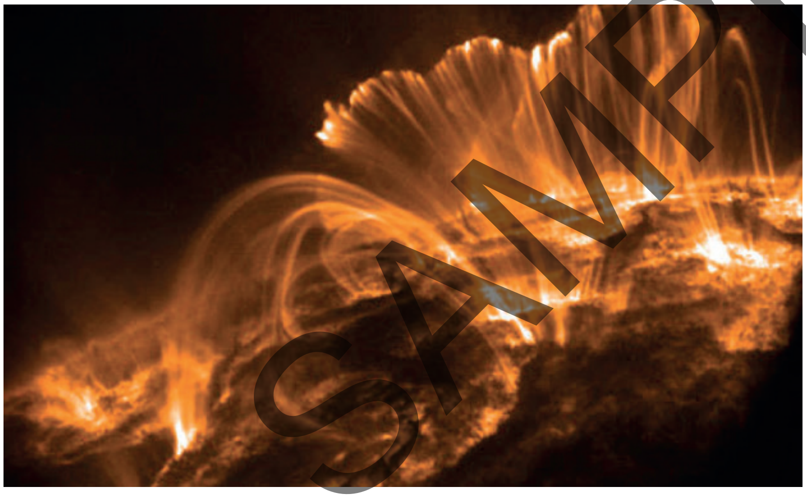


FIGURE 2.3.8 Re-coloured UV image of the surface of the Sun. The white areas reveal the hottest parts.

X-rays and gamma rays

X-rays and gamma rays have much shorter wavelengths than visible light (Figure 2.3.2 on page XX). This means that these forms of electromagnetic radiation have very high penetrating powers. For example, some X-rays can pass through different types of human tissues, which means that they are very useful in medical imaging (Figure 2.3.9).

FIGURE 2.3.9 This X-ray image of a hand can be formed because X-rays can pass through human tissues.

Unfortunately, this useful penetrating property of X-rays comes with inherent dangers. As X-rays pass through a human cell, they can do damage to the tissue, sometimes killing the cells or damaging the DNA in the cell nucleus, leading to harmful cancers. For this reason, a person's exposure to X-rays has to be carefully monitored to avoid harmful side effects.

Similarly, exposure to gamma rays can be very dangerous to human beings. The main natural sources of gamma radiation exposure are the Sun and radioactive isotopes. Fortunately, Earth's atmosphere protects us from most of the Sun's harmful gamma rays, and radioactive isotopes are not commonly found in sufficient quantities to produce harmful doses of radiation.

2.3 Review

SUMMARY

- Light is a form of electromagnetic radiation.
- Electromagnetic waves are transverse waves made up of mutually perpendicular, oscillating electric and magnetic fields.
- Electromagnetic waves can travel through a vacuum. As they do not require a medium to travel through, they are not mechanical waves.
- Electromagnetic radiation travels through a vacuum at approximately $c = 3.0 \times 10^{8}\ \mathrm{m\,s^{-1}}$.
- The wave equation $\lambda = \frac{c}{f}$ can be used to calculate the frequency and wavelength of electromagnetic waves.
- Electromagnetic radiation can be used for a variety of purposes depending on the frequency of the waves.
- The electromagnetic spectrum consists of radio waves, microwaves, infrared waves, visible light, ultraviolet light, X-rays and gamma rays.

KEY QUESTIONS

Knowledge and understanding

1 Outline the key difference between a mechanical wave and a light wave.

2 Arrange the types of electromagnetic radiation below in order of increasing wavelength.

FM radio waves / visible light / infrared radiation / X-rays / microwaves

3 What type of electromagnetic radiation would have a wavelength of 200 nm?

- **A** radio waves
- **B** microwaves
- **C** visible light
- **D** ultraviolet light

4 Give the form of electromagnetic radiation used or emitted in the following applications.

- **a** TV remote control
- **b** mobile phone
- **c** TV signal
- **d** the torch on your phone
- **e** astronomy
- **f** imaging a broken bone

Analysis

5 Calculate the frequencies of the following wavelengths of light.

- **a** red of wavelength 656 nm
- **b** yellow of wavelength 589 nm
- **c** blue of wavelength 486 nm
- **d** violet of wavelength 397 nm

6 Calculate the wavelength (in nm) of light with a frequency of 6.0×10^{14} Hz.

7 Calculate the wavelength of a UHF (ultra-high frequency) television signal with a frequency of 7.0×10^{7} Hz.

8 Calculate the frequency of an X-ray with a wavelength of 200 pm ($1\ \mathrm{pm} = 1 \times 10^{-12}$ m).

Chapter review

02

KEY TERMS

absorb
amplitude
compression
crest
electromagnetic spectrum
electromagnetic wave
frequency
longitudinal
mechanical wave
medium
oscillate
period
pulse
rarefaction
transmit
transverse
trough
wavelength

REVIEW QUESTIONS

Knowledge and understanding

1 Imagine that you watch from above as a stone is dropped into water. Describe the movement of the particles on the surface of the water.

2 State whether the following statements are true or false. Rewrite the false statements to make them true.

- **a** Longitudinal waves occur when particles of the medium vibrate in the opposite direction to the direction of the wave.
- **b** Transverse waves are created when the direction of vibration of the particles is at right angles to the direction of the wave.
- **c** A longitudinal wave is able to travel through air.
- **d** The vibrating string of a guitar is an example of a transverse wave.

3 A sound wave is emitted from a speaker and heard by Lee who is 50 m from the speaker. Lee made a number of statements once he heard the sound. Which one or more of the following statements made by Lee would be correct? Explain your answers.

- **A** Hearing a sound wave tells me that air particles have travelled from the speaker to me.
- **B** Air particles carried energy with them as they travelled from the speaker to me.
- **C** Energy has been transferred from the speaker to me.
- **D** Energy has been transferred from the speaker to me by the oscillation of air particles.

4 State whether the following statements are true or false. Rewrite the false statements to make them true.

- **a** The frequency of a wave is inversely proportional to its wavelength.
- **b** The period of a wave is inversely proportional to its wavelength.
- **c** The amplitude of a wave is not related to its speed.
- **d** Only the wavelength of a wave determines its speed.

5 If you decreased the wavelength of the sound made by a loudspeaker, what effect would this have on the frequency of the sound waves? The speed of sound in air is constant, for a constant temperature.

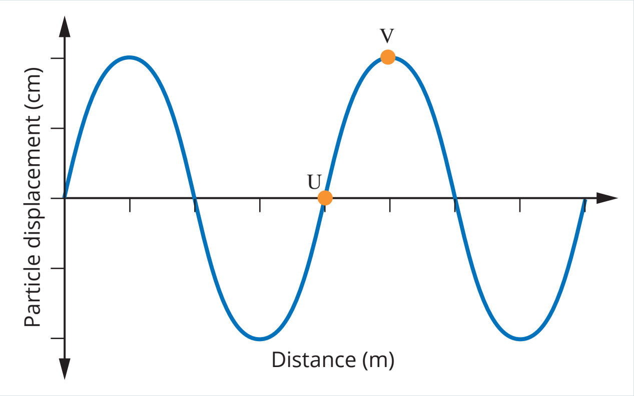
6 What form of electromagnetic radiation is used in the following applications?

- **a** night-vision goggles
- **b** medical imaging

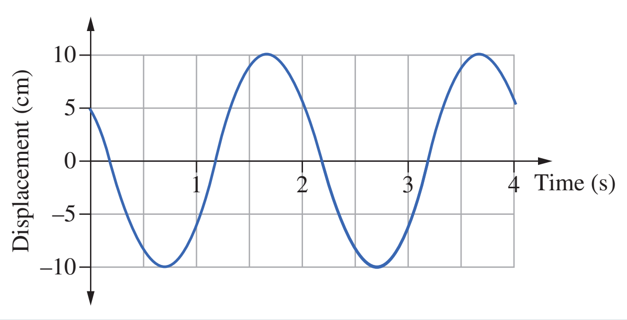
7 Using ideas about the movement of particles in air, explain how you know sound waves only carry energy and not matter from one place to another.

Application and analysis

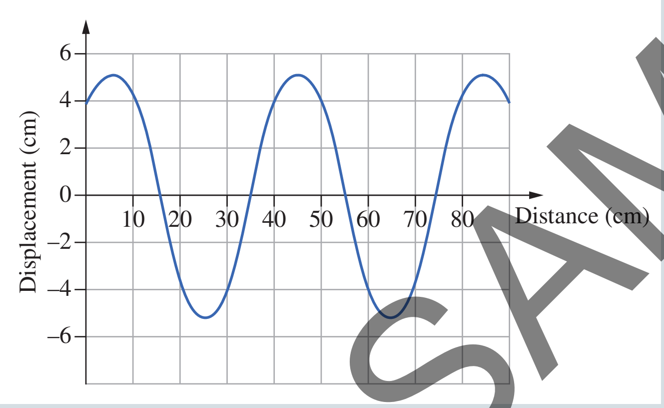
8 The graph below shows a wave moving to the right at a moment in time. In which directions are the particles U and V moving?



9 The displacement–time graph below shows the variation of displacement of a specific point on a wave with time. Identify which of the following wave characteristics can be determined from this type of graph: amplitude, frequency, period, wavelength, wave speed. Clearly state the values of these characteristics.



10 The displacement–distance graph indicates the disturbance of any point on the rope at a specific moment in time. Identify which of the following wave characteristics can be determined from this type of graph: amplitude, frequency, period, wavelength, wave speed. Clearly state the values of these characteristics.



11 The source of waves in a ripple tank vibrates at a frequency of 10.0 Hz. If the wave crests formed are 30.0 mm apart, what is the speed of the waves (in m s^{-1}) in the tank?

12 A submarine's sonar sends out a signal with a frequency of 32 kHz. If the wave travels at 1400 m s^{-1} in seawater, what is the wavelength of the signal?

13 Assuming the speed of sound in water is 1500 m s^{-1}, what would be the wavelength of a sound of frequency 300 Hz?

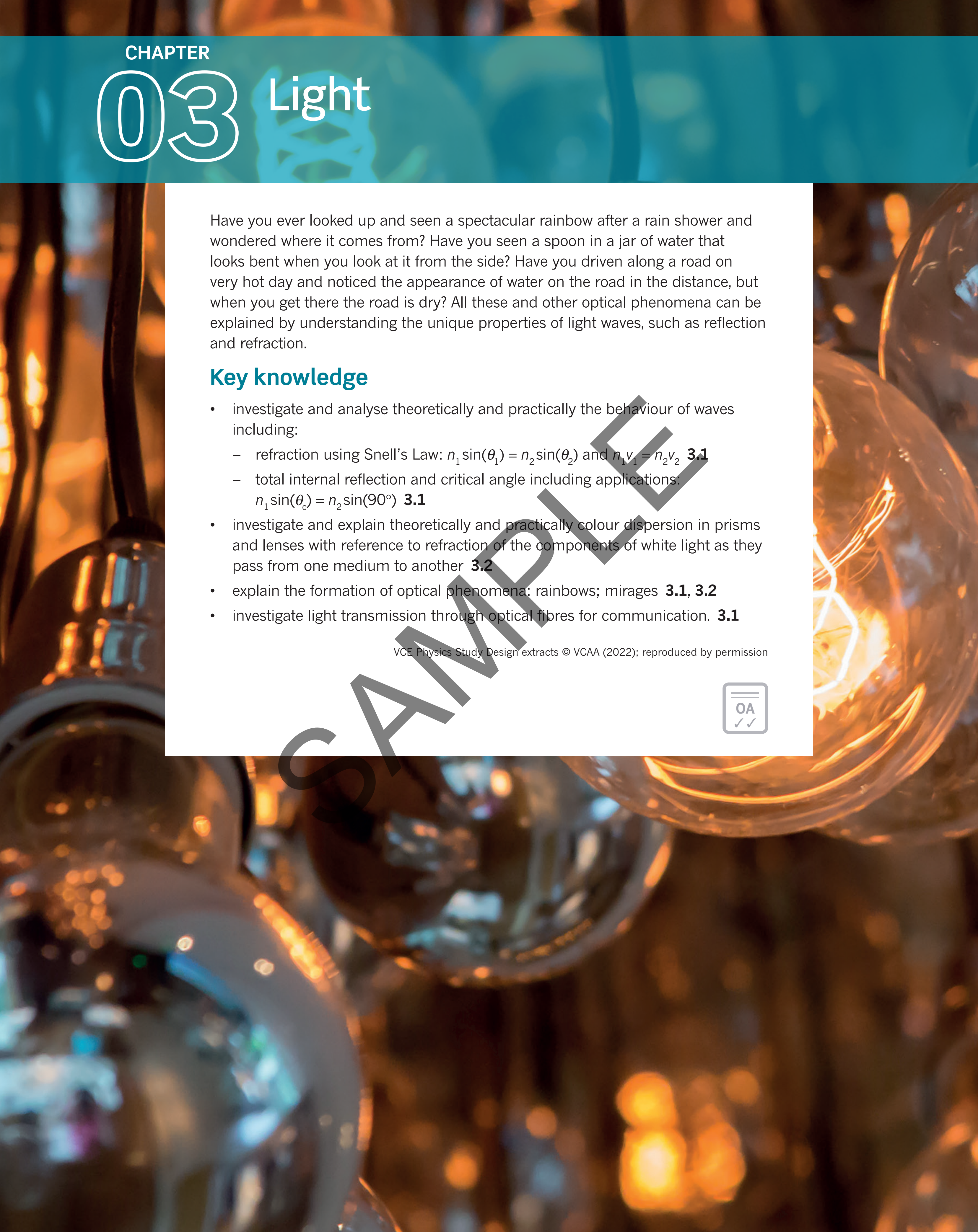
14 Blue light (6.00×10^{14} Hz) has a wavelength of 375 nm in water. Calculate the speed of blue light in water.

15 An AM radio station has a frequency of 612 kHz. If the speed of light is 3.00×10^{8} m s^{-1}, calculate the wavelength of these waves to the nearest metre.

16 Many WiFi routers have a 2.4 GHz band with a range from 2.40 GHz to 2.50 GHz, and a 5 GHz band that ranges from 5.180 GHz to 5.825 GHz. Calculate the range of wavelengths in each band.

17 Compare the microwave oven frequency with the WiFi 2.4 GHz band. Does this interfere with your WiFi router signal? Explain why? You may need to do some research.

18 Concerns have been raised that microwave radiation from mobile phone usage could cause cancers by damaging cells in a similar way to ionisation caused by X-rays and UV radiation. Given your knowledge of wavelengths and that the size of the human cell is 100 μm, how could you respond to this?



CHAPTER
03 Light

Have you ever looked up and seen a spectacular rainbow after a rain shower and wondered where it comes from? Have you seen a spoon in a jar of water that looks bent when you look at it from the side? Have you driven along a road on very hot day and noticed the appearance of water on the road in the distance, but when you get there the road is dry? All these and other optical phenomena can be explained by understanding the unique properties of light waves, such as reflection and refraction.

Key knowledge

- investigate and analyse theoretically and practically the behaviour of waves including:
  - refraction using Snell's Law: $n_1\sin(\theta_1) = n_2\sin(\theta_2)$ and $n_1v_1 = n_2v_2$ **3.1**
  - total internal reflection and critical angle including applications: $n_1\sin(\theta_c) = n_2\sin(90°)$ **3.1**
- investigate and explain theoretically and practically colour dispersion in prisms and lenses with reference to refraction of the components of white light as they pass from one medium to another **3.2**
- explain the formation of optical phenomena: rainbows; mirages **3.1**, **3.2**
- investigate light transmission through optical fibres for communication. **3.1**

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3.1 Reflection and refraction

If you drop a stone into water, water waves will ripple out in a circular fashion, as shown in Figure 3.1.1. The crests of the wave appears as wavefronts that ripple out in two dimensions.

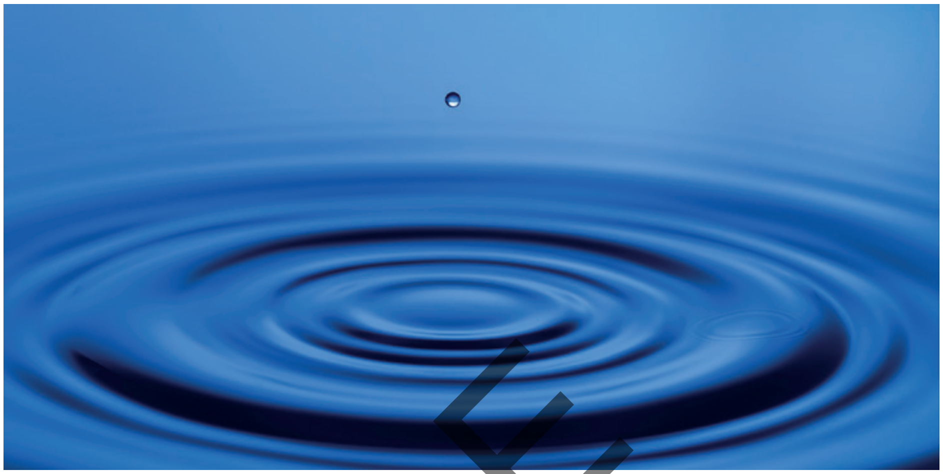


FIGURE 3.1.1 If a stone is dropped into still water the waves will ripple out in a circular fashion.

WAVEFRONTS

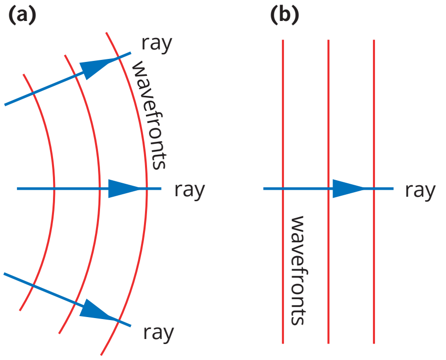


FIGURE 3.1.2 The crests of waves are drawn as wavefronts, shown in red. Rays can be used to illustrate the direction of motion of a wave and are drawn perpendicular to the wavefront of a two- or three-dimensional wave; (a) illustrates circular waves near a point source while (b) shows plane waves.

All two- and three-dimensional waves, such as water waves, travel as **wavefronts**. A wavefront is a continuous line (or surface) that includes all the points reached by a wave at the same instant. When drawing wavefronts (see red curves in Figure 3.1.2), it is common to show the crests of the waves. When close to the source, wavefronts can show considerable curvature (Figure 3.1.2(a)) or may even be spherical when generated in three dimensions. For a wave that has travelled a long distance from its source, the wavefront is nearly straight and is called a **plane wave**. A plane wave is shown in Figure 3.1.2(b). Plane waves in water can also be generated by a long, flat source in a ripple tank.

The direction of motion of any wavefront can be represented by a line drawn perpendicular to the wavefront and in the direction the wave is moving (see blue arrows in Figure 3.1.2). This is called a **ray**.

The wavefront from a light wave can also be drawn in this way.

HUYGENS' PRINCIPLE

The theoretical basis for wave propagation in two dimensions was first explained by the Dutch scientist Christiaan Huygens. Huygens' principle states that each point on a wavefront can be considered as a source of secondary wavelets (i.e. small waves).

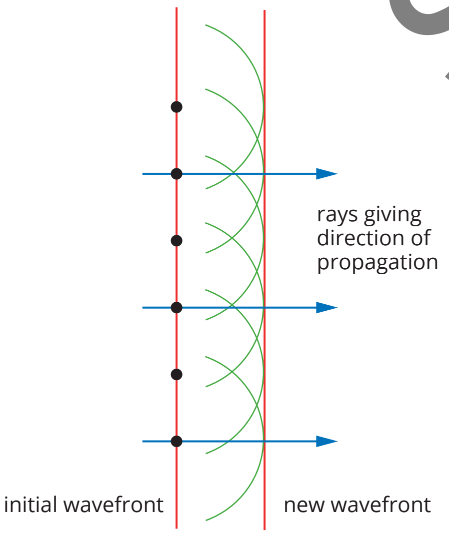


FIGURE 3.1.3 Each point on the wavefront of a plane wave can be considered as a source of secondary wavelets. These wavelets combine to produce a new plane wavefront.

Consider the plane wave shown in Figure 3.1.3. Each point on the initial wavefront can be treated as if it is a point source producing circular waves, some of which are shown in green. After one period, these circular waves will have advanced by a distance equal to one wavelength. Huygens proved mathematically that when the amplitudes of each of the individual circular waves are added, the result is another plane wave as shown by the new wavefront.

This process is repeated at the new wavefront, causing the wave to propagate in the direction shown.

Circular waves are propagated in a similar way, as shown in Figure 3.1.4.

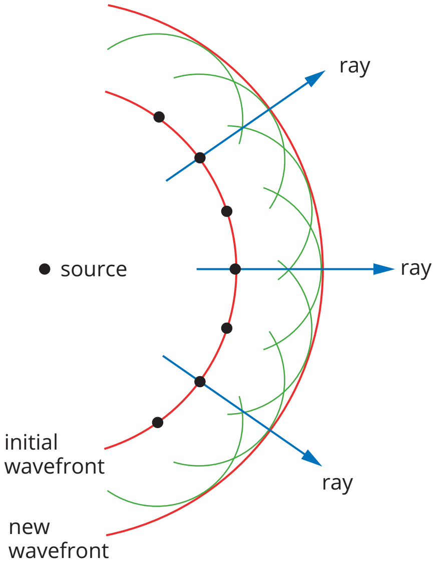
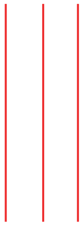


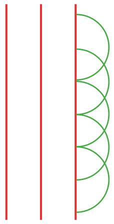
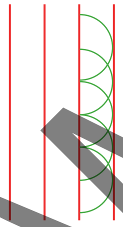
FIGURE 3.1.4 Each point on the wavefront of a circular wave can be considered as a source of secondary wavelets. These wavelets combine to produce a new circular wavefront.

Worked example 3.1.1

APPLYING HUYGENS' PRINCIPLE

On the plane wave shown moving from left to right below, sketch some of the secondary wavelets on the outer wavefront and draw the appearance of the new wave formed after one period.



Thinking	Working
Sketch a number of secondary wavelets on the advancing wavefront. The radius of each secondary wavelet will be the same as the distance between the existing wavefronts.	
Sketch the new wavefront, by drawing a line joining the peak of each secondary wavelet	

Worked example: Try yourself 3.1.1

APPLYING HUYGENS' PRINCIPLE

On the circular waves shown below, sketch some of the secondary wavelets on the outer wavefront and draw the appearance of the new wave formed after one period.

REFLECTED WAVEFRONTS

By using rays to illustrate the path of a wavefront reflecting from a surface, it can be shown that for a two- or three-dimensional wave, the angle from the normal at which the wave strikes a surface will equal the angle from the normal to the reflected wave. The **normal** is an imaginary line at 90° (i.e. perpendicular) to the surface.

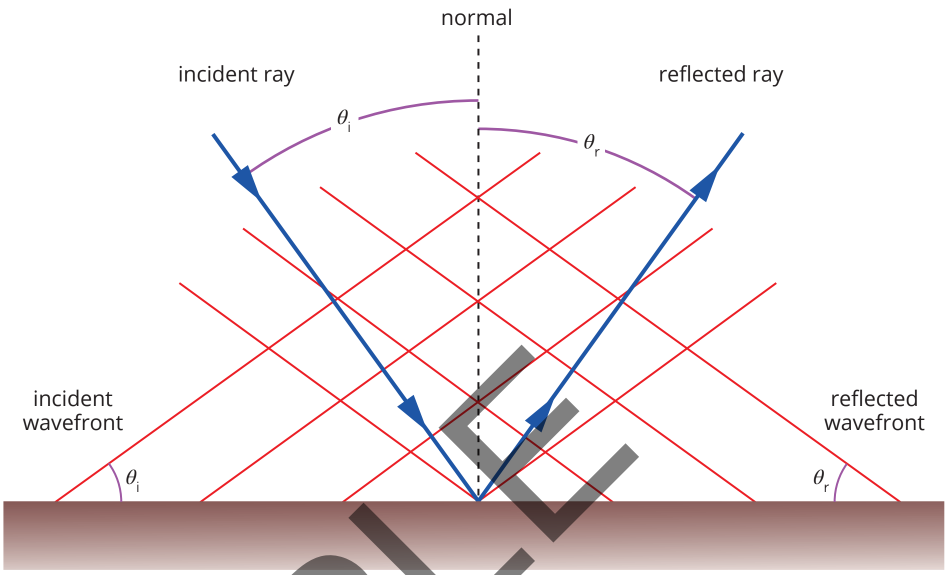


FIGURE 3.1.5 The law of reflection. The angle between the direction of the incident wave and the normal (θ_i) is the same as the angle between the normal and the reflected wave (θ_r).

Law of reflection
angle of incidence = angle of reflection
$\theta_i = \theta_r$

These angles of the incident and reflected waves from the normal are labelled θ_i and θ_r, respectively, in Figure 3.1.5. This is known as the law of reflection. The law of reflection states that the **angle of reflection**, measured from the normal, equals the **angle of incidence** measured from the normal; that is, $\theta_i = \theta_r$.

The law of reflection is true for any surface whether it is straight, curved or irregular. For all surfaces, including curved or irregular surfaces, the normal is drawn perpendicular to the surface at the point of contact of the incident ray or rays.

When wavefronts meet an irregular, rough surface, the resulting reflection can be spread over a broad area. This is because each point on the surface may reflect the portion of the wavefront reaching it in a different direction, as seen in Figure 3.1.6. This is referred to as **diffuse** (spread out) reflection.

When you walk on the beach at the height of summer, there is often a strong glare, a result of diffuse reflection from the sand.

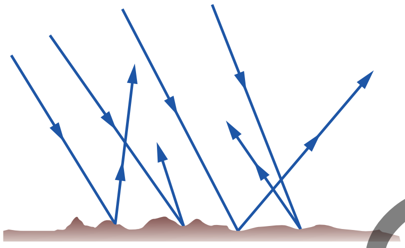


FIGURE 3.1.6 Reflection from an irregular surface. Each incident ray may be reflected in a different direction, depending upon how rough or irregular the reflecting surface is. The resulting wave will be diffuse (spread out).

REFRACTION

Refraction is a change in the direction of light caused by changes in its speed. Changes in the speed of light occur when light passes from one medium (substance) into another. In Figure 3.1.7, the light changes direction as it enters the glass prism, and then again when it leaves the glass prism and re-enters the air.

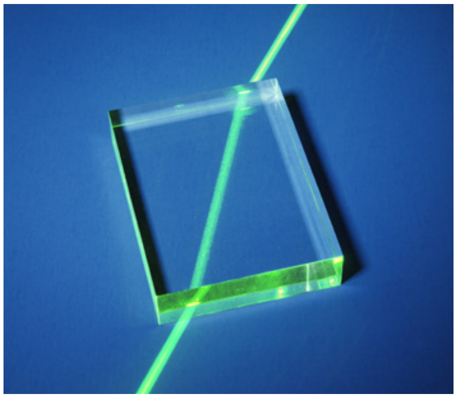


FIGURE 3.1.7 Light refracts as it moves from the air into the glass, causing a change in direction. The light refracts again as it goes from glass to air.

Consider Figure 3.1.8, in which light waves are moving from an incident medium where they have high speed, v_1, into a transmitting medium in which they have a lower speed, v_2. For the same time interval, Δt, in which the wave travels a distance $v_1\Delta t$ (B–D) in the incident medium, it travels a shorter distance $v_2\Delta t$ (A–C) in the transmitting medium. In order to do this, the wavefronts must change direction or 'refract' as shown.

Light waves behave in a similar way when they move from a medium such as air into water. The direction of the refraction depends on whether the waves speed up or slow down when they move into the new medium. In Figure 3.1.9, the light waves slow down as they move from air into glass, so the wavelength decreases and the direction of propagation of the wave is refracted towards the normal. The angle

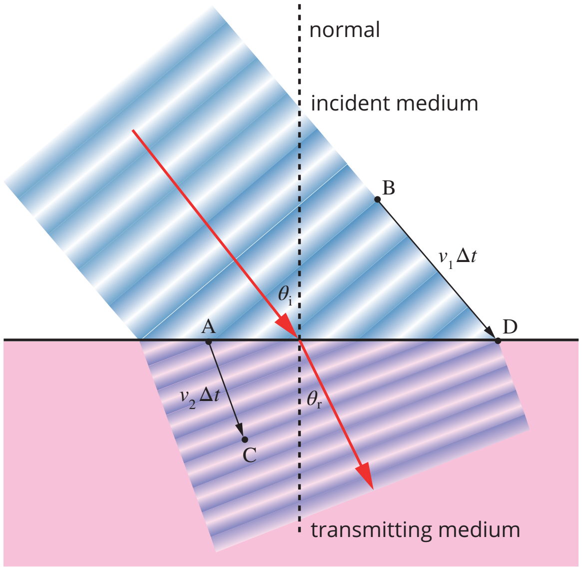


FIGURE 3.1.8 Wave refraction occurs because the distance A–C travelled by the wave in the transmitting medium is shorter than the distance B–D that it travels in the same time in the incident medium.

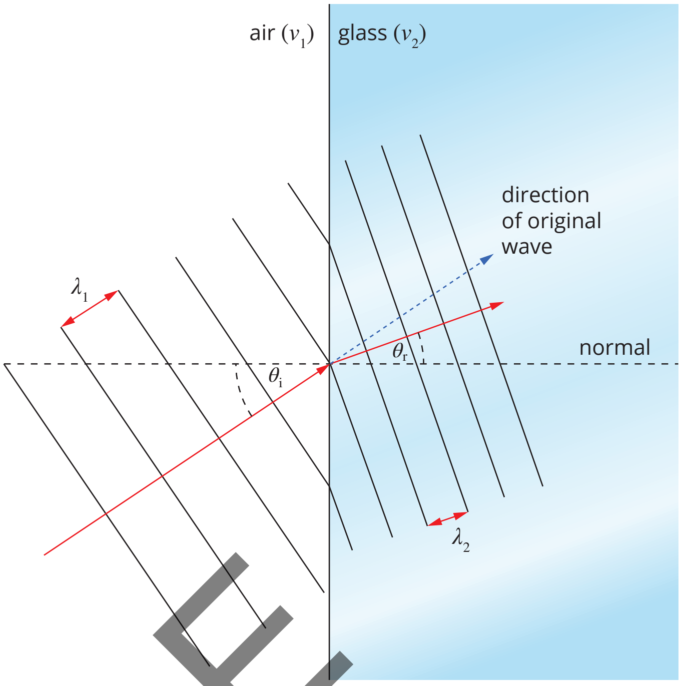


FIGURE 3.1.9 Light waves refract towards the normal when they slow down, $v_2 < v_1$.

of incidence, θ_i, which is defined as the angle between the direction of propagation and the normal, is greater than the angle of refraction, θ_r.

Conversely, when a light wave moves from glass, in which it has low speed, into air, in which it travels more quickly, it is refracted away from the normal, as shown in Figure 3.1.10. In other words, the angle of incidence, θ_i, is less than the angle of refraction, θ_r.

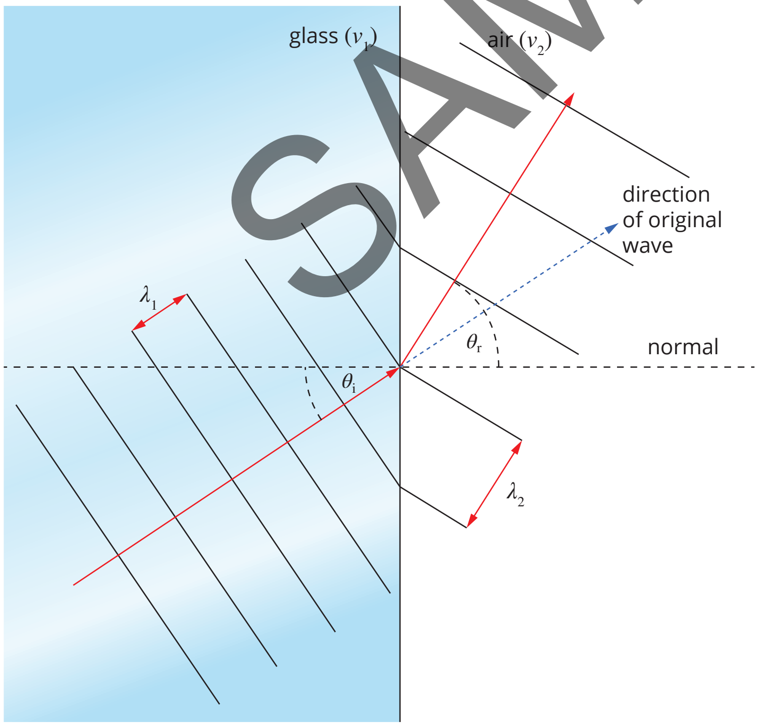


FIGURE 3.1.10 Light waves refract away from the normal when they speed up, $v_2 > v_1$.

Note that when a wave changes its speed, its wavelength also changes correspondingly, but its frequency does not change, as the number of waves per second remains the same.

Refractive index

The amount of refraction that occurs depends on how much the speed of light changes as light moves from one medium to another—when light slows down greatly, it will undergo significant refraction.

The speed of light in a range of different materials is shown in Table 3.1.1.

TABLE 3.1.1 The speed of light in various materials, correct to three significant figures

Material	Speed of light ($\times 10^8$ m s^{-1})
vacuum	3.00
air	3.00
ice	2.29
water	2.25
quartz	2.05
crown glass	1.97
flint glass	1.85
diamond	1.24

Scientists find it convenient to describe the change in speed of a wave using a property called the **refractive index**. The refractive index of a material, *n*, is defined as the ratio of the speed of light in a vacuum, *c*, to the speed of light in the medium, *v*.

$$n = \frac{c}{v}$$

where *n* is the refractive index (note that *n* is dimensionless, i.e. it has no units, it is just a number)
c is the speed of light in a vacuum (3.0×10^8 m s^{-1})
v is the speed of light in the medium.

The refractive index for various materials is given in Table 3.1.2.

TABLE 3.1.2 Refractive indices of various materials

Material	Refractive index, *n*
vacuum	1.00
air	1.00
ice	1.31
water	1.33
quartz	1.46
crown glass	1.52
flint glass	1.62
diamond	2.42

This quantity is also sometimes referred to as the 'absolute' refractive index of the material, to distinguish it from the 'relative' refractive index that might be used when a light wave moves from one medium to another, such as from water to glass.

Worked example 3.1.2

CALCULATING REFRACTIVE INDEX

The speed of light in water is 2.25×10^8 m s^{-1}. Given that the speed of light in a vacuum is 3.00×10^8 m s^{-1}, calculate the refractive index of water.

Thinking	Working
Recall the definition of refractive index.	$n = \frac{c}{v}$
Substitute the appropriate values into the formula and solve.	$n = \frac{3.00 \times 10^8}{2.25 \times 10^8}$ $= \frac{3.00}{2.25}$ $= 1.33$

Worked example: Try yourself 3.1.2

CALCULATING REFRACTIVE INDEX

The speed of light in crown glass (a type of glass used in optics) is 1.97×10^8 m s^{-1}. Given that the speed of light in a vacuum is 3.00×10^8 m s^{-1}, calculate the refractive index of crown glass.

By definition, the refractive index of a vacuum is exactly 1, since $n = \frac{c}{c} = 1$. Similarly, the refractive index of air is effectively equal to 1, because the speed of light in air is practically the same as its speed in a vacuum.

The definition of refractive index allows you to determine changes in the speed of light as it moves from one medium to another.

$n = \frac{c}{v}$, therefore $c = nv$. This applies for any material, therefore:

$$n_1 v_1 = n_2 v_2$$

where n_1 is the refractive index of the first material
v_1 is the speed of light in the first material
n_2 is the refractive index of the second material
v_2 is the speed of light in the second material.

Worked example 3.1.3

SPEED OF LIGHT CHANGES

A wave of light travels from crown glass ($n = 1.52$), in which it has a speed of $1.97 \times 10^8\,\mathrm{m\,s^{-1}}$, into water ($n = 1.33$). Calculate the speed of light in water.

Thinking	**Working**
Recall the formula.	$n_1 v_1 = n_2 v_2$
Substitute the appropriate values into the formula and solve.	$1.52 \times 1.97 \times 10^8 = 1.33 \times v_2$ $\frac{1.52 \times 1.97 \times 10^8}{1.33} = v_2$ $v_2 = 2.25 \times 10^8\,\mathrm{m\,s^{-1}}$

Worked example: Try yourself 3.1.3

SPEED OF LIGHT CHANGES

A light wave travels from water ($n = 1.33$), where it has a speed of $2.25 \times 10^8\,\mathrm{m\,s^{-1}}$, into glass ($n = 1.85$). Calculate the speed of light in glass.

Snell's law

The refractive indices can also be used to determine how much a light wave will refract as it moves from one medium to another. Consider the situation shown in Figure 3.1.11, in which light refracts as it moves from air into water. To simplify the diagram, only the ray is shown and not the wavefronts.

In 1621, the Dutch mathematician Willebrord Snell described the geometry of this situation with a formula that is now known as **Snell's law**.

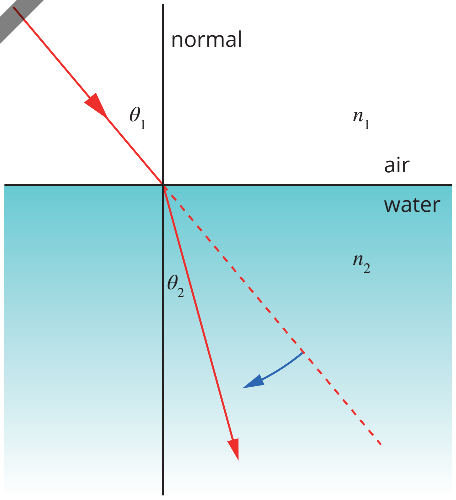


FIGURE 3.1.11 Light refracts as it moves from air into water.

Snell's law

$n_1 \sin\theta_1 = n_2 \sin\theta_2$

where n_1 is the refractive index of the first material

θ_1 is the angle of incidence

n_2 is the refractive index of the second material

θ_2 is the angle of refraction.

Worked example 3.1.4

USING SNELL'S LAW

A light wave in air strikes the surface of a pool of water ($n = 1.33$) at angle of 30° to the normal. Calculate the angle of refraction of the light in water.

Thinking	**Working**
Recall Snell's law.	$n_1 \sin\theta_1 = n_2 \sin\theta_2$
Recall the refractive index of air.	$n_1 = 1.00$
Substitute the appropriate values into the formula to find a value for $\sin\theta_2$.	$1.00 \times \sin 30^\circ = 1.33 \times \sin\theta_2$ $\sin\theta_2 = \frac{1.00 \times \sin 30^\circ}{1.33}$ $= 0.3759$
Calculate the angle of refraction.	$\theta_2 = \sin^{-1} 0.3759$ $= 22.1^\circ$

Worked example: Try yourself 3.1.4

USING SNELL'S LAW

A light wave in air strikes a piece of flint glass ($n = 1.62$) at angle of incidence of 50° to the normal. Calculate the angle of refraction of the light in the glass.

Total internal reflection

When light passes from a medium with low refractive index into one with higher refractive index, it is refracted towards the normal. Conversely, as shown in Figure 3.1.12, when light passes from a medium with a high refractive index to one with a lower refractive index, it is refracted away from the normal (Figure 3.1.12(a)). In this case, as the angle of incidence increases, the angle of refraction gets closer to 90° (Figure 3.1.12(b)). Eventually, at an angle of incidence known as the **critical angle**, the angle of refraction becomes 90° and the light is refracted along the interface between the two mediums (Figure 3.1.12(c)). If the angle of incidence is increased beyond this value, the light ray does not undergo refraction; instead, it is reflected back into the original medium, as if it was striking a perfect mirror (Figure 3.1.12(d)). This phenomenon is known as **total internal reflection** and is used in fibre-optic cables, as shown in Figure 3.1.13. The working of a fibre-optic cable is discussed on page XXX.

As the angle of refraction for the critical angle is 90°, the critical angle is defined by the formula:

Therefore:

$n_1 \sin\theta_c = n_2 \sin 90°$

$\sin 90° = 1$, therefore $n_1 \sin\theta_c = n_2$

Therefore: $\sin\theta_c = \dfrac{n_2}{n_1}$

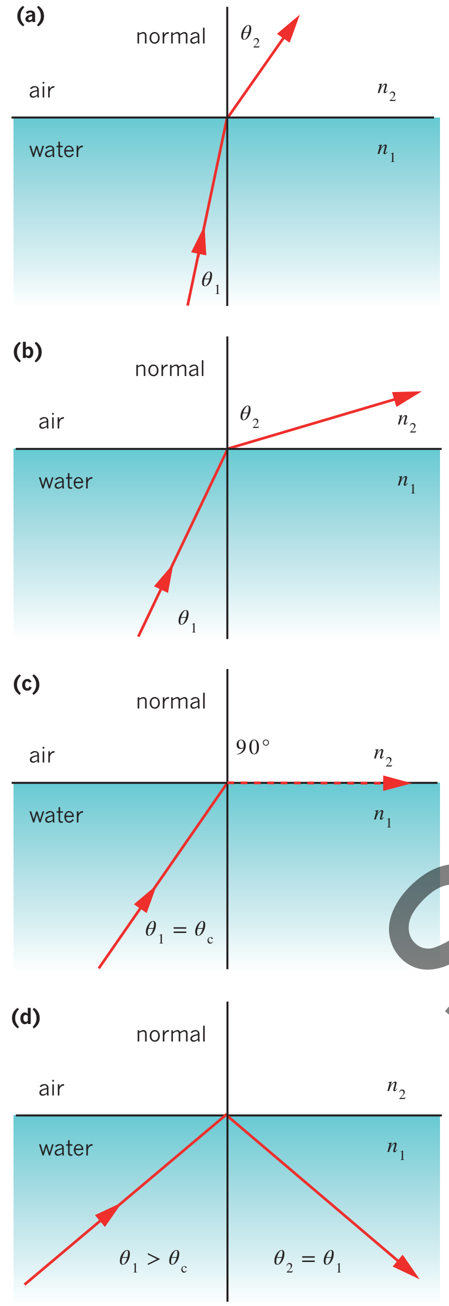


FIGURE 3.1.12 Light refracts as it moves from water into air as shown in diagrams (a) and (b). In diagram (c), the angle of refraction is exactly 90° to the normal and in (d) the light is undergoing total internal reflection.

Worked example 3.1.5

CALCULATING CRITICAL ANGLE

Calculate the critical angle for light passing from water into air.

Thinking	Working
Recall the equation for critical angle.	$\sin\theta_c = \dfrac{n_2}{n_1}$
Substitute the refractive indices of water and air into the formula. (Unless otherwise stated, assume that the second medium is air with $n_2 = 1$.)	$\sin\theta_c = \dfrac{1.00}{1.33}$ $= 0.7519$
Solve for θ_c.	$\theta_c = \sin^{-1} 0.7519$ $= 48.8°$

Worked example: Try yourself 3.1.5

CALCULATING CRITICAL ANGLE

Calculate the critical angle for light passing from diamond into air.

Fibre-optic cables and total internal reflection

The National Broadband Network (NBN) is integral to the functioning of modern society. A key part of this is the fibre-optic network used to send optical signals to your home, school and work. The information is turned into a light wave signal and sent down the fibre-optic cable using a semiconductor laser diode. Fibre-optic

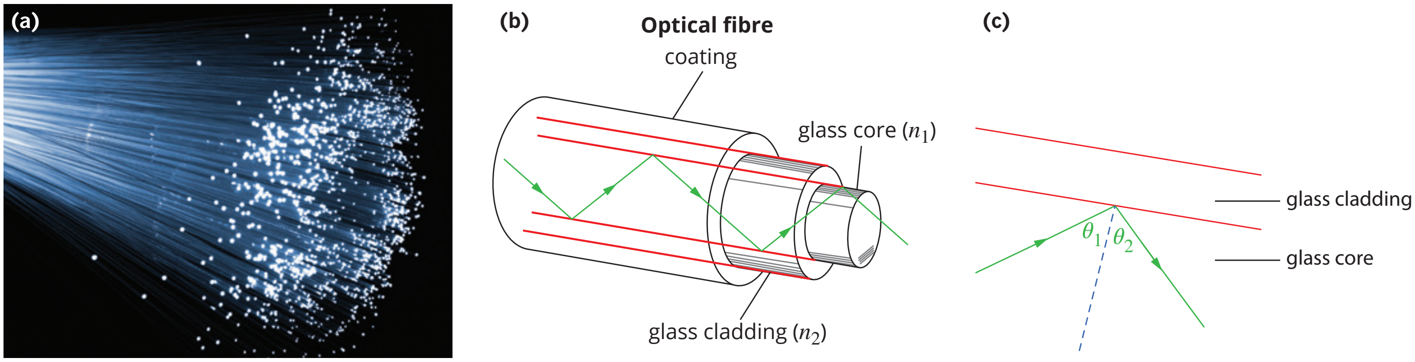


FIGURE 3.1.13 (a) Optical fibres transmit light using total internal reflection. (b) The outer glass cladding is made of glass with a slightly lower refractive index (n_2) than the glass core (n_1). (c) The angle of incidence of the incoming light is shown as θ_1 and the angle of refraction is shown as θ_2.

cables can also be used to send light down a cable for decorative or lighting effects, as shown in Figure 3.1.13(a).

A fibre-optic cable consists of an inner glass core with refractive index n_1, surrounded by an outer glass cladding with refractive index n_2, as shown in Figure 3.1.13(b). The refractive index of the cladding is less than that of the core, ($n_2 < n_1$). At angles greater than the critical angle, total internal reflection occurs from the cladding and light is propagated down the core. Some refraction can occur at the interface between the core and the cladding, so the intensity of the signal gradually reduces. To counteract this, the fibre-optic cable is connected to a semiconductor detector, the signal is electrically amplified and then converted into a light wave by another semiconductor laser diode and sent down another length of fibre-optic cable. The fibre-optic cable is protected by an outer plastic coating as shown.

Optical effects due to refraction

Some everyday optical phenomena can be explained using the principles of refraction.

Apparent position of objects under water

When you look at a fish in the water, where you see the fish is not the real position of the fish. Indigenous Australian fishing techniques allow for this and include aiming lower than where the fish appears to be, and using a spear that has a number of points evenly spread along the shaft, which increases the probability of striking a fish at its real depth.

The **apparent depth** (D_a) and the **real depth** (D_r) of the fish is shown in Figure 3.1.14. This difference between real depth and apparent depth is due to the refraction of the light rays travelling up from the fish through the water to the water–air boundary, and into the air above to the observer. The change in medium results in a change in velocity of the light waves. The light waves travel faster in air, making the light ray bend, or refract, at the water–air boundary. In this case, the

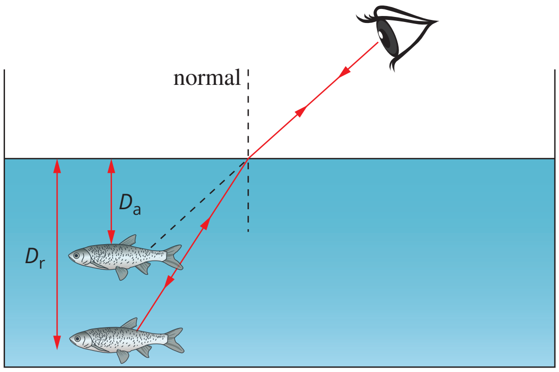
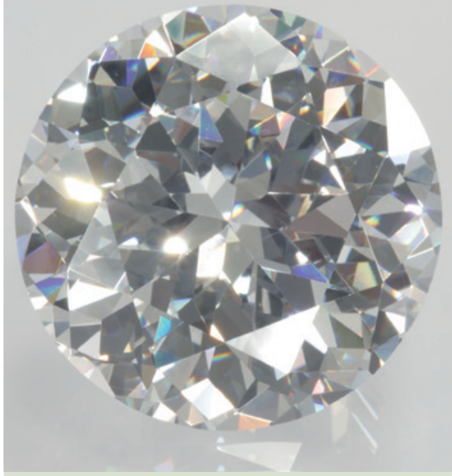


FIGURE 3.1.14 The apparent depth, D_a, of a fish compared to the real depth, D_r, as seen from above the air water interface

PHYSICSFILE

Refractive index of diamonds

Diamond has a very high refractive index; therefore, it has a small critical angle. This means that a light wave that enters a diamond will often bounce around inside the diamond many times before leaving the diamond. A jeweller can cut a diamond to take advantage of this property; this causes the diamond to 'sparkle' (see below), as it appears to reflect more light than is falling on it.



The refractive properties of diamonds mean they appear to sparkle.

light ray speeds up and bends away from the imaginary normal line. The light rays are refracted at the water–air boundary before they enter the observer's eyes, so the fish appears at the apparent depth (D_a) and not the real depth (D_r).

Early sunrise and late sunset

At sunset, you are seeing the Sun when it is already below the horizon. Also, when the Sun is near the horizon during sunset, it appears to be more oval-shaped than circular, as shown in Figure 3.1.15(a). Notice that the shape of the Sun appears to distort as it approaches the horizon.

During sunrise and sunset, light waves from the Sun travel a greater distance through the atmosphere than at midday, when the Sun is directly overhead. The atmosphere consists of layers due to the air thinning with increasing altitude. This means that the density of air decreases with increasing altitude, or in other words, the refractive index of air at the surface of the Earth is higher than that of air in the upper atmosphere. This layered structure of the atmosphere continuously refracts the light rays until they reach the observer's eye. As light travels through the atmosphere it slows down and is continually refracted towards the normal. This leads to the light wave travelling in a curved path as shown in Figure 3.1.15(b). To the observer, the Sun appears to be in a higher position than it actually is. Due to this effect, we can see the Sun even if it is actually below our horizon. The length of a day appears to be about 4 minutes longer than it actually is due to the refraction of sunlight.

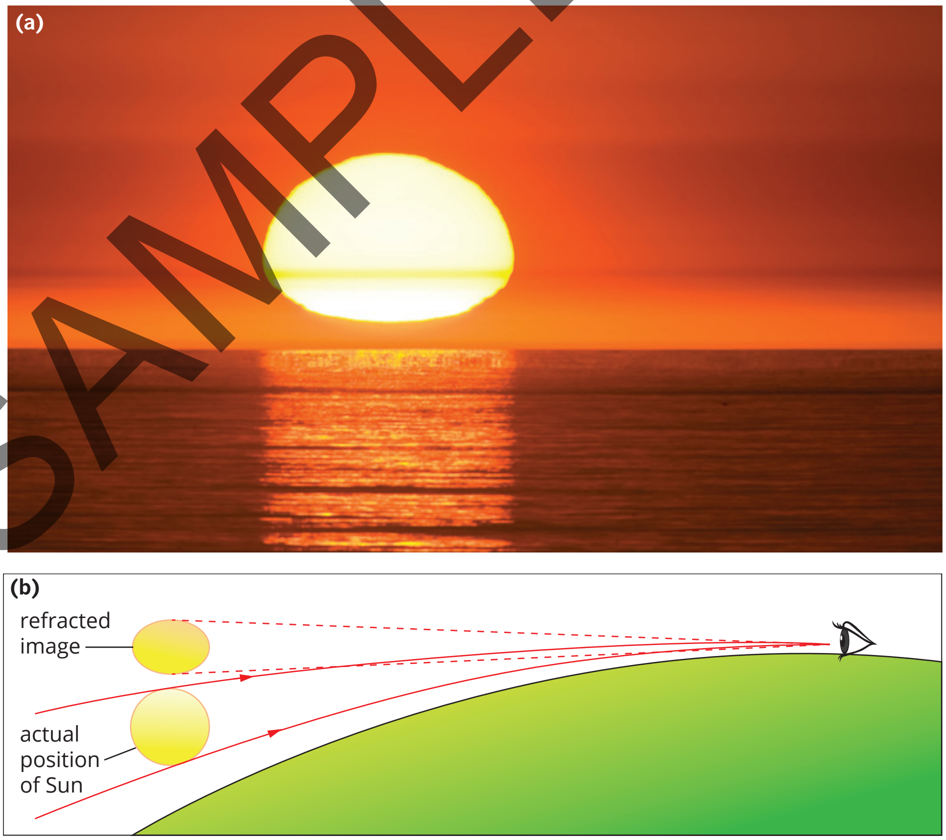


FIGURE 3.1.15 (a) The shape of the Sun appears flatter as it approaches the horizon. It looks less circular and more oval-shaped. (b) At sunset and sunrise, the observed position of the Sun is a refracted image and appears higher than the actual position of the Sun.

Refraction of light by the atmospheric layers also makes the Sun appear flattened or distorted. At sunset and sunrise, the lower part of the Sun is closer to the horizon and light from it is refracted more than light from the top part of the Sun. The observed effect is that the bottom of the Sun is lifted up more than the top. The Sun appears more oval in shape. The circular Sun is the object and the flatter, oval Sun is the image seen by the observer.

Mirages

You are in a car that is travelling down a road on a very hot day. Looking ahead you see the illusion of water on the road similar to that in Figure 3.1.16(a). When you get there, however, the road is completely dry. This effect is known as a mirage and occurs due to refraction effects in the atmosphere.

On a very hot day the atmosphere heats up, leading to the formation of hotter (less dense) layers of air rising above colder (denser) layers of air, which sink down. The variation in temperature and density produces a variation in the refractive index of the air, which effectively curves the direction of the light. This can result in light from the sky being refracted upwards towards you in the oncoming car, as shown in Figure 3.1.16(b), giving the appearance of water. Under certain conditions you can also see a refracted image from an object in front of you, as shown by the red ute.

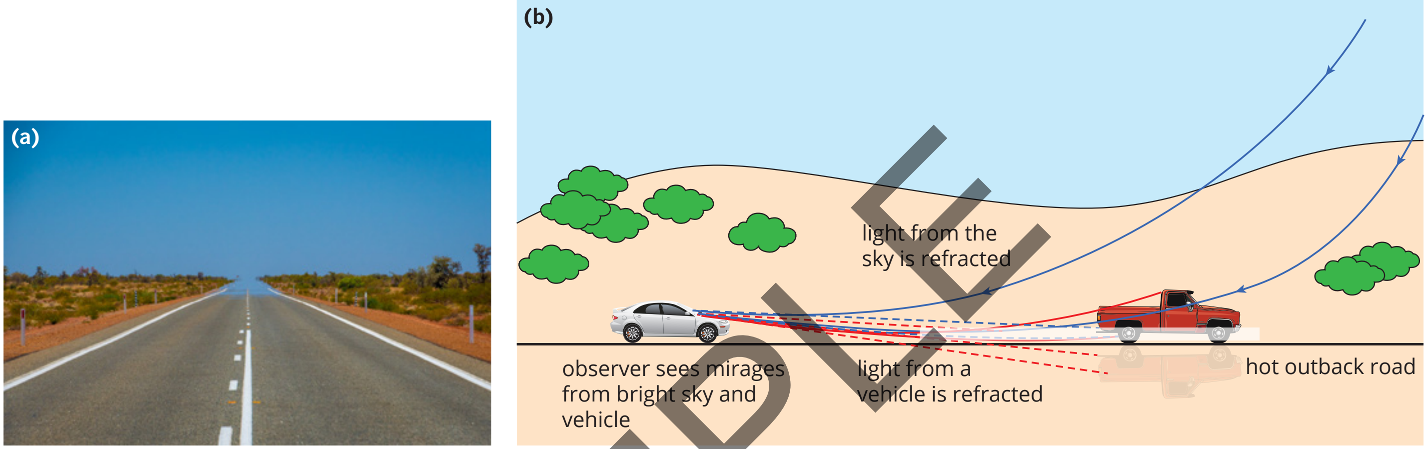


FIGURE 3.1.16 (a) On a hot day a mirage gives the illusion of water on the road. (b) Variations in the atmospheric refractive index lead to refraction of blue light from the sky. In addition, refraction effects can lead to the illusion of the occupants of the blue car seeing an inverted image of the red car.

3.1 Review

SUMMARY

- Wavefronts are the crests of two- or three-dimensional waves.
- Huygens' principle states that each point on a wavefront can be considered as a source of secondary wavelets. These wavelets combine to produce a new wavefront.
- In reflection, the angle of incidence of the wave relative to the normal is equal to the angle of reflection relative to the normal.
- Refraction is the change in the direction of light that occurs when light moves from one medium to another due to a change in the speed of the light waves.
- The refractive index, n, of a material is given by the formula $n = \frac{c}{v}$, where c is the speed of light in a vacuum and v is the speed of light in the material.
- When light moves from one material to another, the change in speed can be calculated using: $n_1v_1 = n_2v_2$
- The amount of refraction of a light wave can be calculated using Snell's law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$
- The critical angle of a material denotes the angle of incidence when the angle of refraction is 90°. It can be calculated using $n_1 \sin\theta_c = n_2 \sin 90°$ or $\sin\theta_c = \frac{n_2}{n_1}$.
- Total internal reflection occurs when the angle of incidence is greater than the critical angle.
- Light is propagated through the glass inner core of fibre-optic cables. Total internal reflection occurs between the inner core glass and the outer cladding glass.
- Optical effects in which the apparent position of an object does not match its true position occur due to changes in refractive index between the source of the light wave and the observer.

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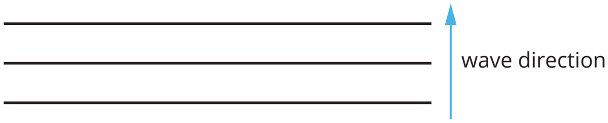
3.1 Review *continued*

KEY QUESTIONS

Knowledge and understanding

1 Copy the diagram below and use Huygens' principle to draw a new wavefront of the plane wave after one period.



2 Choose the correct response from those given in bold to complete the sentences about the refractive indices of types of water.

Although pure water has a refractive index of 1.33, the salt content of sea water means its refractive index is a little higher at 1.38. Therefore, the speed of light in sea water will be **faster than**/**slower than**/**the same as** in pure water.

3 Calculate the speed of light in sea water that has a refractive index of 1.38.

4 Light travels at of $2.25 \times 10^8\,\mathrm{m\,s^{-1}}$ in water and $2.29 \times 10^8\,\mathrm{m\,s^{-1}}$ in ice. If water has a refractive index of 1.33, use this information to calculate the refractive index of ice.

5 Light travels from water (n = 1.33) into glass (n = 1.60). The incident angle is 44°. Calculate the angle of refraction.

6 Wavefronts of light initially travelling in air are incident and parallel to an air–glass boundary (the angle of incidence of the light ray is 0°). Identify which one or more of the following statements is true regarding the wavefront and ray travelling through the glass.

- **A** The wavefronts will not refract or bend as the wave slows down in the glass medium.
- **B** The wavefronts will not refract or bend as the wave speeds up in the glass medium.
- **C** The wavefronts will refract or bend as the wave slows down in the glass medium.
- **D** The wavefronts will refract or bend as the wave speeds up in the glass medium.

7 Assess whether these statements are true or false regarding different types of waves and the angles of incidence and refraction. Rewrite the false statements to make them true.

- **a** When light rays refract away from the normal line at a boundary between two different media, the light wave is travelling faster in this new medium.
- **b** The setting and rising Sun appears flatter than the afternoon Sun because light from the higher part of the Sun refracts more than that from the lower part of the Sun. The observed effect is that the top of the Sun is lowered more than the bottom of the Sun.
- **c** An object in water appears lower than is actually is.

8 **a** The fibre-optic glass cladding has a **higher**/**lower** refractive index than the glass core (choose the correct answer)

- **b** How is light propagated down the fibre-optic cable? (Explain your answer incorporating your response from part a)

Analysis

9 **a** The cladding of a fibre-optic cable has a refractive index of 1.348. The critical angle is 62.3°. Determine the refractive index of the core.

- **b** Determine the speed of light in the core.
- **c** Determine the range of angles, relative to the core–cladding interface, that will be reflected.

10 For which of the following situations can total internal reflection occur?

	Incident medium	Refracting medium
a	air (n = 1.00)	glass (n = 1.55)
b	glass (n = 1.55)	air (n = 1.00)
c	glass (n = 1.55)	water (n = 1.33)
d	glass (n = 1.55)	glass (n = 1.58)

3.2 Dispersion and polarisation

A rainbow is often seen when the Sun appears after a rain shower. The rainbow illustrates that visible light is made up of a spectrum of colours. In the previous section on page XX and in Section 2.3 on page XX, light was described as a wave and its behaviour was explored. Further examples of the wave behaviour of light are dispersion, which is seen in rainbows, and polarisation.

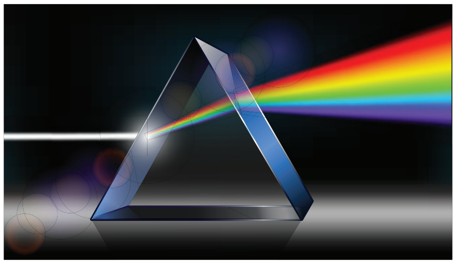


FIGURE 3.2.1 When white light enters a prism, it is split into its component wavelengths or colours.

DISPERSION

When white light passes through a triangular glass prism (as shown in Figure 3.2.1), it undergoes **dispersion**. This spreading out into its component colours is a result of refraction.

As you saw in Section 2.3 on page XX, each different colour of light has a different wavelength (Table 3.2.1). White light is a mixture of light waves of many different wavelengths.

As discussed in the previous section and shown in Figure 3.1.8 on page XX, when light travels from air into a medium such as glass, the wavelength decreases as the waves bunch up. However, each colour travels at a different speed, so that, in effect, a medium has a different refractive index for each wavelength of light. Figure 3.2.2 shows the wavelength dependence of the refractive index for crown glass, acrylic and silica. The refractive index for each material decreases with wavelength. Given that $n = \frac{c}{v}$, the velocity of a wave in these materials increases with wavelength.

For light of longer wavelengths (such as red light), a medium has a lower refractive index, and light travels the fastest. Therefore it will refract at a larger angle.

For light of shorter wavelengths (such as violet light), a medium has the highest refractive index, and light travels the slowest. Therefore it will refract the least.

This leads to the components of visible light being refracted at a range of angles, leading to the rainbow effect seen in Figure 3.2.1. Each wavelength of light is incident at a different angle on the opposite face of the prism, which further exaggerates the dispersion effect.

TABLE 3.2.1 Approximate wavelength ranges for the colours in the visible spectrum in air. 1 nm = 10^{-9} m

Colour	Wavelength (nm)
red	780–622
orange	622–597
yellow	597–577
green	577–492
blue	492–455
violet	455–390

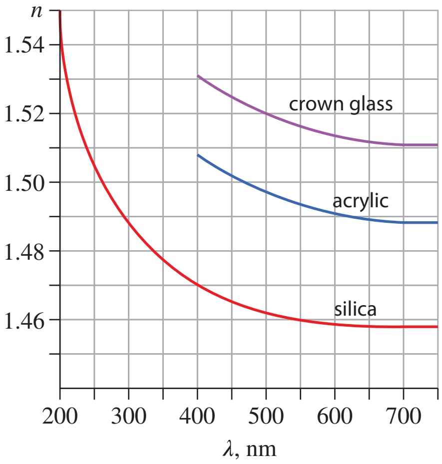
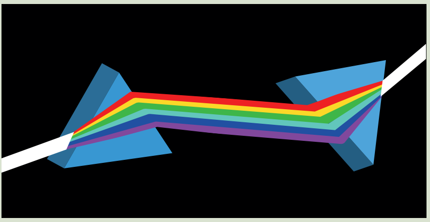


FIGURE 3.2.2 The refractive index of a material varies with wavelength. For glass, the refractive index decreases as wavelength increases.

PHYSICSFILE

Where does colour come from?

In the 17th century, many people believed that white light was 'stained' by its interaction with earthly materials. Isaac Newton very neatly disproved this with a simple experiment using two prisms—one to split light into its component colours and the other to turn it back into white light (see right). This showed that the various colours were intrinsic components of white light since, if colour was a result of 'staining', the second prism should have added more colour rather than less.



Newton's double prism experiment showed that white light is made up of its component colours.

Newton was the first to identify the colours of the spectrum—red, orange, yellow, green, blue, indigo and violet. He chose seven colours by inventing the colour 'indigo', because seven was considered a sacred number.

You can see how white light is formed by the combination of other colours by using a ×10 lens (a microscope objective lens works well) to look at the white part of a computer screen. You will see the red, blue and green pixels that are used to generate the white light.

Worked example 3.2.1

CALCULATING RANGE OF ANGLES FOR DISPERSION

White light is incident on the surface of a triangular prism made of crown glass at an angle of 38° to the normal. Use the graph in Figure 3.2.2 to determine the range of refracted angles for visible light entering the prism. Assume a wavelength range of 400 nm to 700 nm.

Thinking	**Working**
Recall Snell's law.	$n_1 \sin\theta_1 = n_2 \sin\theta_2$
Identify the variables for air.	$n_1 = 1$ for air, $\theta_1 = 38°$
Use the graph to determine the refractive index for crown glass at 400 nm and 700 nm.	Reading from the graph: At 400 nm: $n_2 = 1.531$ At 700 nm: $n_2 = 1.512$
Substitute the refractive index of crown glass at 400 nm and 700 nm into Snell's law to determine the range of wavelengths.	For 400 nm: $\sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2} = \frac{1.00 \times \sin 38°}{1.531} = 0.402$ $\theta_2 = 23.7°$ $\sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2} = \frac{1.00 \times \sin 38°}{1.512} = 0.407$ $\theta_2 = 24.0°$
State the range.	The range of angles within the prism varies from 23.7° to 24.0°.

Worked example: Try yourself 3.2.1

CALCULATING RANGE OF ANGLES FOR DISPERSION

White light is incident on the surface of a triangular prism made of acrylic at an angle of 70° to the normal. Use the graph in Figure 3.2.2 to determine the range of angles for visible light entering the prism. Assume a wavelength range of 400 nm to 700 nm.

Optical effects due to dispersion

Some everyday optical phenomena can be explained using the principles of dispersion.

Colour dispersion in lenses

As each colour of light effectively has a different refractive index in glass, light passing through a glass lens always undergoes some dispersion. This means that coloured images formed by optical instruments such as microscopes and telescopes can suffer from a type of distortion known as chromatic aberration (Figure 3.2.3).

FIGURE 3.2.3 Chromatic aberration causes the coloured fringes that can be seen in the circled regions in this image.

Scientists have developed a number of techniques to deal with this problem, including:

- using lenses with very long focal lengths
- using 'achromatic' lenses—compound lenses that are made of different types of glass with different refractive properties
- taking separate images using coloured filters and then combining these images to form a single multi-coloured image.

The formation of rainbows

Rainbows are spectacular optical phenomena that occur after rainfall or on showery days. They are quite often seen as single rainbows, but they can sometimes form the double image shown in Figure 3.2.4(a).

The next time you see a rainbow, have a look at the direction of the Sun relative to the position of the rainbow. The Sun will generally be behind you. As discussed, light from the Sun that enters Earth's atmosphere consists of a range of wavelengths from violet-blue through to red. After rain, light waves can enter a raindrop. The refractive index of water is higher than the refractive index of air, so refraction occurs as the light enters the raindrop. The refractive index of water, like that for the prism, varies with wavelength; thus, dispersion effects occur such that the angle of refraction is higher for red light than for blue light (Figure 3.2.4(b)). Total internal reflection occurs at the back of the raindrop, then the light is refracted again as it exits the raindrop. This leads to an angular spread of colour from blue through to red, which gives the rainbow its circular shape. We don't see a full circle as Earth gets in the way.

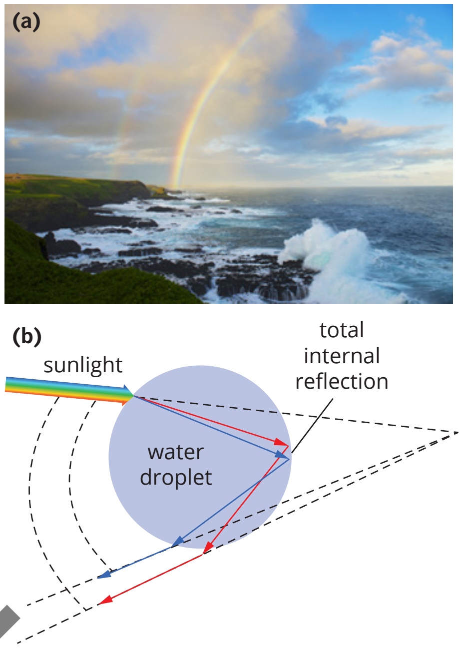


FIGURE 3.2.4 (a) A double rainbow is formed over Phillip Island, Victoria. (b) The formation of a rainbow is due to a combination of reflection and dispersion in raindrops.

POLARISATION

One of the most convincing pieces of evidence for the wave nature of light is the phenomenon of polarisation.

Light is a transverse wave (Chapter 2), which means the wave is vibrating perpendicular to the direction of propagation. Light produced by some sources, such as a light globe or the Sun, is unpolarised and can be thought of as a collection of waves, each vibrating in a different plane but still perpendicular to the direction of travel, as shown in Figure 3.2.5.

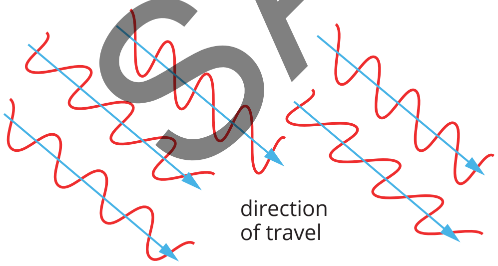


FIGURE 3.2.5 Unpolarised light waves consist of a collection of waves that vibrate perpendicular to the direction of travel but in different planes. Each wave has a different plane of polarisation.

Polarisation occurs when a transverse wave is allowed to vibrate in only one plane. This can be done by using a polarising filter. For example, the light wave in Figure 3.2.6 is already vertically polarised—the wave oscillations occur in the vertical plane only. This means that this wave is unaffected by a polarising filter that is orientated in the vertical plane.

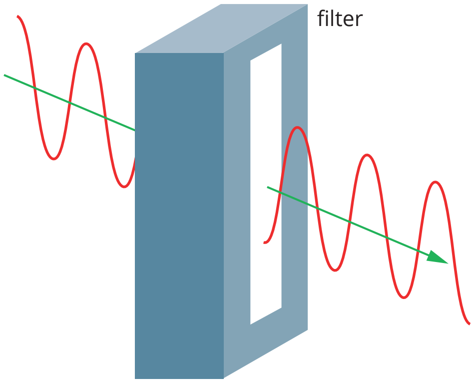


FIGURE 3.2.6 A vertically polarised wave can pass through a vertically orientated polarising filter.

The wave in Figure 3.2.7 is horizontally polarised. It is completely blocked by the vertical polarising filter.

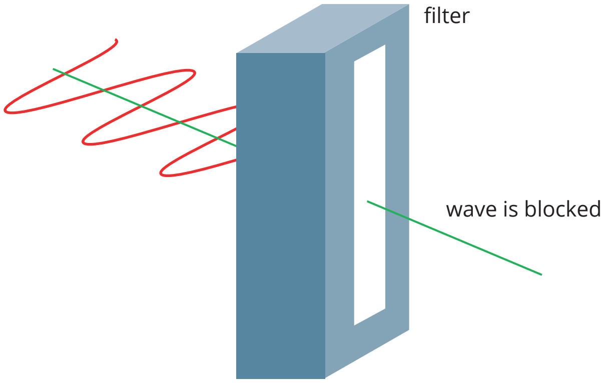


FIGURE 3.2.7 A horizontally polarised wave cannot pass through a vertically orientated polarising filter.

In Figure 3.2.8, the incoming wave is polarised at 45° to the horizontal and vertical planes. The horizontal component of this wave is blocked by the vertical filter, so the ongoing wave is vertically polarised and has a smaller amplitude than the original wave.

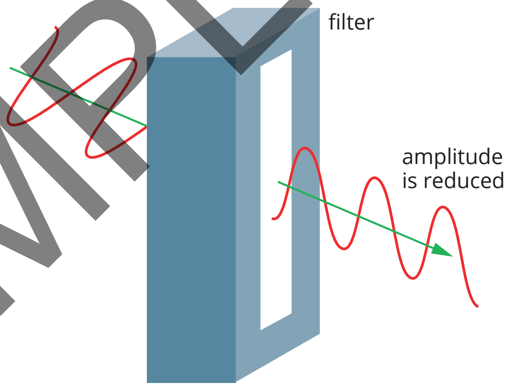


FIGURE 3.2.8 A diagonally polarised wave has its horizontal component blocked by the vertically orientated polarising filter. A vertically polarised wave of reduced amplitude passes through it.

Certain materials can act as polarising filters for light. These materials only transmit the waves or components of waves that are polarised in a particular direction and absorb the rest. Polarising sunglasses work by absorbing the light polarised parallel to a surface, thus reducing glare. Photographers use polarising filters to reduce the glare in photographs or to achieve specific effects (Figure 3.2.9).

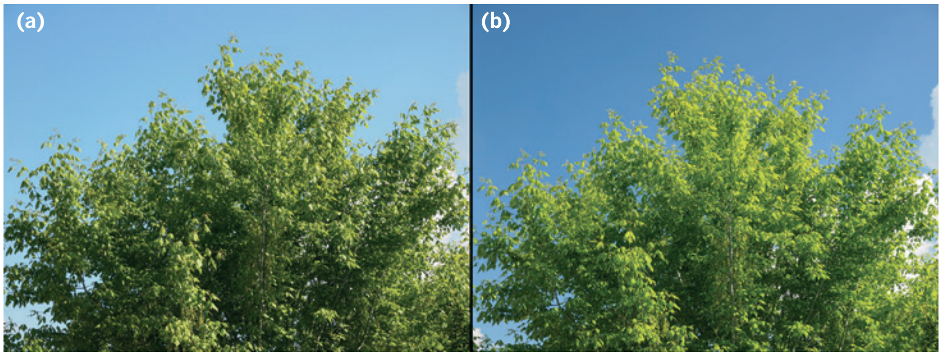
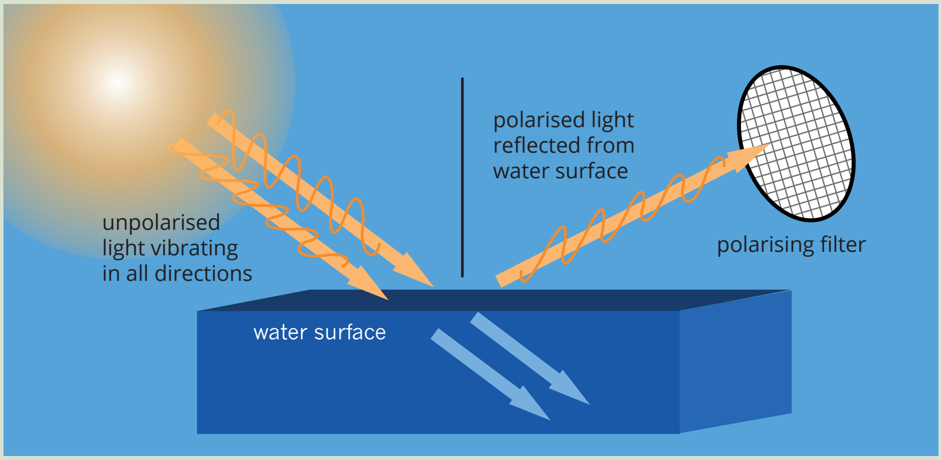


FIGURE 3.2.9 These are photographs taken of the same tree, one (a) without a polarising filter and (b) with a polarising filter.

PHYSICSFILE

Polarising sunglasses

Light that is reflected from a surface, such as water, snow or sand, is partially polarised in a direction parallel to the surface from which it reflects (see right). The polarising plane of polarising sunglasses is selected to absorb this reflected light. This makes polarising sunglasses particularly effective for people involved in outdoor activities such as boating, fishing or skiing.



Polarising sunglasses block light reflected from the surface of water.

3.2 Review

SUMMARY

- Different colours of light have different wavelengths.
- Although all light travels at $3.00 \times 10^8\,\mathrm{m\,s^{-1}}$ in a vacuum, red light travels faster than blue light in a medium. Dispersion occurs because when white light is incident on a medium, such as water or glass, the angle of refraction of red light is greater than that of the blue light.
- Rainbows from water droplets or prisms, and coloured fringes on images from lenses are all due to dispersion.
- Light waves emitted from an unpolarised source can oscillate in multiple planes perpendicular to the direction of propagation.
- Polarisation occurs when light travels through a polarising filter and is only allowed to vibrate in one plane.

KEY QUESTIONS

Knowledge and understanding

1 A rainbow occurs because of dispersion effects in water. State whether these statements are true or false. Rewrite the false statements to make them true.

- **a** Light travels through a water droplet at a higher velocity than in air, which leads to refraction effects in water.
- **b** Red light travels at slower speeds than blue light, which leads to a greater angle of refraction of red light.

2 What is dispersion in lenses and why does it occur?

3 What direction do polarisers on polarising sunglasses need to be to block out glare?

Analysis

4 Calculate the angle of refraction of green light of wavelength 550 nm after it enters a rectangular prism of crown glass at an angle of 35°. Use the graph on Figure 3.2.2 on page XXX.

5 A white light wave enters an acrylic prism at an angle of 60°.

- **a** Explain whether dispersion will occur and why.
- **b** If dispersion will occur, calculate the angle of refraction of red light at 700 nm and blue light at 400 nm

Chapter review

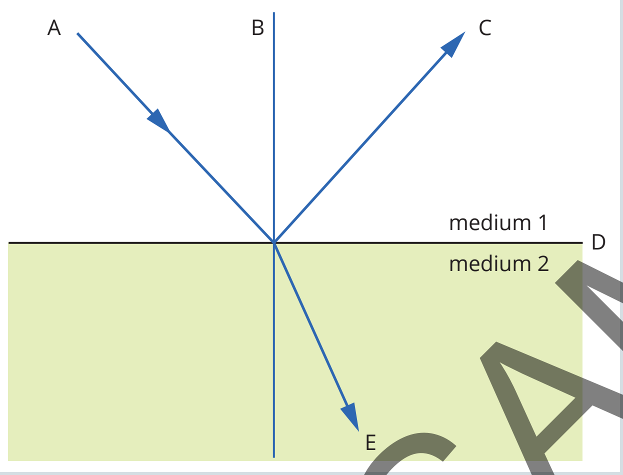
KEY TERMS

angle of incidence
angle of reflection
apparent depth
critical angle
diffuse
dispersion
normal
plane wave
polarisation
ray
real depth
refraction
refractive index
Snell's law
total internal reflection
wavefront

REVIEW QUESTIONS

Knowledge and understanding

1 The figure represents a situation involving the refraction of light. Identify the correct label for each letter from the choices provided:
boundary between media, reflected wave, incident wave, normal, refracted wave



2 Why can chromatic aberration occur in basic lenses?

3 On a very hot day it can look as if there is water on the road. Explain why.

4 Explain briefly why snowboarders and sailors are likely to wear polarising sunglasses.

5 Choose the correct responses from those given in bold to complete the following sentence about refraction.
As light travels from quartz ($n = 1.46$) to water ($n = 1.33$), its speed **increases**/**decreases**, which causes it to refract **away from**/**towards** the normal.

6 Red light (4.5×10^{14} Hz) has a wavelength of 500 nm in water. Calculate the speed of red light in water.

7 A light wave travelling in air strikes a glass boundary at an angle such that the angle between the direction of the light wave and the glass boundary is 90°.

- **a** Explain what happens to the light wave as it passes into the glass. Explain whether the wave refracts.
- **b** Determine whether the frequency of the light ray changes in the glass medium.

8 A person is looking down at a fish below the surface of the water. Select the most correct statement regarding the apparent position and the real position of the fish.

- **A** The real position and the apparent position are identical, as the reflected light from the water surface and the incident light make the same angle with the water's surface.
- **B** The apparent position of the fish would be lower and closer to the person than the real position.
- **C** The real position would be lower in the water than the apparent position.
- **D** The apparent position would be lower and further away than the real position of the fish.

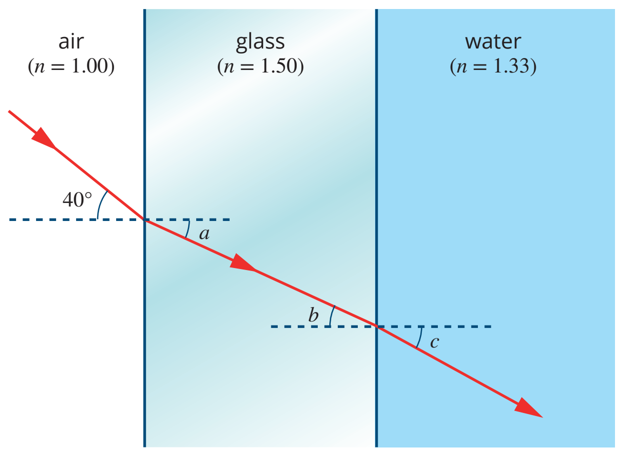
Application and analysis

9 The refractive index of a material is 1.20. Calculate the speed of light in the material.

10 A diver shines a torch up from under the water at an angle of incidence of 32°. The light enters the glass of a glass-bottom boat. If the refractive index of water is 1.33 and that of the glass is 1.52, what is the angle of refraction within the glass?

11 The speed of light in air is $3.00 \times 10^8\,\mathrm{m\,s^{-1}}$. Light strikes an air–perspex boundary at an angle of incidence of 43.0° and its angle of refraction is 28.5°.
Calculate the speed of light in perspex.

12 A light wave, represented by the ray of light, travels from air, through a layer of glass and then into water as shown. Calculate angles *a*, *b* and *c*.



13 A light wave exiting a glass block strikes the inside wall of the glass block and makes an angle of 58.0° with the glass–air boundary. The index of refraction of the glass is 1.52.

a Calculate the angle of incidence.

b Calculate the angle of refraction of the transmitted ray (assuming $n_{air} = 1.00$).

c Determine the angle of deviation (angle between the direction of the incident wave and the refracted wave).

d Calculate the speed of light in the glass.

14 Calculate the critical angle for light travelling between the following media.

	Incident medium	Refracting medium
a	ice ($n = 1.31$)	air ($n = 1.00$)
b	salt ($n = 1.54$)	air ($n = 1.00$)
c	cubic zirconia ($n = 2.16$)	air ($n = 1.00$)

15 A narrow beam of white light enters a crown glass prism with an angle of incidence of 30.0°. In the prism, the different colours of light are slowed to varying degrees. The refractive index for red light in crown glass is 1.50 and for violet light the refractive index is 1.53.

a Calculate the angle of refraction for the red light.

b Calculate the angle of refraction for the violet light.

c Determine the angle through which the spectrum is dispersed.

d Calculate the speed of the violet light in the crown glass. Use $c = 3.00 \times 10^8\,\mathrm{m\,s^{-1}}$.

16 When a light wave refracts, the difference between the angle of incidence and angle of refraction is known as the *angle of deviation*. Sort the following boundaries between media in order of increasing angle of deviation.

A water ($n = 1.33$) to diamond ($n = 2.42$)

B water ($n = 1.33$) to air ($n = 1.00$)

C air ($n = 1.00$) to diamond ($n = 2.42$)

D glass ($n = 1.50$) to air ($n = 1.00$)

17 Two students find a piece of an unknown glass in the laboratory and want to determine its refractive index. They design an experiment in which they vary the angle of incidence and measure the refracted angle. The results obtained by the students are tabulated below.

Angle of incidence, θ_1 (°)	Angle of refraction, θ_2 (°)
0	0
10	4
20	10
30	17
40	25
50	27
60	32
70	33
80	35

a Plot a suitable graph and draw a line of best fit.

b Use the line of best fit to determine the refractive index of the material.

18 **a** A particular fibre-optic cable has a core with refractive index $n_1 = 1.557$ and cladding with refractive index $n_2 = 1.343$. Calculate the speed of light in the core and in the cladding.

b Calculate the critical angle at the interface between the core and the cladding.

c State the range of angles at which total internal reflection will occur. State this angle relative to the surface of the core–cladding interface. This is shown as θ_2 in Figure 3.1.13(c) on page XX.

d A light wave travelling down the core hits the wall of the core at an angle of 15° (relative to the wall of the core). Does total internal reflection or refraction occur?

e Explain why the fibre-optic light wave signal loses intensity.