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 $n_1 v_1 = n_2 v_2$ **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**

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

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.

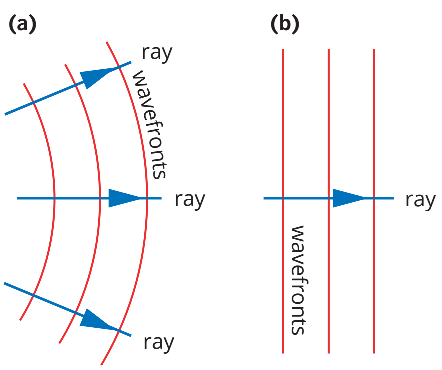


FIGURE 3.1.2 The crests of waves are drawn as wavefronts, shown in red. Rays can be used to illustrate the direction of motion of a wave and are drawn perpendicular to the wavefront of a two- or three-dimensional wave; (a) illustrates circular waves near a point source while (b) shows plane waves.

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).

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.

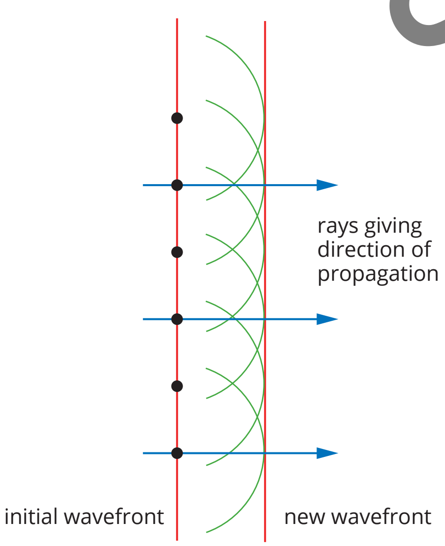


FIGURE 3.1.3 Each point on the wavefront of a plane wave can be considered as a source of secondary wavelets. These wavelets combine to produce a new plane wavefront.

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

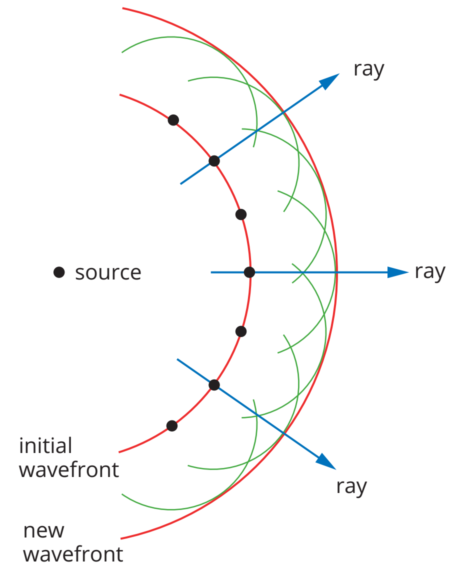
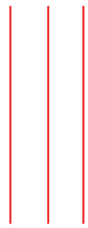


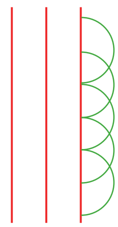
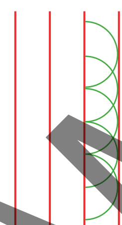
FIGURE 3.1.4 Each point on the wavefront of a circular wave can be considered as a source of secondary wavelets. These wavelets combine to produce a new circular wavefront.

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.

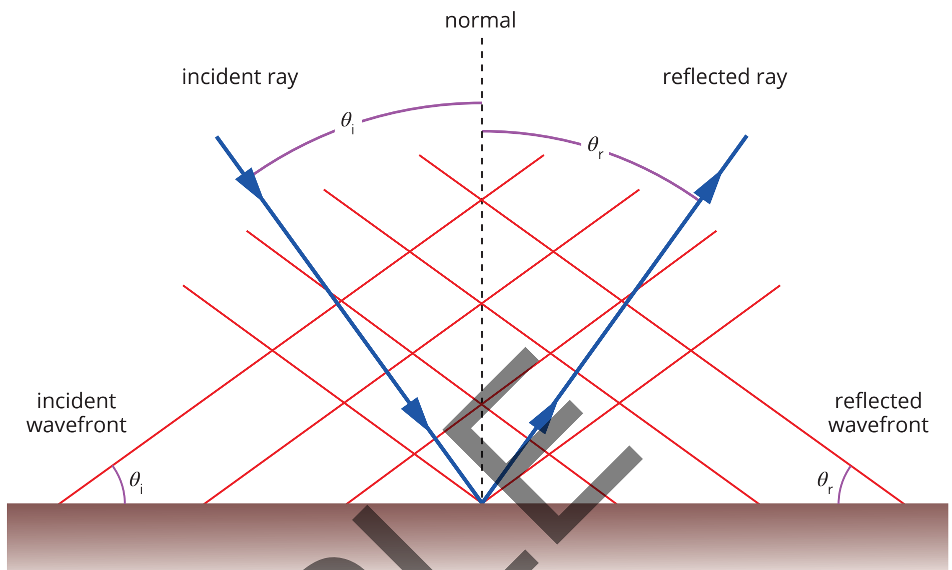


FIGURE 3.1.5 The law of reflection. The angle between the direction of the incident wave and the normal (θ_i) is the same as the angle between the normal and the reflected wave (θ_r).

> **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.

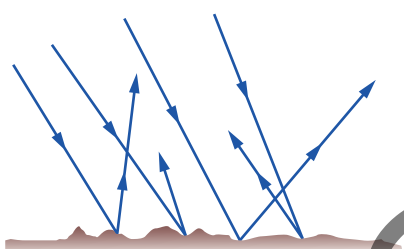


FIGURE 3.1.6 Reflection from an irregular surface. Each incident ray may be reflected in a different direction, depending upon how rough or irregular the reflecting surface is. The resulting wave will be diffuse (spread out).

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.

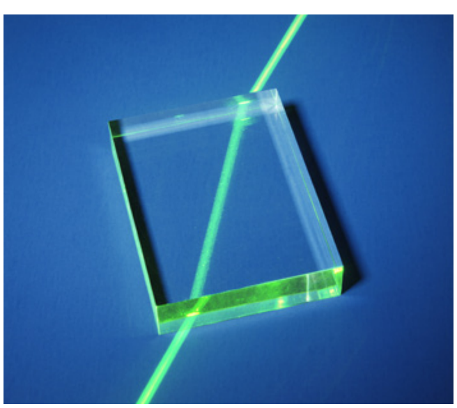


FIGURE 3.1.7 Light refracts as it moves from the air into the glass, causing a change in direction. The light refracts again as it goes from glass to air.

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

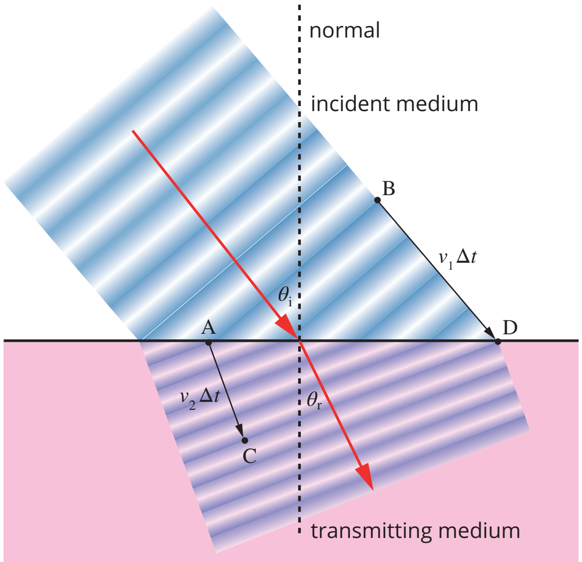


FIGURE 3.1.8 Wave refraction occurs because the distance A–C travelled by the wave in the transmitting medium is shorter than the distance B–D that it travels in the same time in the incident medium.

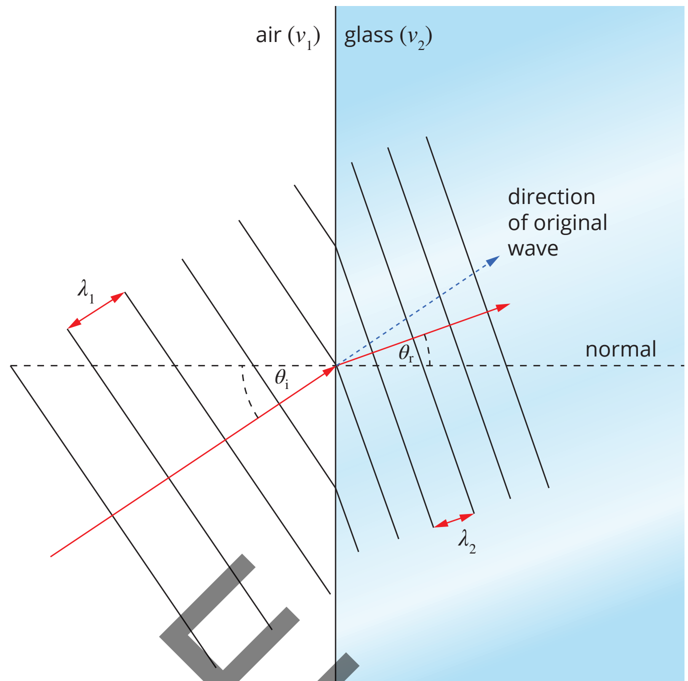


FIGURE 3.1.9 Light waves refract towards the normal when they slow down, $v_2 < v_1$.

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.

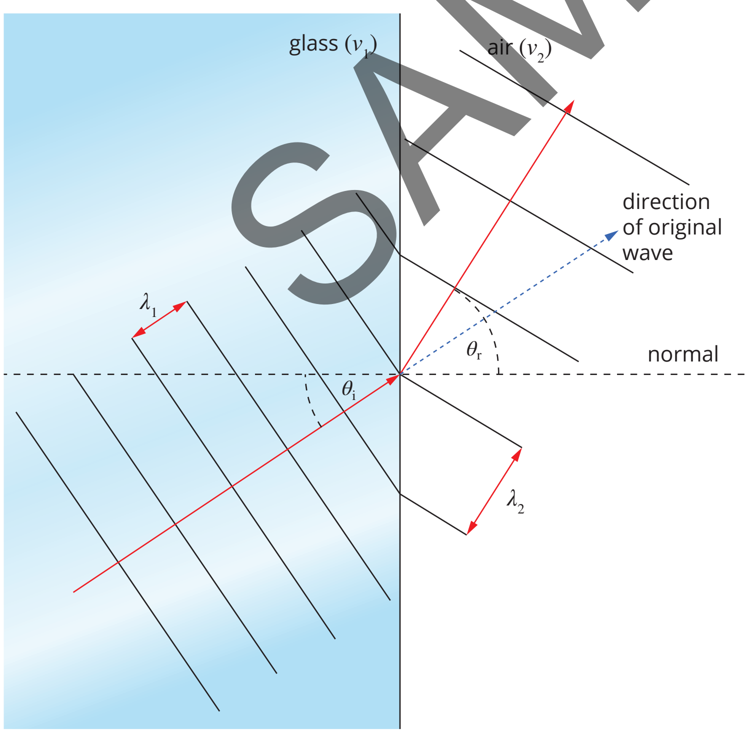


FIGURE 3.1.10 Light waves refract away from the normal when they speed up, $v_2 > v_1$.

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 $1.97 \times 10^8\,\text{m s}^{-1}$, 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.	$1.52 \times 1.97 \times 10^8 = 1.33 \times v_2$ $\frac{1.52 \times 1.97 \times 10^8}{1.33} = v_2$ $v_2 = 2.25 \times 10^8\,\text{m s}^{-1}$

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 $2.25 \times 10^8\,\text{m s}^{-1}$, 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**.

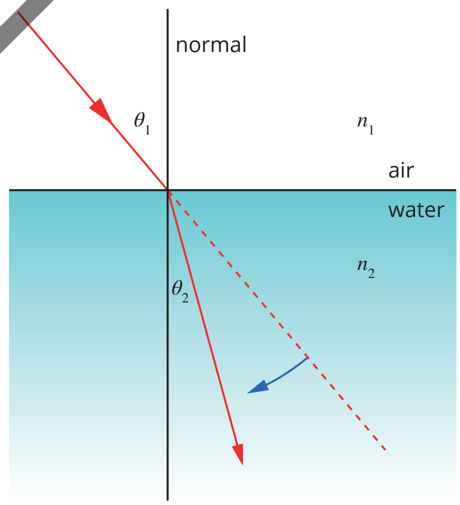


FIGURE 3.1.11 Light refracts as it moves from air into water.

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 $\sin\theta_2$.	$1.00 \times \sin 30° = 1.33 \times \sin\theta_2$ $\sin\theta_2 = \frac{1.00 \times \sin 30°}{1.33}$ $= 0.3759$
Calculate the angle of refraction.	$\theta_2 = \sin^{-1} 0.3759$ $= 22.1°$

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

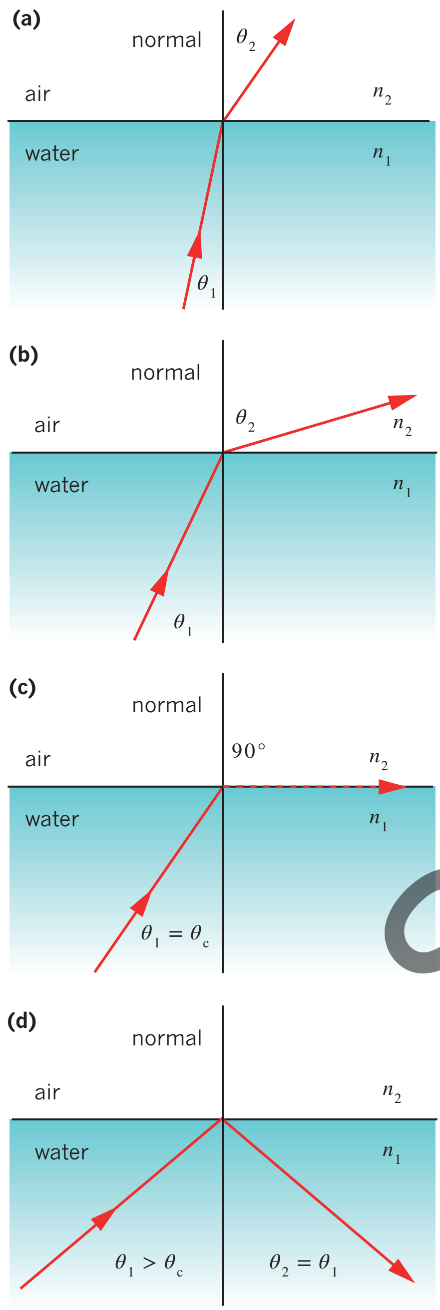


FIGURE 3.1.12 Light refracts as it moves from water into air as shown in diagrams (a) and (b). In diagram (c), the angle of refraction is exactly 90° to the normal and in (d) the light is undergoing total internal reflection.

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: $\sin\theta_c = \frac{n_2}{n_1}$

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.	$\sin\theta_c = \frac{n_2}{n_1}$
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.)	$\sin\theta_c = \frac{1.00}{1.33}$ $= 0.7519$
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

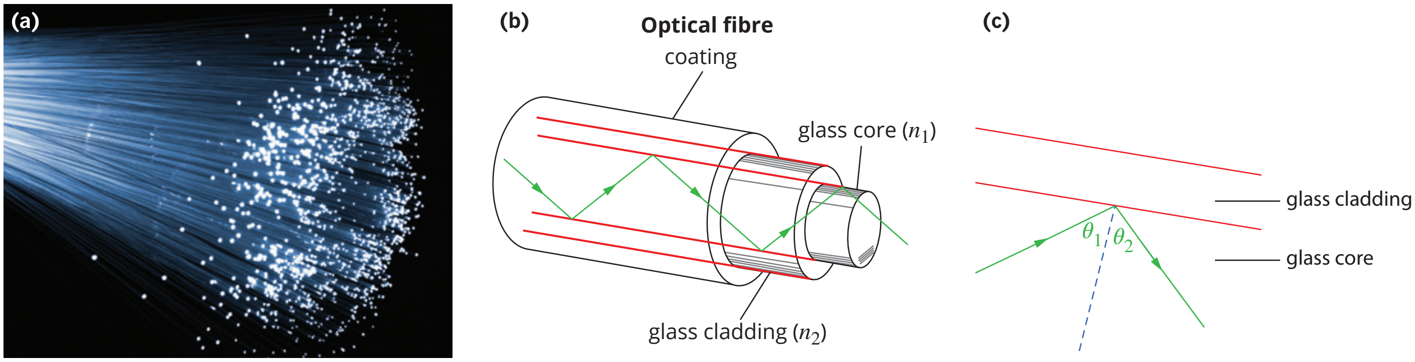


FIGURE 3.1.13 (a) Optical fibres transmit light using total internal reflection. (b) The outer glass cladding is made of glass with a slightly lower refractive index (n_2) than the glass core (n_1). (c) The angle of incidence of the incoming light is shown as θ_1 and the angle of refraction is shown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

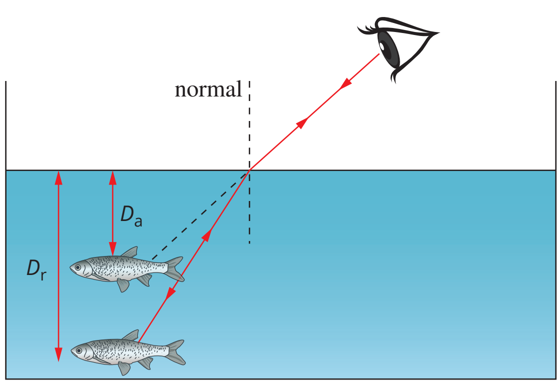


FIGURE 3.1.14 The apparent depth, D_a, of a fish compared to the real depth, D_r, as seen from above the air water interface

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.

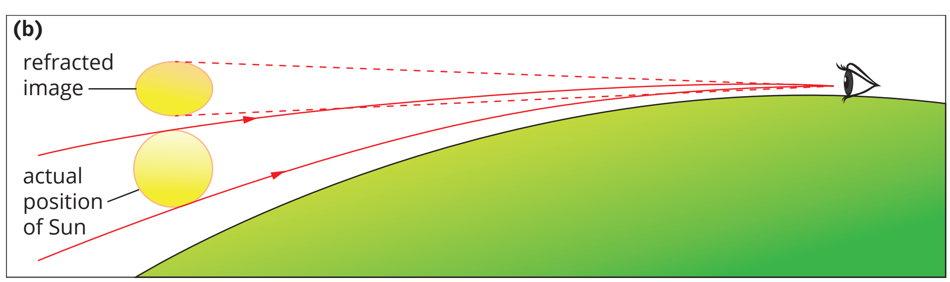


FIGURE 3.1.15 (a) The shape of the Sun appears flatter as it approaches the horizon. It looks less circular and more oval-shaped. (b) At sunset and sunrise, the observed position of the Sun is a refracted image and appears higher than the actual position of the Sun.

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.

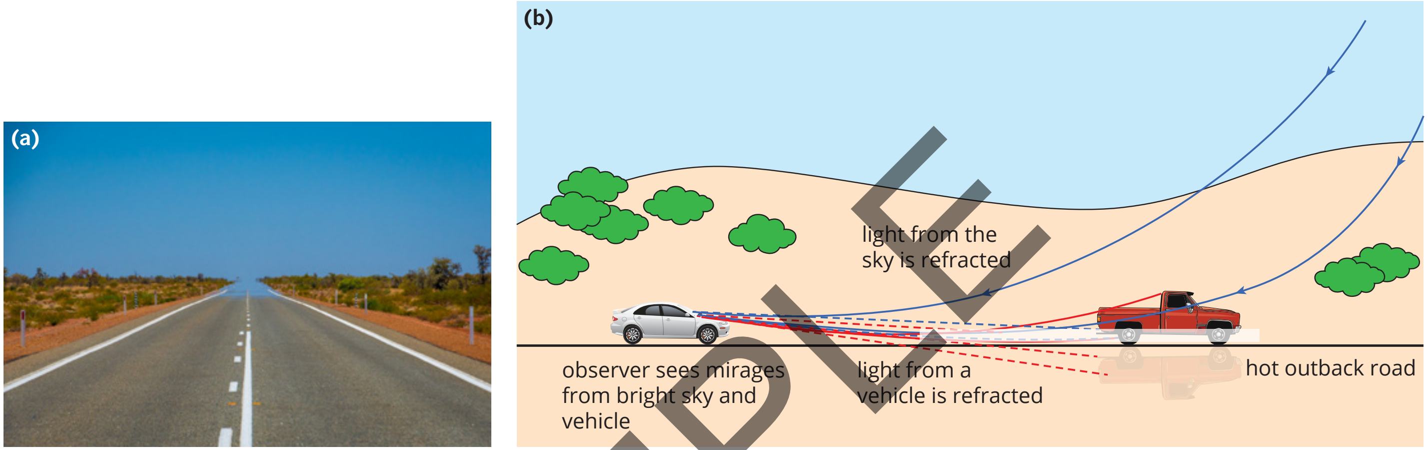


FIGURE 3.1.16 (a) On a hot day a mirage gives the illusion of water on the road. (b) Variations in the atmospheric refractive index lead to refraction of blue light from the sky. In addition, refraction effects can lead to the illusion of the occupants of the blue car seeing an inverted image of the 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: $n_1 v_1 = n_2 v_2$
- 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.

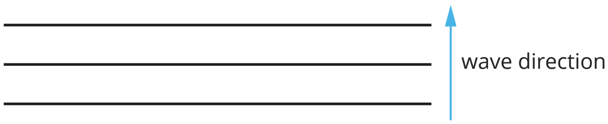
continued over page

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.

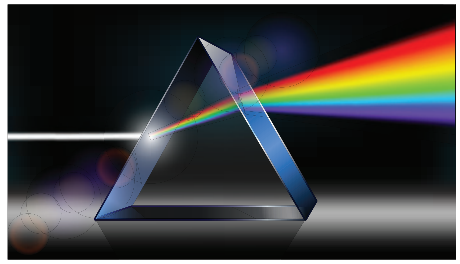


FIGURE 3.2.1 When white light enters a prism, it is split into its component wavelengths or colours.

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.

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

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.

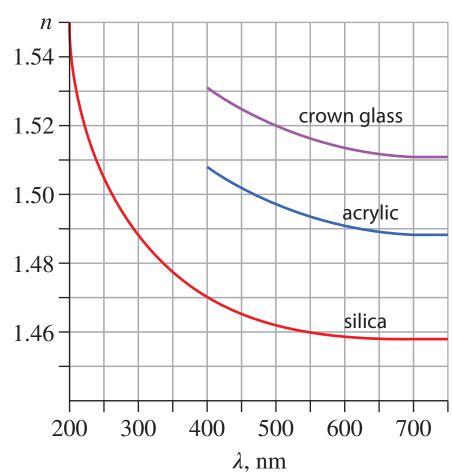


FIGURE 3.2.2 The refractive index of a material varies with wavelength. For glass, the refractive index decreases as wavelength increases.

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.

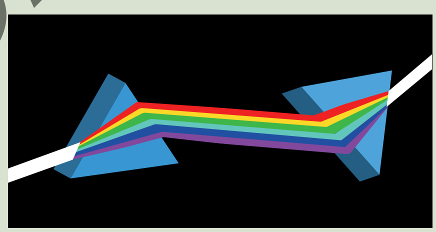
For light of shorter wavelengths (such as violet light), a medium has the highest refractive index, and light travels the slowest. Therefore it will refract the least.

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.

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.

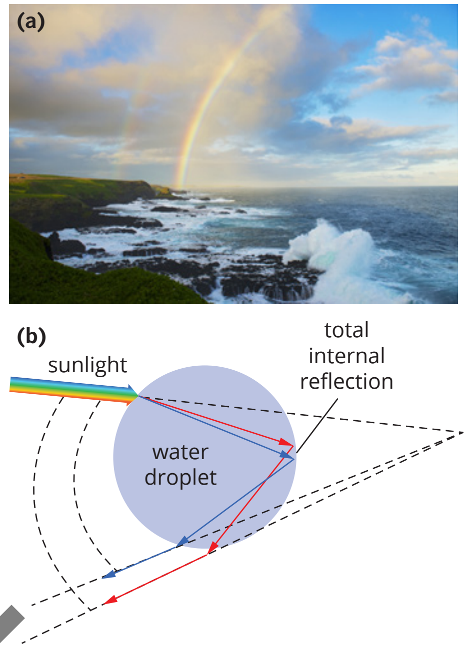


FIGURE 3.2.4 (a) A double rainbow is formed over Phillip Island, Victoria. (b) The formation of a rainbow is due to a combination of reflection and dispersion in raindrops.

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.

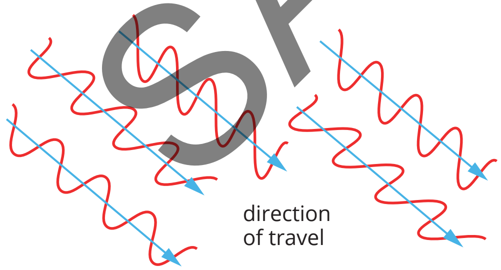


FIGURE 3.2.5 Unpolarised light waves consist of a collection of waves that vibrate perpendicular to the direction of travel but in different planes. Each wave has a different plane of polarisation.

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.

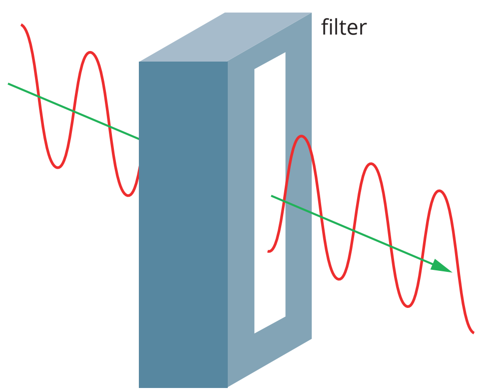


FIGURE 3.2.6 A vertically polarised wave can pass through a vertically orientated polarising filter.

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

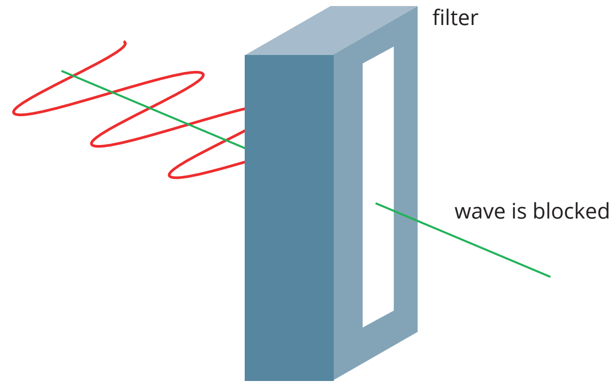


FIGURE 3.2.7 A horizontally polarised wave cannot pass through a vertically orientated polarising filter.

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.

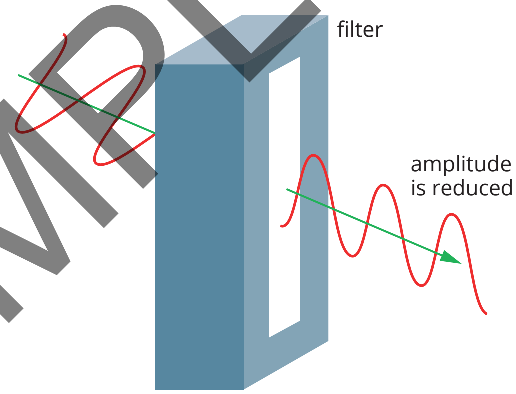


FIGURE 3.2.8 A diagonally polarised wave has its horizontal component blocked by the vertically orientated polarising filter. A vertically polarised wave of reduced amplitude passes through it.

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).

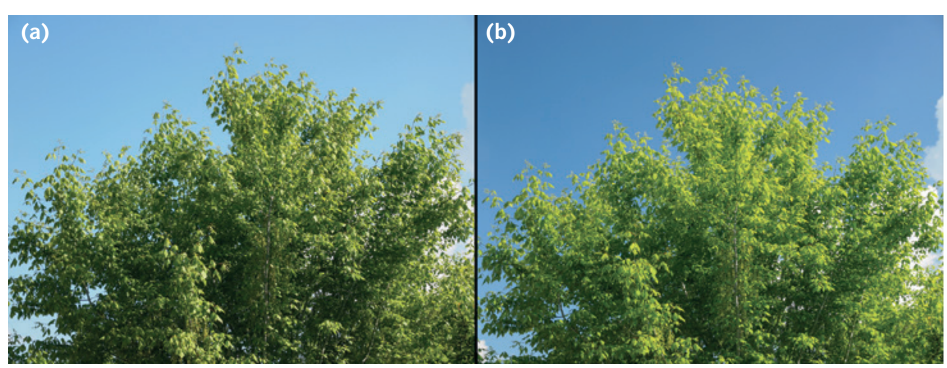
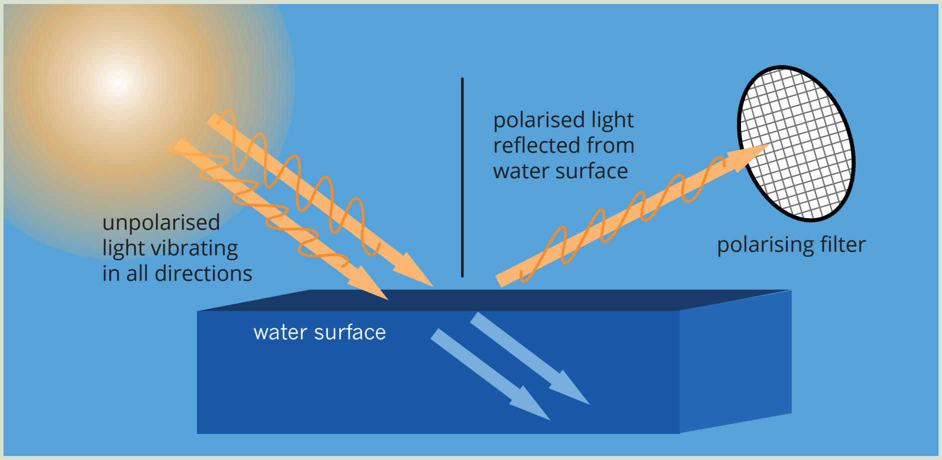


FIGURE 3.2.9 These are photographs taken of the same tree, one (a) without a polarising filter and (b) with a polarising filter.

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 $3.00 \times 10^8 \, m\,s^{-1}$ 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

03

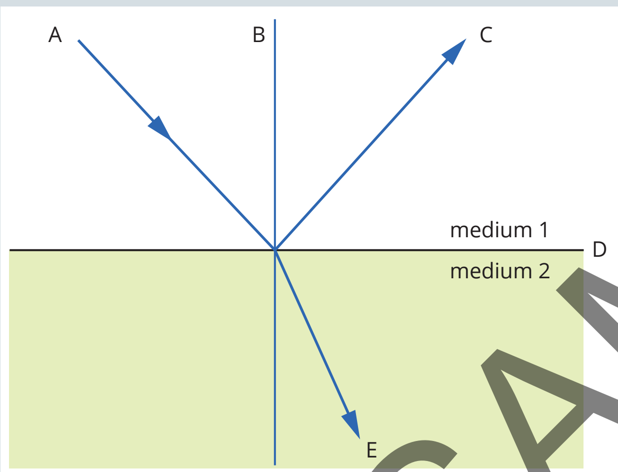
KEY TERMS

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.

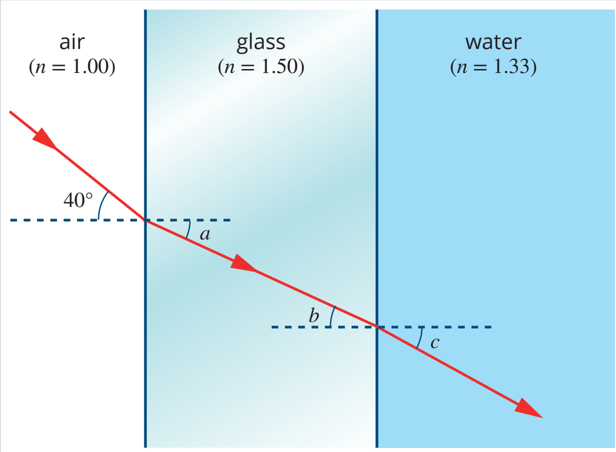
Application and analysis

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 $3.00 \times 10^{8}\,\text{m s}^{-1}$. 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 $c = 3.00 \times 10^8\,\text{m s}^{-1}$.

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.