PHYSICS UNIT 3 WAVES

There are many different types of waves. They affect all of our lives. Sometimes they are useful and can be a tremendous benefit to the way we live. Sometimes they can be dangerous and pose a real risk to life. It is therefore very important that we understand the main features and properties of waves.

7 PROPERTIES OF WAVES

Talking to someone using a mobile phone is something most of us do several times a day. The technology that had to be developed for this to happen was based on a thorough understanding of the properties of waves.

In this chapter you will learn about different types of waves and their properties (characteristics).

▲ Figure 7.1 Using microwaves to communicate

LEARNING OBJECTIVES

- Explain the difference between longitudinal and transverse waves
- Know the definitions of amplitude, wavefront, frequency, wavelength and period of a wave
- Know that waves transfer energy and information without transferring matter
- Know and use the relationship between the speed, frequency and wavelength of a wave:

  wave speed = frequency × wavelength

  $v = f \times \lambda$
- Use the relationship between frequency and time period:

  $$\text{frequency} = \frac{1}{\text{time period}}$$

  $$f = \frac{1}{T}$$
- Use the above relationships in different contexts including sound waves and electromagnetic waves
- Explain that all waves can be reflected and refracted
- Explain why there is a change in the observed frequency and wavelength of a wave when its source is moving relative to an observer, and that this is known as the Doppler effect

UNITS

In this unit, you will need to use degrees (°) as the unit of angle, hertz (Hz) as the unit of frequency, metre (m) as the unit of length, metre per second (m/s) as the unit of speed and second (s) as the unit of time.

WHAT ARE WAVES?

Waves are a way of transferring energy from place to place. As we can see in Figure 7.1 we often use them to transfer information. All these transfers take place with no matter being transferred.

▲ Figure 7.2 Waves are produced if we drop a stone into a pond. The circular wavefronts spread out from the point of impact, carrying energy in all directions, but the water in the pond does not move from the centre to the edges.

WHAT ARE WAVEFRONTS?

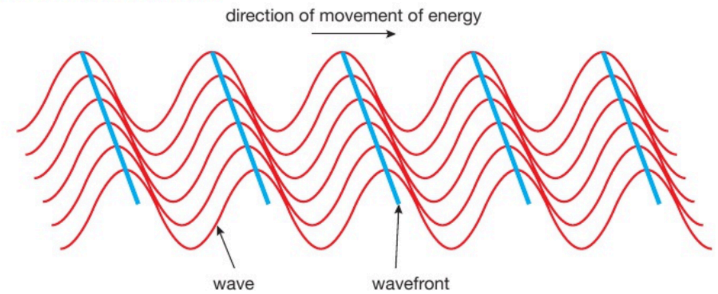


Figure 7.3 Wavefronts are created by overlapping lots of different waves. A wavefront is a line where all the vibrations are in phase and the same distance from the source.

TRANSVERSE WAVES

Waves can be produced in ropes and springs. If you move one end of a spring from side to side you will see waves travelling through it. The energy carried by these waves moves along the spring from one end to the other, but if you look closely you can see that the coils of the spring are vibrating (shaking) across the direction in which the energy is moving. This is an example of a **transverse wave**.

A transverse wave is one that vibrates, or oscillates, at right angles to the direction in which the energy or wave is moving. Examples of transverse waves include light waves and waves travelling on the surface of water.

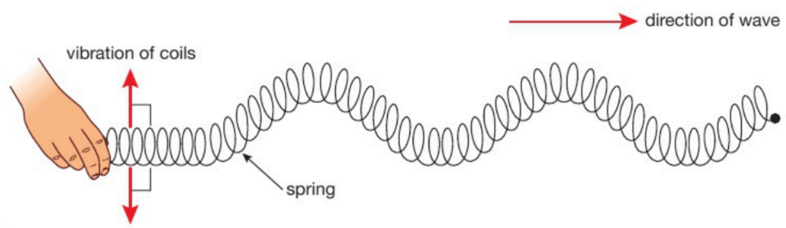


Figure 7.4 A transverse wave vibrates at right angles to the direction in which the wave is moving.

LONGITUDINAL WAVES

If you push and pull the end of a spring in a direction parallel to its axis, you can again see energy travelling along it. This time however the coils of the spring are vibrating in directions that are along its length. This is an example of a **longitudinal wave**.

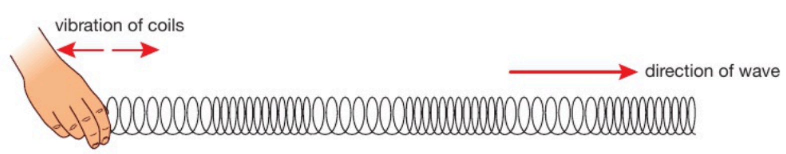


Figure 7.5 A longitudinal wave vibrates along the direction in which the wave is travelling.

A longitudinal wave is one in which the vibrations, or oscillations, are along the direction in which the energy or wave is moving. Examples of longitudinal waves include sound waves.

DESCRIBING WAVES

When a wave moves through a substance, its particles will move from their equilibrium (resting position). The maximum movement of particles from their resting or equilibrium position is called its **amplitude** (A).

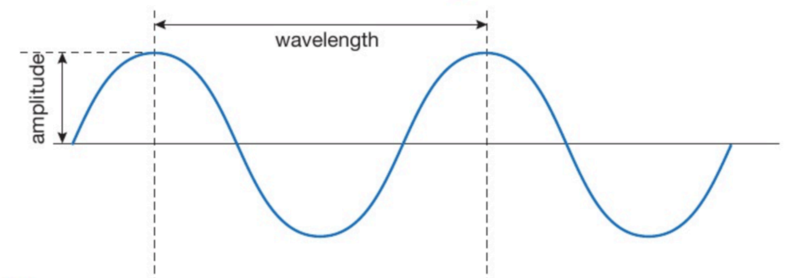


Figure 7.6 A wave has amplitude and wavelength.

The distance between a particular point on a wave and the same point on the next wave (for example, from crest to crest) is called the **wavelength** (λ).

KEY POINT

λ is the Greek letter lambda and is the usual symbol for wavelength.

If the source that is creating a wave vibrates quickly it will produce a large number of waves each second. If it vibrates more slowly it will produce fewer waves each second. The number of waves produced each second by a source, or the number passing a particular point each second, is called the frequency of the wave (*f*). Frequency is measured in hertz (Hz). A wave source that produces five complete waves each second has a frequency of 5 Hz.

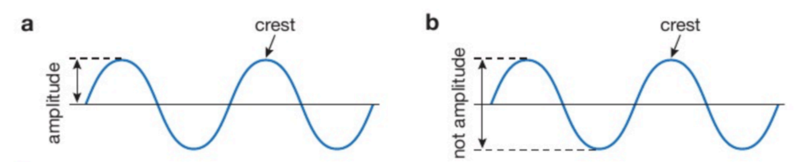


Figure 7.7 The amplitude of a wave is as shown in **a**, and not as in **b**.

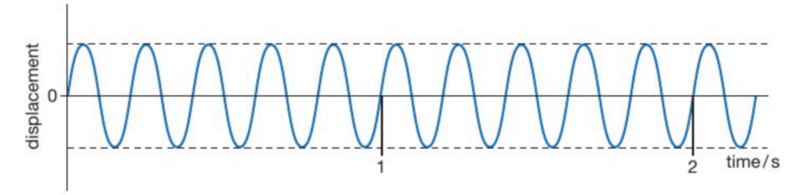


Figure 7.8 This graph shows a wave with a frequency of 5 Hz.

The time it takes for a source to produce one wave is called the **time period** of the wave (*T*). It is related to the frequency (*f*) of a wave by the equation:

$$\text{frequency, } f\text{ (Hz)} = \frac{1}{\text{time period, } T\text{ (s)}}$$

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

This equation can also be written as

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

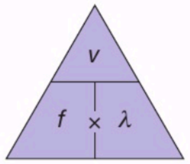


Figure 7.9 You can use the triangle method for rearranging equations like $v = f \times \lambda$.

HINT

If an examination question asks you to write out the equation for calculating wave speed, wavelength or frequency, always give the actual equation such as $v = f \times \lambda$. You may not be awarded a mark if you just draw the triangle.

EXAMPLE 1

Calculate the period of a wave with a frequency of 200 Hz.

$$T = \frac{1}{f}$$
$$= \frac{1}{200\ \text{Hz}}$$
$$= 0.005 \text{ or } 5\ \text{ms}\ (1000\ \text{ms} = 1\ \text{s})$$

THE WAVE EQUATION

There is a relationship between the wavelength (λ), the frequency (f) and the wave speed (v) that is true for all waves:

wave speed, v (m/s) = frequency, f (Hz) × wavelength, λ (m)

$$v = f \times \lambda$$

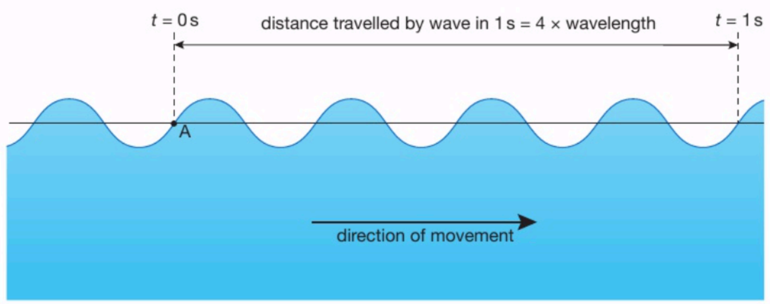


Figure 7.10 A wave with a frequency of 4 Hz

Imagine that you have created water waves with a frequency of 4 Hz. This means that four waves will pass a particular point each second. If the wavelength of the waves is 3 m, then the waves travel 12 m each second. The speed of the waves is therefore 12 m/s.

$$v = f \times \lambda$$
$$= 4\ \text{Hz} \times 3\ \text{m}$$
$$= 12\ \text{m/s}$$

EXAMPLE 2

A **tuning fork** creates sound waves with a frequency of 170 Hz. If the speed of sound in air is 340 m/s, calculate the wavelength of the sound waves.

$$v = f \times \lambda$$
So $\lambda = \frac{v}{f}$
$$= \frac{340\ \text{m/s}}{170\ \text{Hz}}$$
$$= 2\ \text{m}$$

Figure 7.11 A tuning fork

THE RIPPLE TANK

We can study the behaviour of water waves using a ripple tank.

When the motor is turned on, the wooden bar vibrates creating a series of ripples or wavefronts on the surface of the water. A light placed above the tank creates patterns of the water waves on the floor. By observing the patterns we can see how the water waves are behaving.

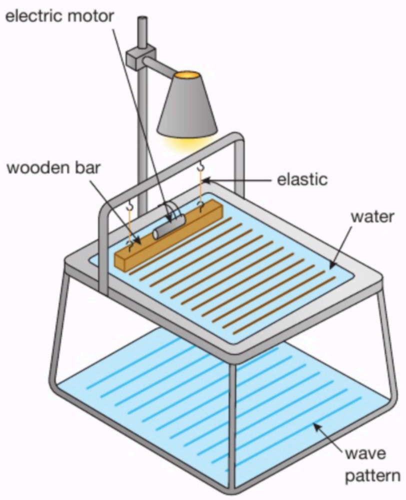


Figure 7.12 The light shines through the water and we can see the patterns of the waves.

WAVELENGTH AND FREQUENCY

The motor can be adjusted to produce a small number of waves each second. The frequency of the waves is small and the pattern shows that the waves have a long wavelength.

At higher frequencies, the water waves have shorter wavelengths. The speed of the waves does not change.

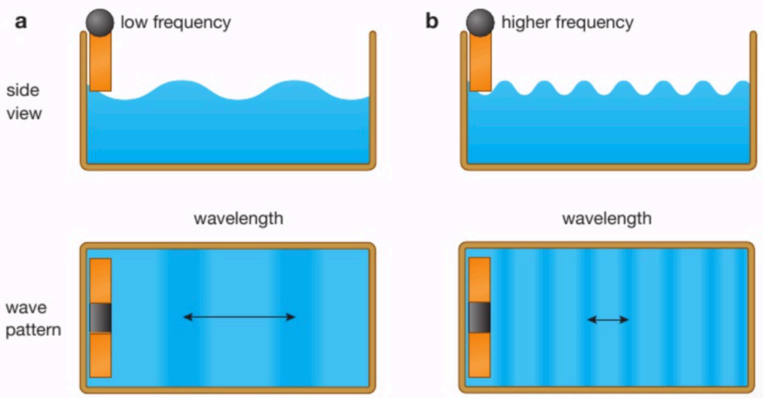


Figure 7.13 When the frequency of the waves is low, the wavelength is long. When the frequency is higher, the wavelength is shorter.

REFLECTION

All waves can be reflected. If they hit a straight or flat barrier, the angle at which they leave the barrier surface is equal to the angle at which they meet the surface – that is, the waves are reflected from the barrier at the same angle as they strike it. This is described by the 'Law of Reflection' which states that:

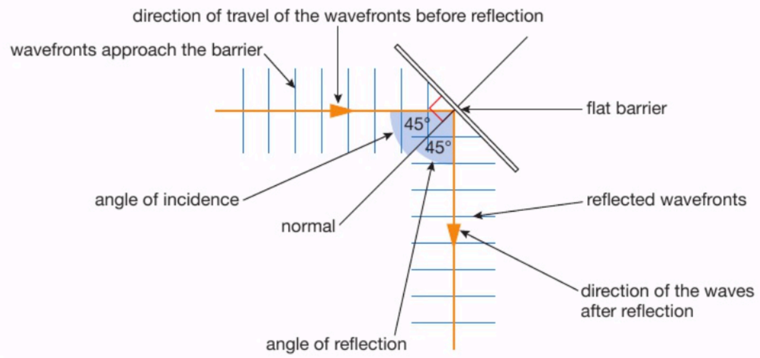
*The **angle of incidence** is equal to the **angle of reflection**.*

KEY POINT

A normal is a line drawn at right angles to a surface.

The angle of incidence is the angle between the direction of the waves as they approach the barrier and the normal.

The angle of reflection is the angle between the direction of the waves after striking the barrier and the normal.

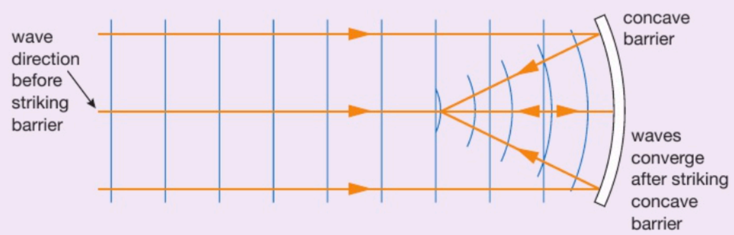


▲ Figure 7.14 Waves striking a flat barrier are reflected. The angle at which they strike the barrier is the same as the angle at which they are reflected.

EXTENSION WORK

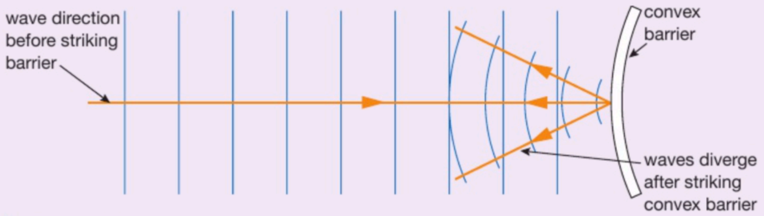
Although you will not be asked this in your exam, it is interesting to see how waves are reflected from curved surfaces.

When the waves strike a concave barrier, they are made to converge (come together).



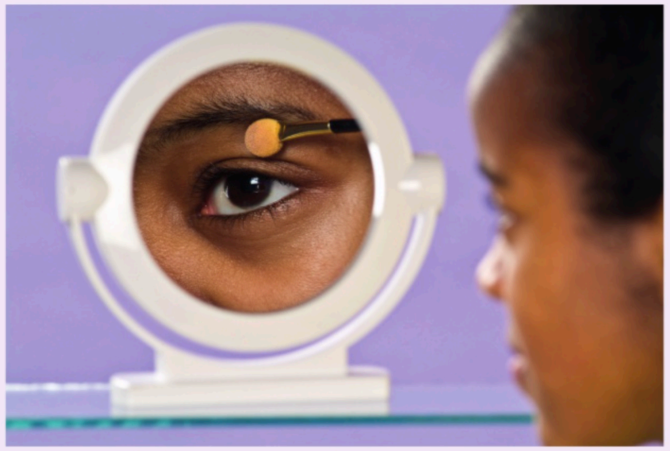
▲ Figure 7.15 Waves striking a concave barrier are reflected and converge.

▲ Figure 7.16 Radio telescopes have concave reflecting dishes so that the signals from space reflect and converge onto a detector that is placed in front of the dish.

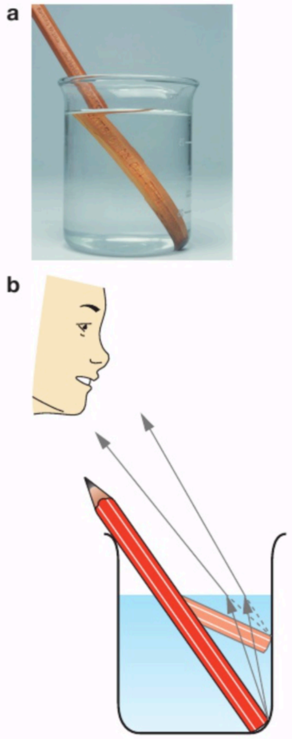


▲ Figure 7.17 Waves striking a convex barrier are reflected backwards and spread out.

When waves are reflected by a surface that is curved outwards (convex), they diverge (spread out).



▲ Figure 7.18 The light waves reflected from this concave make-up mirror create a magnified image.



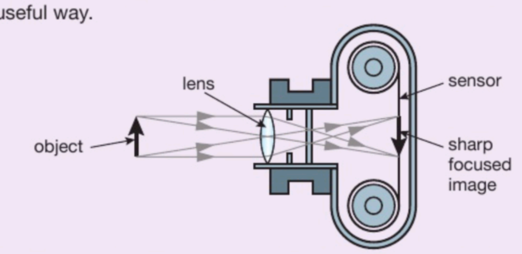
▲ Figure 7.19 **a** The pencil seems to bend at the air/water boundary. **b** Why the pencil appears to be bent. Rays of light are refracted at the water surface.

REFRACTION

The pencil in Figure 7.19 is straight but it seems to bend at the surface of the water. This happens because light waves in water travel more slowly than light waves in air. This change in speed as they leave the water causes the light waves to change direction. This change in direction is called refraction. All waves – light waves, sound waves, water waves – can be refracted.

EXTENSION WORK

Many optical instruments such as microscopes, telescopes and cameras use specially shaped pieces of glass or plastic (called lenses) to bend or refract light waves in a useful way.



▲ Figure 7.20 In this camera, light waves are refracted by a glass lens to create a sharp image on the sensor or film. Refraction occurs because light travels more slowly in glass than in air.

THE DOPPLER EFFECT

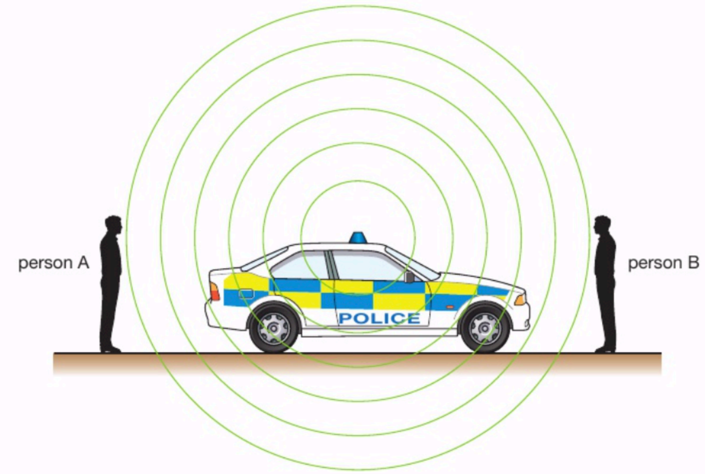


Figure 7.21 A stationary source of sound

When a car is not moving the sound waves we receive from its engine or from its horn arrive as a series of equally (evenly) spaced wavefronts. People in front of and behind the car hear sound of the same frequency and wavelength.

Figure 7.22 A moving source of sound

If the car is moving, the wavefronts are no longer evenly spaced. Ahead of the car the wavefronts will be compressed as the car is moving in this direction. The waves will have a shorter wavelength and a higher frequency. Person B therefore hears a sound that has a higher **pitch** than when the car was stationary. Behind the car the waves are stretched out so person A hears a sound with a longer wavelength and lower frequency – that is, the pitch appears to have decreased.

These apparent changes in frequency, which occur when a source of waves is moving, is called the **Doppler effect** and is a property of all waves.

CHAPTER QUESTIONS

More questions on wave properties can be found at the end of Unit 3 on page 588.

SKILLS CRITICAL THINKING

1 a Explain the difference between a transverse wave and a longitudinal wave.

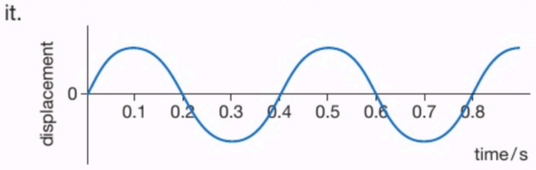
b Give one example of each.

SKILLS INTERPRETATION

c Draw a diagram of a transverse wave. On your diagram, mark the wavelength and amplitude of the wave.

SKILLS ANALYSIS, PROBLEM SOLVING

2 The diagram below shows the displacement of water as a wave travels through it.



From the diagram calculate:

a the period of the wave

b the frequency of the wave.

SKILLS PROBLEM SOLVING

3 The speed of sound in water is approximately 1500 m/s.

a What is the frequency of a sound wave with a wavelength of 1.5 m?

b What is the period of this wave?

SKILLS CRITICAL THINKING

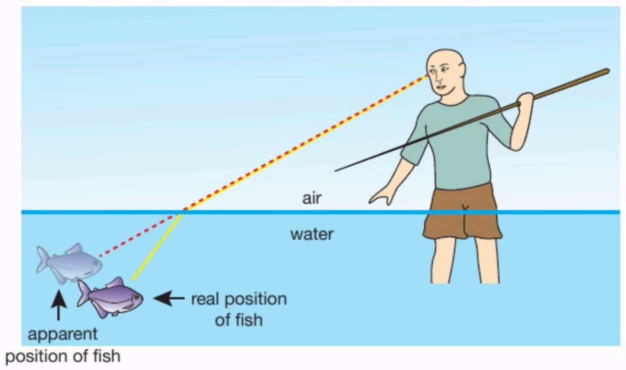
4 a Explain why the sound produced by the horn of an approaching car seems to have a higher frequency than one that is stationary.

SKILLS REASONING

b If the same car approached at a much higher speed how would this affect the frequency of the sound heard?

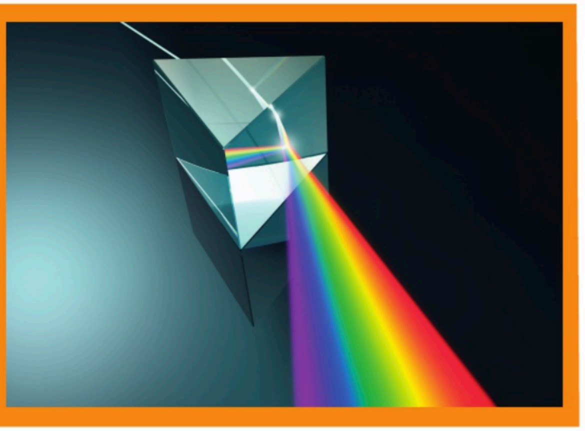
c Describe the frequency of the sound heard by the observer if the car is moving away at high speed.

5 Explain why this hunter should not aim at the fish he can see.



8 THE ELECTROMAGNETIC SPECTRUM

The electromagnetic spectrum is a family of waves, varying in wavelength and frequency. Although it is continuous, it is helpful to consider smaller groups of waves within the spectrum. These groups have distinct properties.
As we will see in this chapter, understanding the different properties allows us to use these waves in many situations including cooking and communication.



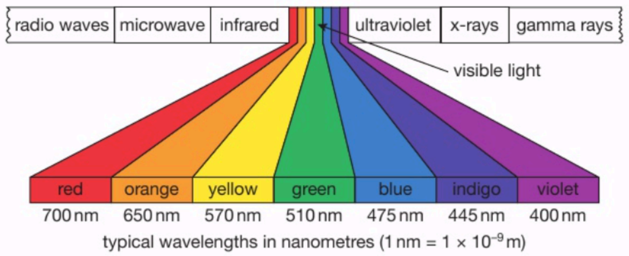
▶ Figure 8.1 When we shine white light through a prism it splits up forming a band of colours. This band is one small part of the electromagnetic spectrum.

LEARNING OBJECTIVES

- Know that light is part of a continuous electromagnetic spectrum that includes radio, microwave, infrared, visible, ultraviolet, x-ray and gamma ray radiations and that all these waves travel at the same speed in free space
- Know the order of the electromagnetic spectrum in terms of decreasing wavelength and increasing frequency, including the colours of the visible spectrum
- Explain some of the uses of electromagnetic radiations, including:
  - radio waves: broadcasting and communications
  - microwaves: cooking and satellite transmissions
  - infrared: heaters and night vision equipment
  - visible light: optical fibres and photography
  - ultraviolet: fluorescent lamps
  - x-rays: observing the internal structure of objects and materials, including for medical applications
  - gamma rays: sterilising food and medical equipment
- Explain the detrimental effects of excessive exposure of the human body to electromagnetic waves, including:
  - microwaves: internal heating of body tissue
  - infrared: skin burns
  - ultraviolet: damage to surface cells and blindness
  - gamma rays: cancer, mutation

  and describe simple protective measures against the risks

THE ELECTROMAGNETIC SPECTRUM



▲ Figure 8.2 The complete electromagnetic spectrum

The **electromagnetic spectrum** (EM spectrum) is a continuous spectrum of waves, which includes the visible spectrum. At one end of the spectrum the waves have a very long wavelength and low frequency, while at the other end the waves have a very short wavelength and high frequency. All the waves have the following properties:

1. They all transfer energy.
2. They are all transverse waves.
3. They all travel at 300 000 000 m/s, the speed of light in a **vacuum** (free space).
4. They can all be reflected and refracted.

Remember that the wave equations we met in the previous chapter can be applied to any member of the electromagnetic spectrum.

EXAMPLE 1

Yellow light has a wavelength of 5.7×10^{-7} m. What is the frequency and period of yellow light waves?

$$v = f \times \lambda$$

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

$$= \frac{3 \times 10^{8}\ \text{m/s}}{5.7 \times 10^{-7}\ \text{m}}$$

$$= 5.26 \times 10^{14}\ \text{Hz}$$

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

$$= \frac{1}{5.26 \times 10^{14}\ \text{Hz}}$$

$$= 1.9 \times 10^{-15}\ \text{s}$$

The table below shows the different groups of waves in order, and gives some of their uses.

	Typical frequency / Hz	Typical wavelength / m	Sources	Detectors	Uses
Radio waves	10^{5}–10^{10}	10^{3}–10^{-2}	radio transmitters, TV transmitters	radio and TV aerials	long-, medium- and short-wave radio, TV (UHF)
Microwaves	10^{10}–10^{11}	10^{-2}–10^{-3}	microwave transmitters and ovens	microwave receivers	mobile phone and satellite communication, cooking
Infrared (IR)	10^{11}–10^{14}	10^{-3}–10^{-6}	hot objects	skin, blackened thermometer, special photographic film	infrared cookers and heaters, TV and stereo remote controls, night vision
Visible light	10^{14}–10^{15}	10^{-6}–10^{-7}	luminous objects	the eye, photographic film, light-dependent resistors	seeing, communication (optical fibres), photography
Ultraviolet (UV)	10^{15}–10^{16}	10^{-7}–10^{-8}	UV lamps and the Sun	skin, photographic film and some fluorescent chemicals	fluorescent tubes and UV tanning lamps
X-rays	10^{16}–10^{18}	10^{-8}–10^{-10}	x-ray tubes	photographic film	x-radiography to observe the internal structure of objects, including human bodies
Gamma rays	10^{18}–10^{21}	10^{-10}–10^{-14}	radioactive materials	Geiger–Müller tube	sterilising equipment and food, radiotherapy

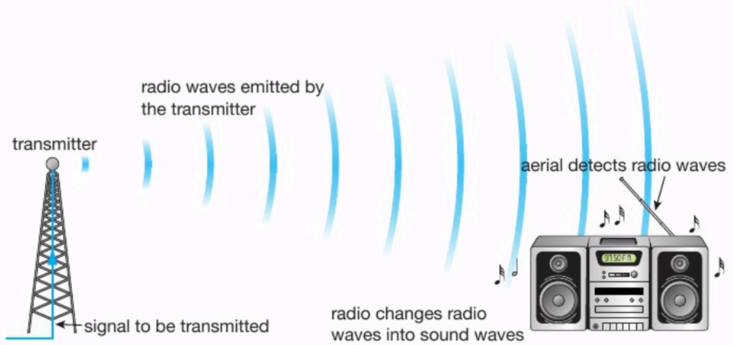
HINT

To remember the order of the waves in the electromagnetic spectrum try using 'Graham's Xylophone Uses Very Interesting Musical Rhythms'.

You do not need to remember the values of frequency and wavelength given in the table but you do need to know the order of the groups and which has the highest frequency or longest wavelengths. Most importantly, you need to realise that it is these differences in wavelength and frequency that give the groups their different properties – for example, gamma rays have the shortest wavelengths and highest frequencies, and carry the most energy.

RADIO WAVES

Radio waves have the longest wavelengths in the electromagnetic spectrum. They are used mainly for communication.

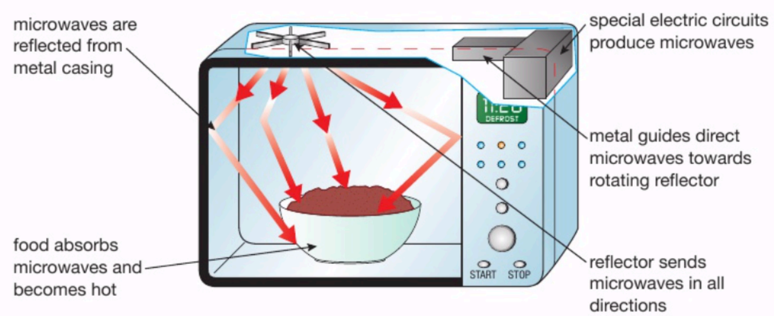


▲ Figure 8.3 Radio waves are emitted by a transmitter and detected by an aerial.

Radio waves are given out (**emitted**) by a transmitter. As they arrive at an aerial, they are detected and the information they carry can be received. Televisions and FM radios use radio waves with the shorter wavelengths to carry their signals.

MICROWAVES

Microwaves are used for communications, radar and cooking foods. Radar uses radio waves to find the position of things.



▲ Figure 8.4 Food cooks quickly in a microwave oven because water molecules in the food absorb the microwaves.

Food placed in a microwave oven cooks more quickly than in a normal oven. This is because water **molecules** in the food absorb the microwaves and become very hot. The food therefore cooks throughout rather than just from the outside.

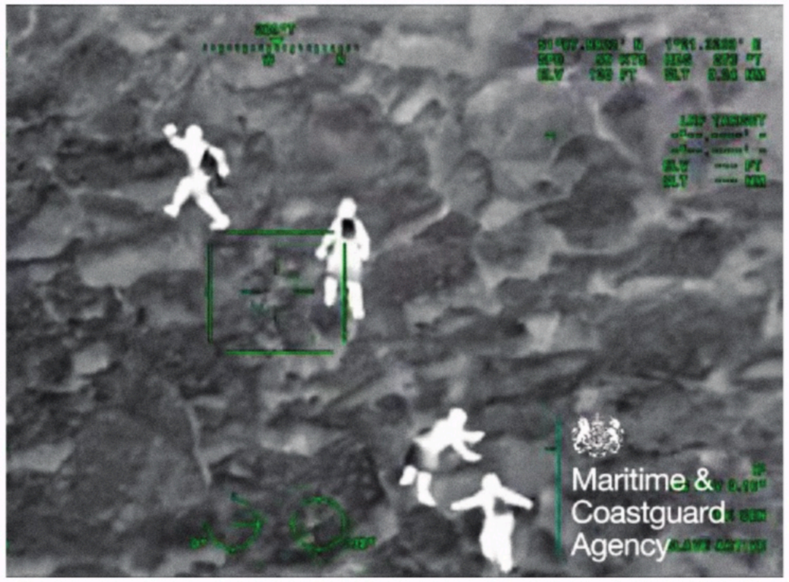
Microwave ovens have metal screens that reflect microwaves and keep them inside the oven. This is necessary because if microwaves can cook food, they can also heat human body tissue! The microwaves used by mobile phones transmit much less energy than those used in a microwave oven, so they do not cook your brain when you use the phone.

Microwaves are used in communications. The waves pass easily through the Earth's atmosphere and so are used to carry signals to orbiting satellites. From here, the signals are passed on to their destination or to other orbiting satellites. Messages sent to and from mobile phones are also carried by microwaves. The fact that we are able to use mobile phones almost anywhere in the home and at work confirms that microwaves can pass through glass, brick and so on.

INFRARED

All objects, including your body, emit infrared (IR) radiation. The hotter an object is, the more energy it will emit as infrared. Energy is transferred by infrared radiation to bread in a toaster or food under a grill. Electric fires also transfer heat energy by infrared.

Special cameras designed to detect infrared waves can be used to create images even when there is no visible light. These cameras have many uses, including searching for people trapped in collapsed buildings, searching for criminals and checking for heat loss from buildings.



▲ Figure 8.5 It is not possible to see these people trapped at the bottom of a cliff using normal visible light. By using infrared detectors they can be found easily and rescued.

▲ Figure 8.6 Signals are carried from this remote control to a TV by infrared waves.

Infrared radiation is also used in remote controls for televisions, DVD players and stereo systems. It is very convenient for this purpose because the waves are not harmful. They have a low **penetrating power** and will therefore operate only over small distances, so they are unlikely to interfere with other signals or waves.

The human body can be harmed by too much infrared radiation, which can cause skin burns.

VISIBLE LIGHT

▲ Figure 8.7 Using visible light

This is the part of the electromagnetic spectrum that is visible to the human eye. We use it to see. Visible light from lasers is used to read compact discs and barcodes. It can also be sent along optical fibres, so it can be used for communication or for looking into hard-to-reach places such as inside the body of a patient (see page 583). Visible light can be detected by the sensors in digital cameras, and used to take still photographs or videos. Information stored on DVDs is also read using visible light.

EXTENSION WORK

When talking about light and colour, we often refer to the seven colours in the visible spectrum. These colours are red, orange, yellow, green, blue, indigo and violet; red light has the longest wavelength and lowest frequency. If you look back at Figure 8.1, you may only be able to make out six colours – most people have difficulty separating indigo and violet (two types of purple). Sir Isaac Newton (1642–1727) discovered that 'white' light can be split up into different colours. He believed that the number seven had magical significance, and so he decided there were seven colours in the spectrum!

ULTRAVIOLET LIGHT

▲ Figure 8.8 UV light can cause sunburn so we need to protect our skin.

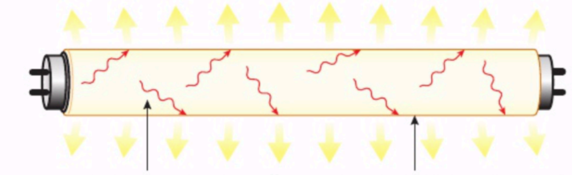
Part of the light emitted by the Sun is ultraviolet (UV) light. UV radiation is harmful to human eyes and can damage the skin.

UV light causes the skin to tan, but overexposure (too much) will lead to sunburn and blistering. Ultraviolet radiation can also cause skin cancer and blindness. Protective goggles or glasses and skin creams can block the UV rays and will reduce the harmful effects of this radiation.

The **ozone layer** in the Earth's atmosphere absorbs large quantities of the Sun's UV radiation. In recent years there was real concern that the amount of ozone in the atmosphere was decreasing due to pollution, which would increase numbers of skin cancer. However, there is now evidence to show that the ozone layer is recovering.

Some chemicals glow (shine), or fluoresce, when under UV light. This property of UV light is used in security marker pens. The special ink is invisible in normal light but becomes visible in UV light.

▲ Figure 8.9 This red code is only visible under UV light.

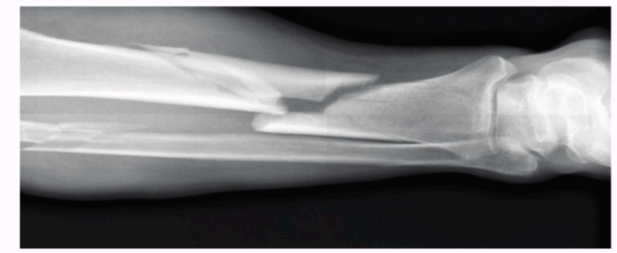


▲ Figure 8.10 Fluorescent tubes glow when UV light hits the fluorescent coating in the tube.

Fluorescent tubes glow (shine) because the UV light they produce strikes a special coating (covering) on the inside of the tube, which then emits visible light.

X-RAYS

X-rays pass easily through soft body tissue but cannot pass through bones. As a result, radiographs or x-ray pictures can be taken to check a patient's bones.



▲ Figure 8.11 X-ray of a broken leg

▲ Figure 8.12 X-rays were used to see what was in this suitcase.

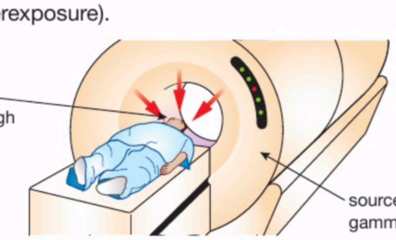
Working with x-rays can cause cancer. Radiographers, who take x-rays, are at risk and have to stand behind lead screens or wear protective clothing.

X-rays are also used in industry to check the internal structures of objects – for example, to look for cracks and faults in buildings or machinery – and at airports as part of the security checking procedure.

GAMMA RAYS

Gamma rays, like x-rays, are highly penetrating rays and can cause damage to living cells. The damage can cause mutations (negative changes), which can lead to cancer. They are used to **sterilise** medical instruments, to kill microorganisms so that food will keep for longer and to treat cancer using radiotherapy. Gamma rays can both cause and cure cancer. Large doses of gamma rays targeted directly at the cancerous growth can be used to kill the cancer cells completely.

Like x-rays the use of lead screens, boxes and aprons can prevent the damage caused by gamma rays (overexposure).



▲ Figure 8.13 The gamma rays are aimed carefully so that they cross at the exact location of the cancerous cells.

CHAPTER QUESTIONS

More questions on using waves can be found at the end of Unit 3 on page 588.

SKILLS CRITICAL THINKING

1 a Name four wave properties that are common to all members of the electromagnetic spectrum.
  b Name three types of wave that can be used for communicating.
  c Name two types of wave that can be used for cooking.
  d Name one type of wave that is used to treat cancer.
  e Name one type of wave that might be used to ‘see’ people in the dark.
  f Name one type of wave that is used for radar.

SKILLS REASONING

2 Explain why:
  a microwave ovens cook food much more quickly than normal ovens
  b x-rays are used to check for broken bones
  c it is important not to damage the ozone layer around the Earth
  d food stays fresher for longer after it has been exposed to gamma radiation.

3 a Explain one way in which you could prevent overexposure (damage) by the following waves:
    i x-rays
    ii ultraviolet waves.

SKILLS CRITICAL THINKING

  b Select one of the above waves and then describe one consequence of overexposure.

SKILLS INTERPRETATION

4 Copy and complete the table below for four more different wave groups within the electromagnetic spectrum.

Type of radiation	Possible harm	Precautions
x-rays	cancer	lead screening

9 LIGHT AND SOUND WAVES

We see objects because they emit or reflect light. In this chapter you will learn how light behaves when it reflects from different surfaces, and what happens when light travels from one transparent material to another. Sound waves are longitudinal waves and not transverse waves like light. Nevertheless they can be reflected and refracted in just the same way. In this chapter you will learn about the nature and behaviour of sound waves, and how we make use of them in our everyday lives.

▲ Figure 9.1 In the Hall of Mirrors at the fairground the reflection of light can be very confusing!

LEARNING OBJECTIVES

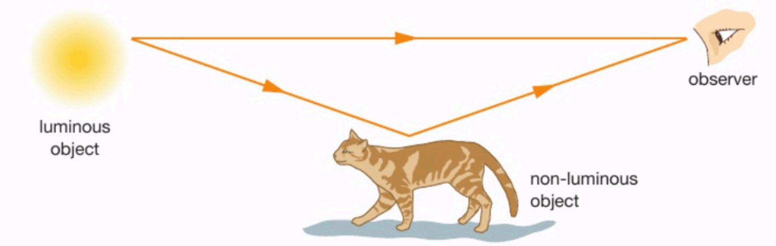
- Know that light waves are transverse waves and that they can be reflected and refracted
- Use the law of reflection (the angle of incidence equals the angle of reflection)
- Draw ray diagrams to illustrate reflection and refraction
- Practical: investigate the refraction of light, using rectangular blocks, semi-circular blocks and triangular prisms
- Know and use the relationship between refractive index, angle of incidence and angle of refraction:
  $n = \frac{\sin i}{\sin r}$
- Practical: investigate the refractive index of glass, using a glass block
- Describe the role of total internal reflection in transmitting information along optical fibres and in prisms
- Explain the meaning of critical angle c
- Know and use the relationship between critical angle and refractive index:
  $\sin c = \frac{1}{n}$
- Know that sound waves are longitudinal waves that can be reflected and refracted

▲ Figure 9.2 Cataracts mean that light cannot enter the eye correctly.

SEEING THE LIGHT

The patient shown in Figure 9.2 has a cataract. The front of one of his eyes has become so cloudy that he is unable to see. Nowadays it is possible to remove this damaged part of the eye and replace it with a clear plastic that will allow light to enter the eye again.

There are many sources of light, including the Sun, the stars, fires, light bulbs and so on. Objects such as these that emit their own light are called luminous objects. When the emitted light enters our eyes we see the object. Most objects, however, are non-luminous. They do not emit light. We see these non-luminous objects because of the light they reflect.



▲ Figure 9.3 Luminous objects, such as the Sun, give out light. Non-luminous objects only reflect light.

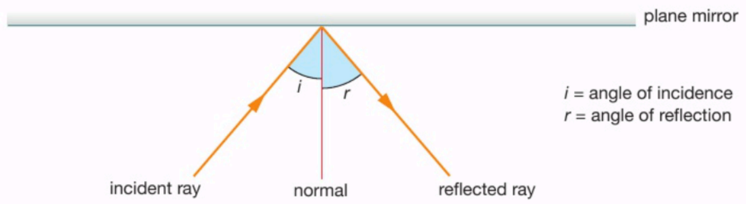
REFLECTION

When a ray of light strikes a plane (flat) mirror, it is reflected so that the angle of incidence (*i*) is equal to the angle of reflection (*r*).

KEY POINT

The angle of incidence is the angle between the incident ray and the normal.

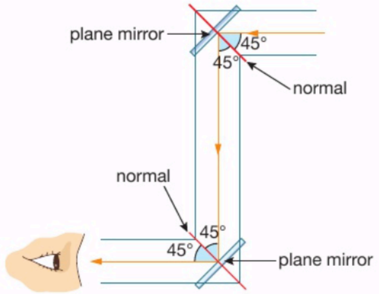
The angle of reflection is the angle between the reflected ray and the normal.



▲ Figure 9.4 Light is reflected from a plane mirror. The angle of incidence is equal to the angle of reflection. The normal is a line at right angles to the mirror.

Mirrors are often used to change the direction of a ray of light. One example of this is the simple periscope, which uses two mirrors to change the direction of rays of light.

Rays from the object strike the first mirror at an angle of 45° to the normal. The rays are reflected at 45° to the normal and so are turned through an angle of 90° by the mirror. At the second mirror the rays are again turned through 90°. Changing the direction of rays of light in this way allows an observer to use a periscope to see over or around objects.



▲ Figure 9.5 A periscope is used to see over or around objects.

REFRACTION

▲ Figure 9.6 This rainbow is caused by refraction.

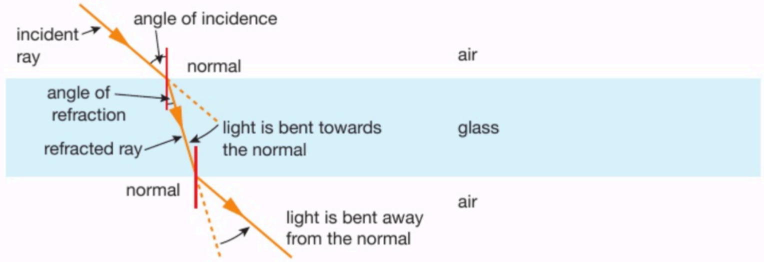
KEY POINT

A medium is a material, such as glass or water, through which light can travel. The plural of medium is media.

KEY POINT

Light does travel more slowly in air than in a vacuum but the difference is tiny.

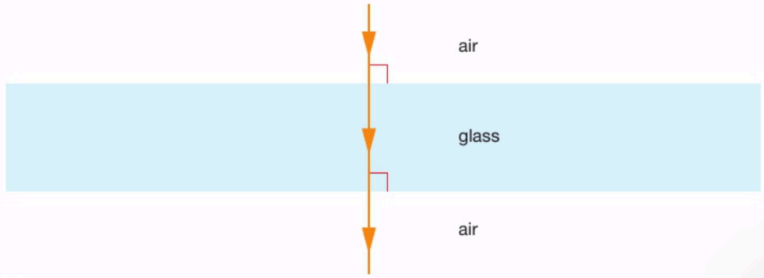
Rays of light can travel through many different transparent media, including air, water and glass. Light can also travel through a vacuum. In a vacuum and in air, light travels at a speed of 300 000 000 m/s. In other media it travels more slowly. For example, the speed of light in glass is approximately 200 000 000 m/s. When a ray of light travels from air into glass or water it slows down as it crosses the border between the two media. This change in speed may cause the ray to change direction. This change in direction of a ray is called refraction.



▲ Figure 9.7 This light ray is being refracted twice – once as it travels from air into glass and then as it travels from glass to air.

As a ray enters a glass block, it slows down and is refracted towards the normal. As the ray leaves the block it speeds up and is refracted away from the normal.

If the ray strikes the boundary between the two media at 90°, the ray continues without change of direction (Figure 9.8).



▲ Figure 9.8 If the light hits the boundary at 90° the ray does not bend.

REFRACTIVE INDEX

Different materials can bend rays of light by different amounts. We describe this by using a number called the **refractive index** (n). The refractive index of glass is about 1.5 and water is 1.3. This tells us that under similar circumstances glass will refract light more than water.

We can use the equation below to calculate the refractive index of a material:

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

where i is the angle of incidence and r is the **angle of refraction**.

EXAMPLE 1

In an experiment similar to the one shown in Figure 9.9, the angle of incidence was measured as 30° and the angle of refraction as 19°. Calculate the refractive index of the glass block.

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

$$= \frac{\sin 30}{\sin 19}$$

$$= \frac{0.5}{0.33}$$

$$= 1.52$$

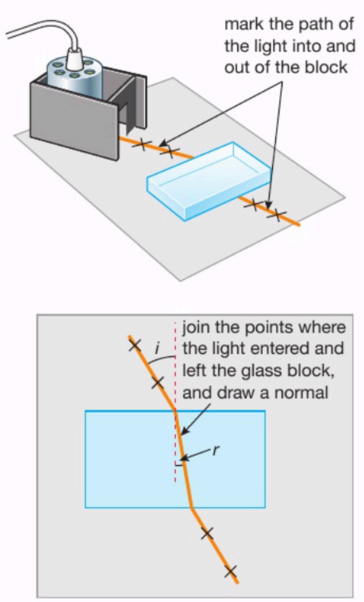
ACTIVITY 1

▼ PRACTICAL: INVESTIGATE THE REFRACTIVE INDEX FOR GLASS

You can investigate the refractive index of glass using a ray box and a rectangular glass block.

1. Shine a ray of light onto one of the sides of the glass block, so that the ray emerges on the opposite side of the block. Mark the directions of both of these rays with crosses.
2. Draw around the glass block before removing it.
3. Using the crosses, draw in the direction of both rays.
4. Draw in the direction of the ray that travelled inside the glass block.
5. Draw a normal (a line at 90° to the glass surface) where the ray enters the block.
6. Measure the angles of incidence (i) and refraction (r) (see Figure 9.9).
7. Use the equation $n = \frac{\sin i}{\sin r}$ to find the refractive index of the glass block.

Safety note: Ray box lamps get hot enough to burn skin and char paper. Glass blocks and prisms should be handled carefully and not knocked together – they can splinter or shatter.



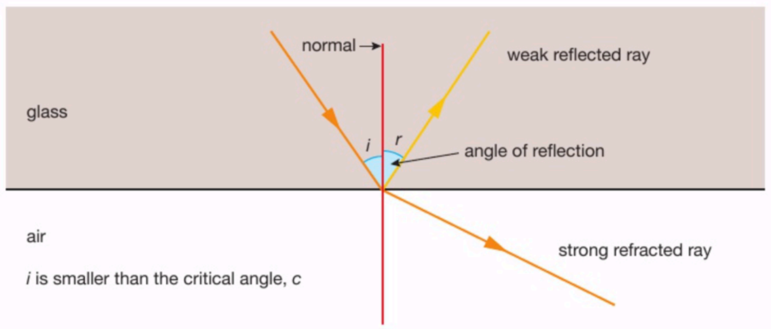
▲ Figure 9.9 How to investigate refraction using a rectangular glass block

KEY POINT

The symbol 'r' is used for both the angle of reflection and the angle of refraction.

TOTAL INTERNAL REFLECTION

When a ray of light with a small angle of incidence passes from glass into air, most of the light is refracted away from the normal but if we look carefully we can see that there is a small amount that is reflected from the boundary. Total internal reflection only occurs when rays of light are travelling towards a boundary with a less optically dense medium (a medium with a lower refractive index).

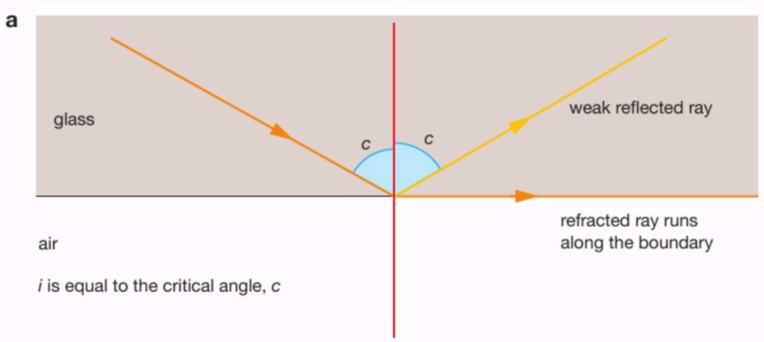


▲ Figure 9.10 A ray of light travelling from glass to air

But as the angle of incidence in the glass increases, the angle of refraction also increases until it reaches a special angle called the critical angle (c). The angle of refraction now is 90°.

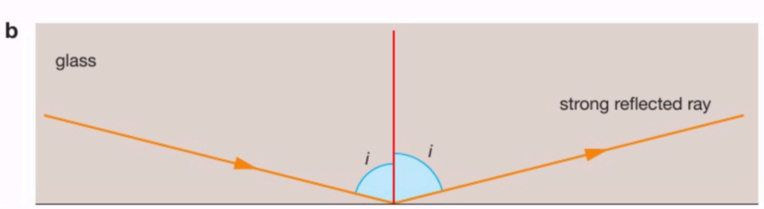
The critical angle is the smallest possible angle of incidence at which light rays are totally internally reflected.

a



▲ Figure 9.11a Ray of light strikes glass/air boundary at the critical angle

b



▲ Figure 9.11b When i is greater than c total internal reflection occurs.

When i is greater than the critical angle, all the light is reflected at the boundary. No light is refracted. The light is totally internally reflected.

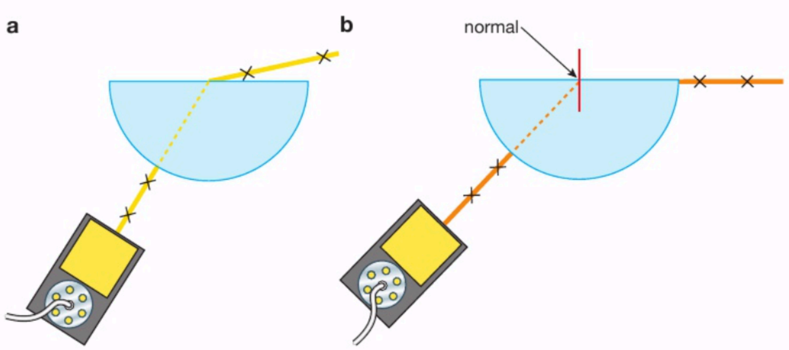
ACTIVITY 2

▼ PRACTICAL: INVESTIGATE TOTAL INTERNAL REFLECTION

Safety note: Ray box lamps get hot enough to burn skin and char paper. Glass blocks and prisms should be handled carefully and not knocked together – they can splinter or shatter.

You can investigate total internal reflection in the laboratory using a semi-circular glass block and a ray box. As shown in Figure 9.12a, a ray of light is directed at the centre of the straight side of the block through the curved side. (We do this because the incident ray will then always hit the edge of the glass block at 90°, so there are no refraction effects to take into account as the light goes into the block.)

Now by carefully increasing and decreasing the angle at which the ray strikes the flat edge of the glass block, we can discover the smallest angle at which most of the light is refracted along the edge of the glass block (see Figure 9.12b). This angle is the critical angle.



▲ Figure 9.12 **a** A semi-circular glass block used to demonstrate total internal reflection **b** Light striking the edge of the glass block at the critical angle

For light passing from glass to air, the critical angle is typically 42° and the critical angle for light passing from water to air is 49°.

The critical angle for a particular medium is related to its refractive index by this equation:

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

EXAMPLE 2

The refractive index for a type of glass is 1.45. Calculate the critical angle.

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

$$\sin c = \frac{1}{1.45}$$

$$\sin c = 0.69$$

$$c = 43.6°$$

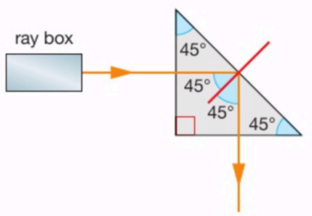
We sometimes use **prisms** rather than mirrors to reflect light. The light is totally internally reflected by the prism.

ACTIVITY 3

▼ PRACTICAL: INVESTIGATE TOTAL INTERNAL REFLECTION IN PRISMS

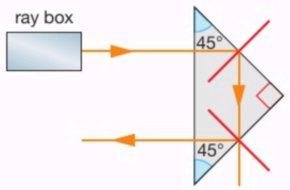
Safety note: Ray box lamps get hot enough to burn skin and char paper. Glass blocks and prisms should be handled carefully and not knocked together – they can splinter or shatter.

If you shine a ray of light into a prism as shown in Figure 9.13 it will strike the far surface at an angle of 45°. The critical angle for glass is about 42° so the ray will be totally internally reflected. You will see therefore that the ray will be reflected through an angle of 90°.



▲ Figure 9.13 Turning through 90° using total internal reflection

If you shine a ray into the prism as shown in Figure 9.14 the ray will be reflected through an angle of 180° – that is, it will go back in the direction from which it came.

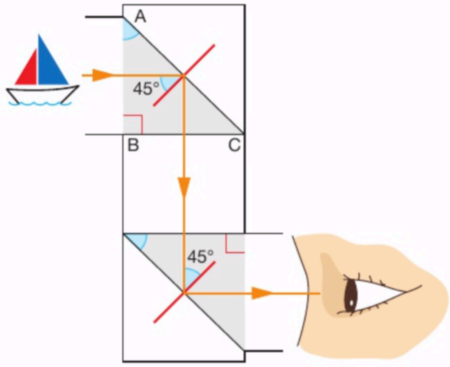


▲ Figure 9.14 Turning through 180° using total internal reflection

USING TOTAL INTERNAL REFLECTION

THE PRISMATIC PERISCOPE

The images produced by prisms are often brighter and clearer than those produced by mirrors. A periscope that uses prisms to reflect the light is called a prismatic periscope. Light passes through the surface AB of the first prism at 90° and so does not change direction (it is undeviated). It then strikes the surface AC of the prism at an angle of 45°. The critical angle for glass is 42° so the ray is totally internally reflected and is turned through 90°. When it leaves the first prism the light travels to a second prism. The second prism is positioned so that the ray is again totally internally reflected. The ray emerges parallel to the direction in which it was originally travelling.



▲ Figure 9.15 Total internal reflection in a prismatic periscope

BICYCLE AND CAR REFLECTORS

Figure 9.17 Reflectors like these can save lives.

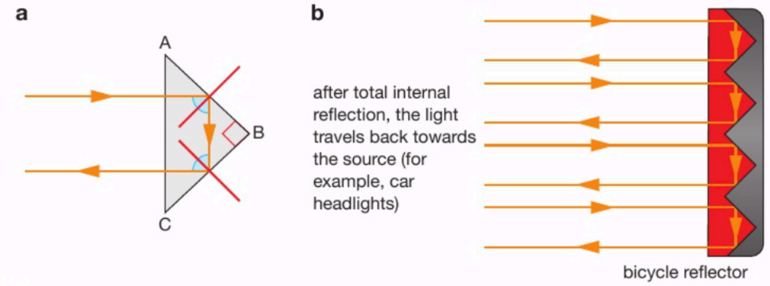


Figure 9.16 Prisms can also be used as reflectors.

Light entering the prism in Figure 9.16 is totally internally reflected twice. It emerges from the prism travelling back in the direction from which it originally came. This arrangement is used in bicycle or car reflectors.

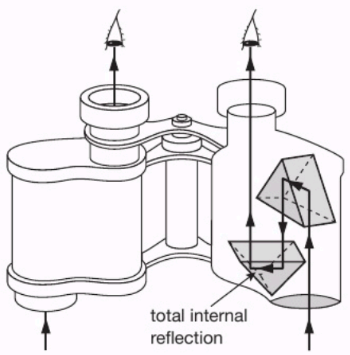


Figure 9.18 Total internal reflection inside binoculars

Figure 9.19 Prismatic binoculars

Binoculars also make use of total internal reflection within prisms.

Each side of a pair of binoculars contains two prisms to totally internally reflect the incoming light. Without the prisms, binoculars would have to be very long to obtain large **magnifications** and would look like a pair of telescopes.

OPTICAL FIBRES

One of the most important **applications** for total internal reflection is the optical fibre. This is a very thin piece of fibre composed of two different types of glass. The centre is made of a glass that has a high refractive index surrounded by a different type of glass that has a lower refractive index.

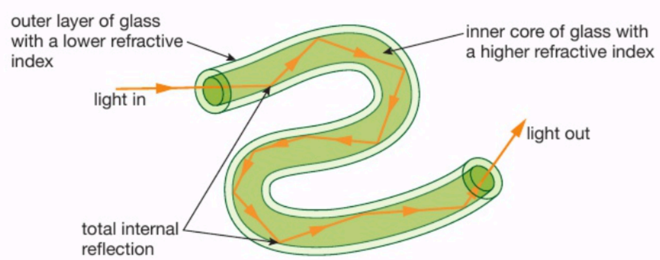


Figure 9.20 In an optical fibre, light undergoes total internal reflection.

Figure 9.21 Optical fibres

As the fibres are very narrow, light entering the inner **core** always strikes the boundary of the two glasses at an angle that is greater than the critical angle. No light escapes across this boundary. The fibre therefore acts as a 'light pipe' providing a path that the light follows even when the fibre is curved.

Large numbers of these fibres fixed together form a bundle. Bundles can carry sufficient light for images of objects to be seen through them. If the fibres are tapered (narrower at one end) it is also possible to produce a magnified image.

Figure 9.22 shows optical fibres in an endoscope. The endoscope is used by doctors to see the inside the body – for example, to examine the inside of the stomach. Endoscopes can also be used by engineers to see hard-to-reach parts of machinery.

Light travels down one bundle of fibres and shines on the object to be viewed. Light reflected by the object travels up a second bundle of fibres. An image of the object is created by the eyepiece.

THE ENDOSCOPE

By using optical fibres to see what they are doing, doctors can carry out operations through small holes made in the body, rather than through large cuts. This is called 'keyhole surgery'. This is less stressful for patients and usually leads to a more rapid recovery.

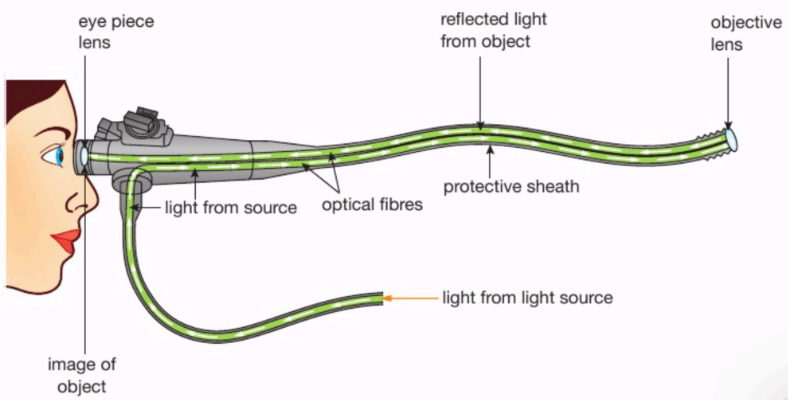


Figure 9.22 Optical fibres are used in endoscopes to see inside the body.

OPTICAL FIBRES IN TELECOMMUNICATIONS

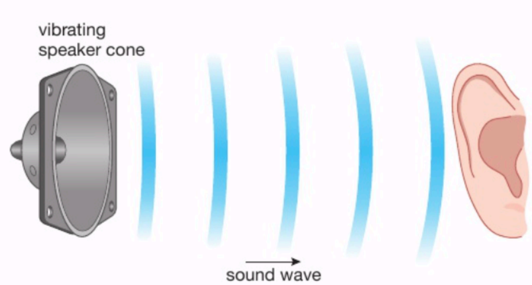
Modern telecommunications systems use optical fibres rather than copper wires to transmit messages as less energy is lost. Electrical signals from a telephone are converted into light energy produced by tiny lasers, which send pulses (small amounts) of light into the ends of optical fibres. A light-sensitive detector at the other end changes the pulses back into electrical signals, which then flow into a telephone receiver (ear piece).

SOUND WAVES

Figure 9.23 shows part of the sound system used by a band playing at a concert. This equipment must produce sounds that are loud enough to be heard by all the audience and the sound quality must be good enough for the music to be appreciated. We are going to look at how sounds are made and how they travel as waves.

▲ Figure 9.23 The sound produced by the speakers must be loud but also of good quality.

Sounds are produced by objects that are vibrating. We hear sounds when these vibrations, travelling as sound waves, reach our ears.



▲ Figure 9.24 The loudspeaker vibrates and produces sound waves.

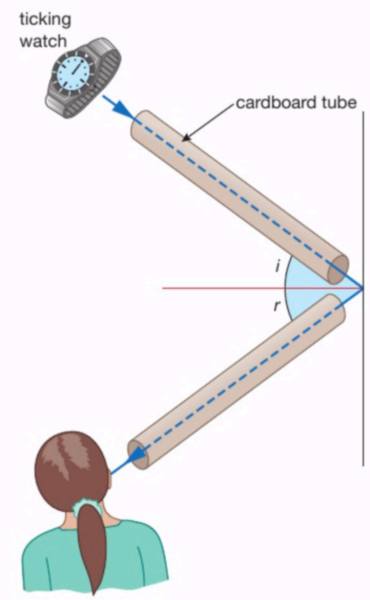
EXTENSION WORK

You will not be tested on this more detailed description of how sounds from a loudspeaker are heard. As the speaker cone moves to the right, it pushes air molecules closer together, creating a **compression**. These particles then push against neighbouring particles so that the compression appears to be moving to the right. Behind the compression as the speaker cone moves to the left is a region where the particles are spread out. This region is called a rarefaction. After the cone has vibrated several times, it has created a series of compressions and rarefactions travelling away from it. This is a longitudinal sound wave (see page 560). When the waves enter the ear, they strike the eardrum and make it vibrate. These vibrations are changed into electrical signals, which are then detected by the brain.

REFLECTION

Sound waves behave in the same way as any other wave.

When a sound wave strikes a surface it may be reflected. Like light waves, sound waves are reflected from a surface so that the angle of incidence is equal to the angle of reflection (see Figure 9.25).

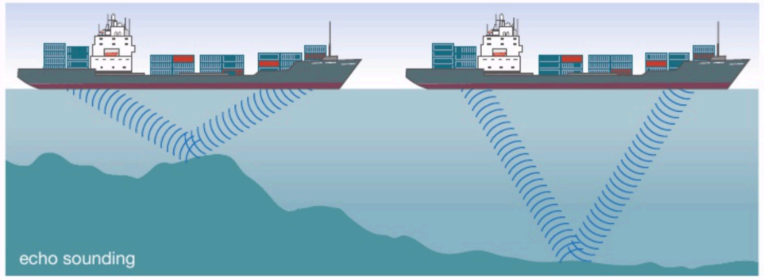


▲ Figure 9.25 Sound waves are reflected in the same way that light rays are reflected.

Ships often use echoes to discover the depth of the water beneath them. This is called echo sounding.

1 Sound waves are emitted from the ship and travel to the seabed (sea floor).
2 Some of these waves are reflected from the seabed back up to the ship.
3 Equipment on the ship detects these sound waves.
4 The time it takes the waves to make this journey is measured.
5 Knowing this time, the depth of the sea below the ship can be calculated.

The system of using echoes in this way is called **sonar** (Sound, Navigation And Ranging).

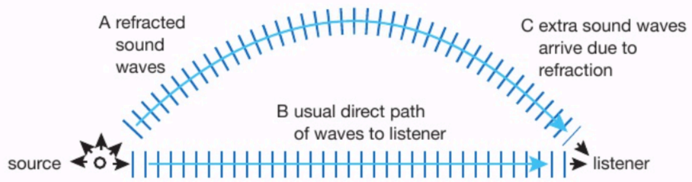


▲ Figure 9.26 Reflected sound can be used to tell ships about the depth of the sea beneath them.

REFRACTION OF SOUND

All waves can be refracted, even sound waves! For example, if some parts of a sound wave are travelling through warm air, they will travel more quickly than those parts travelling through cooler air. As a result the direction of the sound wave will change. It will be refracted.

Although it is not possible to see sound waves being refracted, we can sometimes hear their effect. Standing at the edge of a large pond or lake we can sometimes hear sounds from things on the other side of the water much more clearly than we would expect. This is due to refraction. Figure 9.27 explains how this happens.



▲ Figure 9.27 Why sometimes sounds travelling across water are louder than we expect

1 Most of the sound we hear travels to us in a straight line (Path B).
2 But some sound travels upwards (Path A).
3 If the temperature conditions are right, then as the sound waves travel through the air they are refracted and follow a curved path downwards (Path C).
4 We now receive two sets of sound waves.
5 So the sound we hear seems louder and clearer.

CHAPTER QUESTIONS

More questions on refraction can be found at the end of Unit 3 on page 588.

SKILLS INTERPRETATION, PROBLEM SOLVING

1 Draw a ray diagram to show how a ray of light can be turned through 100° using two plane mirrors. Mark on your diagram a value for the angle of incidence at each of the mirrors.

SKILLS INTERPRETATION

2 a Draw a diagram to show the path of a ray of light travelling from air into a rectangular glass block at an angle of about 45°.
  b Show the path of the ray as it emerges from the block.

SKILLS CRITICAL THINKING

  c Explain why the ray changes direction each time it crosses the air/glass boundary.

SKILLS INTERPRETATION

  d Draw a second diagram showing a ray that travels through the block without its direction changing.

SKILLS PROBLEM SOLVING

3 In an experiment to measure the refractive index of a type of glass, the angle of refraction was found to be 31° when the angle of incidence was 55°.
  a Calculate the refractive index of the glass.
  b What would the angle of refraction be for a ray with an angle of incidence of 45°?
  c Calculate the critical angle for the glass.

SKILLS INTERPRETATION

4 a Draw a diagram to show how a prism can create a rainbow of colours.

SKILLS CRITICAL THINKING

  b Explain how these colours are produced by the prism.

SKILLS INTERPRETATION

5 Draw three ray diagrams to show what happens to a ray of light travelling in a glass block in the following situations. It hits a face of the block at an angle:
  a less than the critical angle
  b equal to the critical angle
  c greater than the critical angle.

SKILLS CRITICAL THINKING

6 a What is meant by 'total internal reflection of light' and under what conditions does it occur?

SKILLS INTERPRETATION

  b Draw a diagram to show how total internal reflection takes place in a prismatic periscope.

SKILLS REASONING

  c Give one advantage of using prisms in a periscope rather than plane mirrors.

SKILLS INTERPRETATION

  d Draw a second diagram to show how a prism could be used to turn a ray of light through 180°. Give one application of a prism used in this way.

SKILLS INTERPRETATION, CRITICAL THINKING

7 a Explain why a ray of light entering an optical fibre is unable to escape through the sides of the fibre. Include a ray diagram in your explanation.

SKILLS CRITICAL THINKING

  b Explain how doctors use optical fibres to see inside the body.
  c Name one other use of optical fibres.

UNIT QUESTIONS

SKILLS CRITICAL THINKING

1 a Which of the following does not move as a transverse wave?

A ultraviolet light
B sound wave
C surface water wave
D microwave

(1)

b Which of these effects describes the change in pitch we hear when a fast moving motorbike goes past?

A total internal reflection
B refraction
C reflection
D Doppler

(1)

c Which of the following does not make use of total internal reflection?

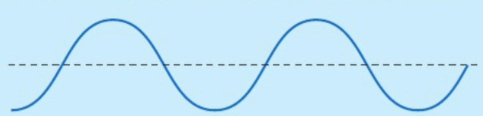
A oscilloscope
B endoscope
C prismatic periscope
D optical fibres

(1)

(Total 3 marks)

SKILLS INTERPRETATION

2 The diagram below shows the cross-section of a water wave.



a Copy this diagram and mark on it:

i the wavelength of the wave (λ) **(1)**

ii the amplitude of the wave (A). **(1)**

SKILLS PROBLEM SOLVING

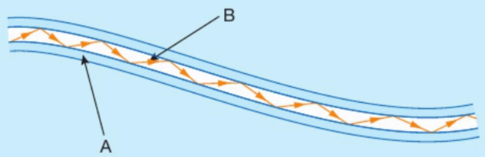
b i A water wave travelling at 20 m/s has a wavelength of 2.5 m. Calculate the frequency of the wave. **(3)**

ii Calculate the time period of the above wave. **(1)**

(Total 6 marks)

SKILLS ANALYSIS

3 The diagram below shows a ray of light travelling down an optical fibre.



SKILLS ANALYSIS

a What is A? **(1)**

b What is B? **(1)**

SKILLS CRITICAL THINKING

c Why is light reflected from the boundary between A and B? **(2)**

d Describe one medical use for optical fibres. **(1)**

(Total 5 marks)

4 a i Explain the difference between a longitudinal wave and a transverse wave. **(1)**

ii Give one example of each type of wave. **(2)**

A girl stands 500 m from a tall building and bangs two pieces of wood together. At the same moment her friend starts a stopwatch. The sound waves created by the two pieces of wood hit the building and are reflected. When the two girls hear the echo they stop the stopwatch and note the time. The girls repeat the experiment four more times. The results are shown in the table below.

Experiment	Time (seconds)
1	2.95
2	3.00
3	2.90
4	3.20
5	2.95

SKILLS EXECUTIVE FUNCTION

b Why did the girls repeat the experiment five times? **(1)**

SKILLS PROBLEM SOLVING

c Calculate the speed of sound using the results. **(6)**

SKILLS EXECUTIVE FUNCTION

d One of the girls thought that their answer might be affected by wind. Was she correct? Explain your answer. **(2)**

(Total 12 marks)

SKILLS CRITICAL THINKING

5 The electromagnetic spectrum contains the following groups of waves: infrared, ultraviolet, x-rays, radio waves, microwaves, visible spectrum and gamma rays.

a Put these groups of waves in the order they appear in the electromagnetic spectrum starting with the group that has the longest wavelength. **(2)**

b Write down four properties that all of these waves have in common. **(4)**

c Write down one use for each group of waves. **(7)**

d Which three groups of waves could cause cancer? **(3)**

e Which three groups of waves can be used to communicate **(3)**

(Total 19 marks)

SKILLS PROBLEM SOLVING

6 a A ray of light hits the outside surface of a glass block with an angle of incidence of 38°. Its angle of refraction inside the block is 24°.

i Calculate the refractive index of the glass. **(4)**

ii Calculate the critical angle for this glass. **(2)**

b Calculate the refractive index for a piece of glass whose critical angle is 42°. **(3)**

(Total 9 marks)