Block 3

Physics of waves

In December 2004, a giant tsunami caused by an underwater earthquake devastated coastal regions in several countries around the Indian Ocean. Hundreds of thousands of people lost their lives.

Earthquakes are vibrations that carry vast amounts of energy. They travel right through the Earth and can be detected thousands of kilometres away. Surprisingly, earthquakes have also proved useful. Because we can understand how they travel through solids and liquids, geologists have been able to use information from earthquakes to build up a detailed picture of the inner structure of the Earth.

In this block we will look at how the idea of waves can be used to explain sound and light.

The tsunami of 2004 arriving on a beach in Thailand. The woman is running down the beach to warn her children. The family was lucky – they all survived.

12 Sound

Core Describing the production of sounds
Core Measuring the speed of sound
Core Relating pitch and loudness to frequency and amplitude
Core Describing how sound travels

The sound of music

Most musicians have to tune their instruments before they start to play. Guitarists in a band adjust the tension of their strings so that they play the correct notes. If you have heard a symphony orchestra play, you may have noticed that the oboist usually plays a single clear note, and the other instrumentalists tune to this note. If they all played slightly different notes, the effect would be very uncomfortable on our ears.

Most music we hear is played by instruments tuned to a standard scale, like the notes of a piano keyboard. However, not all instruments are tuned in the same way. The Scottish bagpipes, for example, play notes on a slightly different scale. A pipe band playing together can sound very exciting (Figure 12.1). But when mixed with other instruments, the notes can clash to produce a very unpleasant effect. In a similar way, the instruments of an Indonesian *Gamelan* band (Figure 12.2) play notes on a different scale.

In this chapter, we will look at musical sounds (and other sounds, too), how they are produced, and how they travel. We will also look at why different instruments sound different to our ears.

Figure 12.1 These pipers play instruments that produce notes on an unusual scale, different from the conventional scale of a piano. Because the scale is different from what we are used to, the music can at first seem off-key. The Scottish pipes were often played before battles, to give the Scottish troops courage and to alarm the enemy.

Figure 12.2 *Gamelan* bands can be heard in Indonesia and other countries of the Pacific rim. They include string and woodwind instruments, and are specially noted for their range of percussion instruments – gongs, drums, chimes, marimbas and so on. For people who are used to listening to conventional western music (popular or classical), it can take some time to tune in to the complex rhythms and harmonies produced by a *Gamelan* orchestra.

12.1 Making sounds

Different musical instruments produce sounds in different ways.

- **String instruments.** The strings are plucked or bowed to make them vibrate. In most string instruments, the vibrations are transmitted to the body of the instrument, which also vibrates, along with the air inside it. The vibrations may be too small or too fast to see, but they can be shown up using laser techniques (see Figure 12.3).

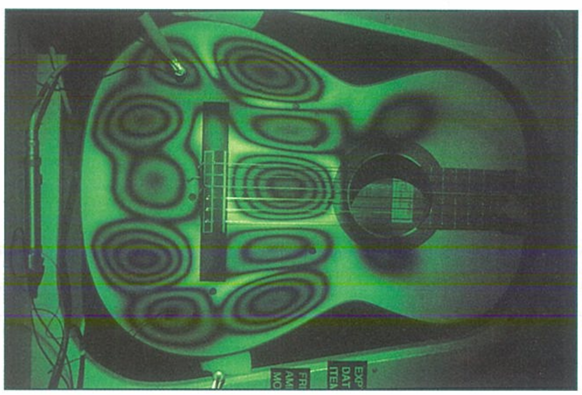


Figure 12.3 Although the player only touches the strings of a guitar, the instrument's whole body vibrates to produce the notes we hear. This is shown up in this image, produced by shining laser light onto the guitar. Different notes produce different patterns of vibration, and this helps to give each note its particular quality.

- **Wind instruments.** The 'air column' inside the instrument is made to vibrate, by blowing across the end of or into the tube (Figure 12.4). The smallest instruments have a straight air column.

Figure 12.4 Two recorders can look very similar, but the lower one is made of wood and the other of plastic. A flute may be of wood or metal. This tells us that it is not the material that the instrument is made of that matters. It is the air inside that vibrates to produce the desired note. Blowing into the instrument causes the air column inside it to vibrate, and the vibrations are transferred to the air outside.

Bigger instruments capable of playing deeper notes (such as a horn or tuba) have an air column that is bent around so that the instrument is not inconveniently long. Some instruments have a reed in the mouthpiece. This vibrates as the player blows across it, causing the air to vibrate.

- **Percussion instruments.** These instruments are played by striking them (Figure 12.5). This produces vibrations – of the keys of a xylophone, the skin of a drum, or the metal body of a gong, for example.

In each case, part (or all) of the instrument is made to vibrate. This causes the air nearby to vibrate, and the **vibrations** travel through the air to the audience's ears. Some vibrations also reach us through the ground, so that they make our whole body vibrate (see Figure 12.5). If you sit close to a loud band or orchestra, you may feel your whole body vibrating in response to the music.

Figure 12.5 Evelyn Glennie is one of the world's top solo percussionists, despite the fact that she is deaf. She has trained herself to be sensitive to vibrations that reach her body through the ground. This allows her to follow the rhythm of a piece of music, as well as to detect the subtle differences in tone between different percussion instruments.

Sounds travel through the air as vibrations. These vibrations can travel through any material – through the solid ground, through the glass panes of a window, through water. If you put a battery-powered radio on the side of the bath and submerge your ears, you will hear the sounds from the radio travelling through the solid bath and the liquid water to your ears.

QUESTIONS

1 Which of the following materials can sound travel through: wood, air, water?

2 When a woodwind instrument such as a flute produces a note, what part of it vibrates?

12.2 At the speed of sound

The speed of sound in air is about 330 m/s, or 1 200 km/h. That is about ten times the speed of cars on a major highway. When someone speaks, it seems to us that we hear the sound they make as soon as they make it. However, it takes a small amount of time to reach our ears. For example, if we are speaking to someone who is just 1 m away, the time for sounds to travel between us is:

$$\frac{1\text{ m}}{330\text{ m/s}} = 0.003\text{ s} = 3\text{ ms (3 milliseconds)}$$

This is far too short a time for us to notice.

However, there are occasions when we may notice the time it takes for sounds to travel. For example, imagine that you shout at a distance from a long high wall or cliff. After you shout, you may hear an **echo**. The sound has reflected from the hard surface and back to your ears (see Figure 12.6). Worked example 1 shows how to calculate the time it takes for the sound to travel to a wall and back again.

If you watch people playing a game such as cricket or baseball, you may notice a related effect. You see someone hitting a ball. A split second later you hear the sound of the ball being struck. The time interval between seeing the hit and hearing it occurs because the sound travels relatively slowly to your ears, while

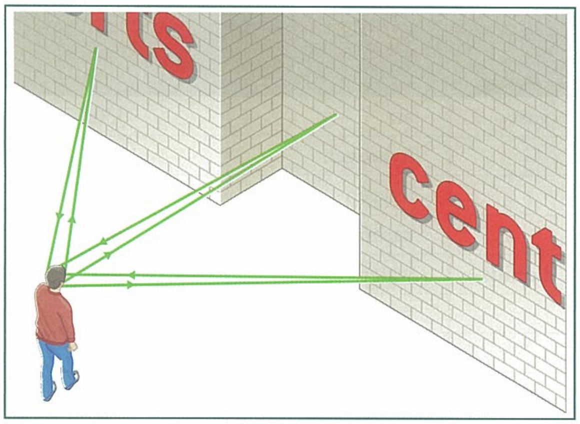


Figure 12.6 An echo is heard when a sound reflects off a hard surface such as a large wall. Sound travels outwards from the source, and bounces off the wall. Some of it will return to the source. If there are several reflecting surfaces, several echoes may be heard.

the light travels very quickly to your eyes. So the light reaches you first, and you see before you hear. When cricket matches are televised, they may use a microphone buried in the pitch to pick up the sounds of the game, so that there is no noticeable gap between what you see and what you hear.

For the same reason, we usually see a flash of lightning before we hear the accompanying roll of thunder. Count the seconds between the flash and the bang. Then divide this by three to find how far away the lightning is, in kilometres. This works because the sound takes roughly 3 s to travel 1 km, whereas the light travels the same distance in a few microseconds.

Worked example 1

A man shouts loudly close to a high wall (see Figure 12.6). He hears one echo. If the man is 40 m from the wall, how long after the shout will the echo be heard? (Speed of sound in air = 330 m/s.)

Step 1: Calculate the distance travelled by the sound. This is twice the distance from the man to the wall (since the sound travels there and back).

$$\text{distance travelled by sound} = 2 \times 40\,\text{m} = 80\,\text{m}$$

Step 2: Calculate the time taken for the sound to travel this distance.

$$\text{time taken} = \frac{\text{distance}}{\text{speed}} = \frac{80\,\text{m}}{330\,\text{m/s}} = 0.24\,\text{s}$$

So the man hears the echo 0.24 s (about a quarter of a second) after his shout.

Measuring the speed of sound

One way to measure the speed of sound in the lab is to find out how long a sound takes to travel a measured distance, just as you might measure the speed of a moving car or cyclist. Since sound travels at a high speed, you need to be able to measure short time intervals. Figure 12.7 shows one method.

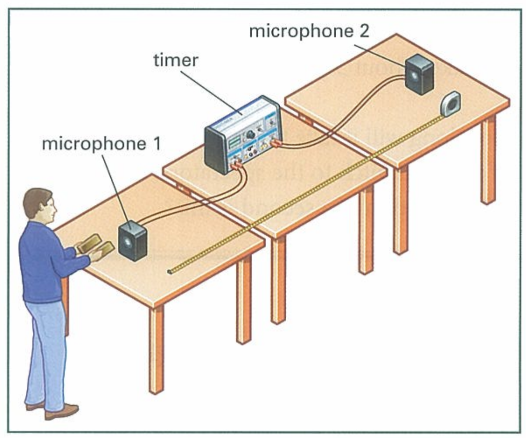


Figure 12.7 A 'time-of-flight' method for measuring the speed of sound. The wooden blocks and the two microphones are arranged in a straight line. The bang from the blocks is picked up first by microphone 1 and then by microphone 2. The first activates the timer, and the second stops it. The speed of sound is calculated from the distance between the two microphones and the time taken by the sound to travel between them.

When the student bangs the two blocks of wood together, it creates a sudden, loud sound. The sound reaches one microphone, and a pulse of electric current travels to the timer. The timer starts running. A fraction of a second later, the sound reaches the second microphone. A second pulse of current stops the timer. Now the timer indicates the time taken for the sound to travel from one microphone to the other.

It is important that the two microphones should be a reasonable distance apart – say, three or four metres. The further apart the better, since this will give a longer 'time of flight' for the sound to travel from one microphone to the other.

Activity 12.1 Measuring the speed of sound in air

Use echoes to help you to measure the speed of sound in air.

QUESTION

3 Sound takes about 3 ms (3 milliseconds) to travel 1 m.

a How long will it take to travel from the centre of a cricket pitch to the spectators, 200 m away?

b What fraction of a second is this?

E

Different materials, different speeds

We talk about 'the speed of sound' as 330 m/s. In fact, it is more correct to say that this is the speed of sound in air at 0 °C. The speed of sound changes if the temperature of the air changes, if it is more humid, and so on. (Note also that some people talk about 'the velocity of sound', but there is no need to use the word 'velocity' here, since we are not talking about the direction in which the sound is travelling – see Chapter 2.)

Table 12.1 shows the speed of sound in some different materials. You can see that sound travels faster through solids than through gases. Its speed in water (a liquid) is in between its speed in solids and gases.

E

	Material	Speed of sound / m/s
gases	air	330
	hydrogen	1280
	oxygen	316
	carbon dioxide	268
liquids	water	1500
	sea water	1530
	mercury	1450
solids	glass	5000
	iron, steel	5100
	lead	1200
	copper	3800
	wood (oak)	3800

Table 12.1 The speed of sound in different materials (measured at standard temperature and pressure).

QUESTIONS

4 Look at the experiment to measure the speed of sound shown in Figure 12.7. Explain why the wooden blocks and the two microphones must be in a straight line.

5 Which travels faster, light or sound? Describe **one** observation that supports your answer.

12.3 Seeing sounds

When a flautist plays her flute, she sets the air inside it vibrating. A trumpeter does the same thing. Why do the two instruments sound so different? The flute and the trumpet each contain an 'air column', which vibrates to produce a musical note. Because the instruments are shaped differently, the notes produced sound different to our ears.

An image of the notes can be produced by playing the instrument next to a microphone connected to an oscilloscope (Figure 12.8). The microphone receives the vibrations from the instrument and converts them to an electrical signal, which is displayed on the oscilloscope screen. The trace on the screen shows the regular up-and-down pattern of the vibrations that make up the sound.

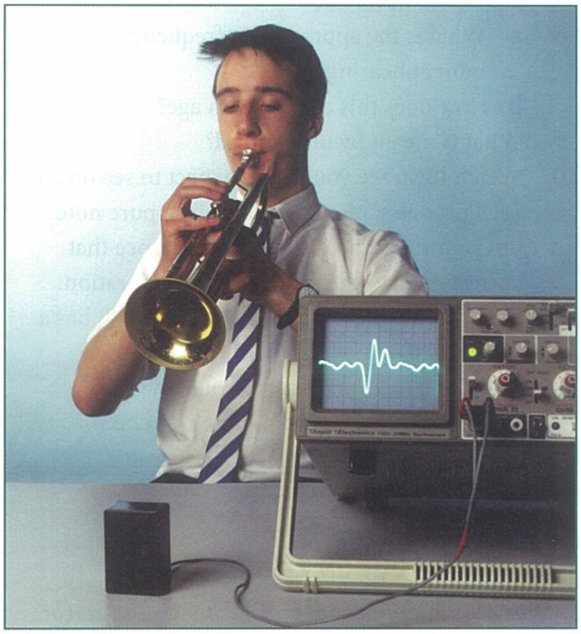


Figure 12.8 To display the vibrations of a musical note, it is converted to an electrical signal by a microphone and displayed on the screen of an oscilloscope. The trace on the screen shows the regular pattern of vibration of the sounds.

Pure notes

A signal generator can produce pure notes that have a very simple shape when displayed on an oscilloscope screen, as shown in Figure **12.9**. As shown in the diagram, we can make an important measurement from this graph. This is the time for one complete vibration, known as the **period** T of the vibration. This is related to the **frequency** f of the sound:

period T = number of seconds for one vibration

frequency f = number of vibrations per second

Hence we can write the following equation:

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

Frequency is measured in hertz (Hz). A frequency of 1 Hz is one vibration per second.

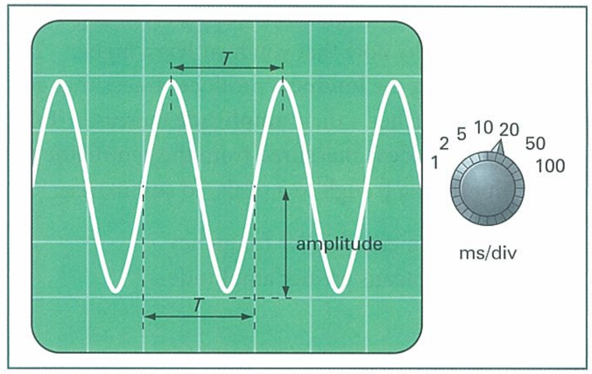


Figure 12.9 A pure note has the shape shown in this oscilloscope trace. The setting of the oscilloscope timebase is indicated on the right. This tells you how much time is represented by the divisions on the horizontal scale.

High and low, loud and soft

You can understand how an oscilloscope works by connecting it up to a signal generator. With a low-frequency note (say, 0.1 Hz), you will see that there is a single dot, which moves steadily across the oscilloscope screen. The electrical signal from the signal generator makes it move up and down in a regular way. Increasing the frequency makes the dot go up and down faster, until it blurs into a continuous line.

Changing the settings on the signal generator allows you to see the traces for notes of different frequencies and loudnesses. A loudspeaker will let you hear them as well. As shown in Figure **12.10**, increasing the

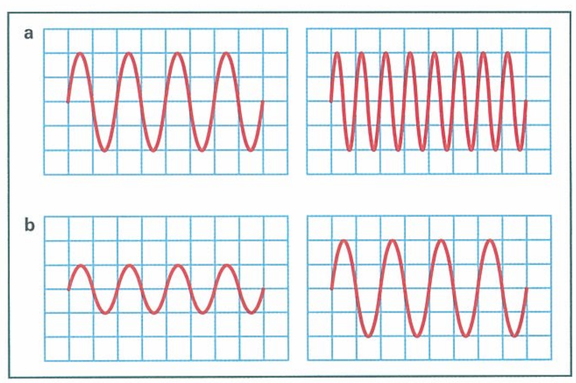


Figure 12.10 **a** Two notes with the same amplitude, and hence the same loudness. The second has more waves squashed into the same space, so its frequency is higher. Its pitch is higher too (it sounds higher). **b** Two notes with the same frequency. The second has a greater amplitude, so that it sounds louder.

frequency of the note squashes the vibrations together on the screen. The note that you hear has a higher **pitch**. Increasing the **loudness** produces traces that go up and down further – their **amplitude** increases. Take care: the amplitude is measured from the centre line to a peak, not from a trough to a peak. To summarise:

- higher pitch means higher frequency
- louder note means greater amplitude.

Range of hearing

A piano keyboard covers a wide range of notes, with frequencies ranging from about 30 Hz at the bottom end to about 3 500 Hz at the top end. Most other instruments cover a narrower range than this. For example, a violin ranges from about 200 Hz to 2 500 Hz. The range of human hearing is greater than this. Typically, we can hear notes ranging from about 20 Hz up to about 20 000 Hz (20 kHz, or 20 kilohertz). However, older people gradually lose the ability to hear high-pitched sounds. Their **upper limit of hearing** decreases by about 2 kHz every decade of their age.

Sounds that are more high-pitched than the upper limit of hearing (above 20 kHz) are too high to hear, and are known as **ultrasound**. Sounds below 20 Hz are too low to hear, and are known as **infrasound**.

Activity 12.2 Seeing sounds

Use a signal generator and an oscilloscope to show traces for different sounds, and test your range of hearing.

QUESTIONS

6 What happens to the pitch of a sound if its frequency increases?

7 What happens to the loudness of a sound if its amplitude decreases?

8 **a** What is the approximate frequency range of human hearing?
b How does this change with age?

9 What is meant by **ultrasound**?

10 Sketch the trace you would expect to see on an oscilloscope screen, produced by a pure note. On your diagram, indicate the distance that corresponds to the period T of the vibration.

11 Sound A has a period of 0.010 s; sound B has a period of 0.020 s.
a Which has the greater frequency?
b Which will sound more high-pitched?

12.4 How sounds travel

Sounds are vibrations that travel through the air (or another material), produced by vibrating objects. How can we picture the movement of the molecules of the air as a sound travels through? Figure **12.11** shows how the vibrations of a tuning fork are transmitted through the air. As the prong of the fork moves to the right, it pushes on the air molecules on that side, squashing them together. These molecules push on their neighbours, which become compressed, and which in turn push on their neighbours, and so on.

It is important to note that the individual air molecules do not travel outwards from the vibrating fork. The air

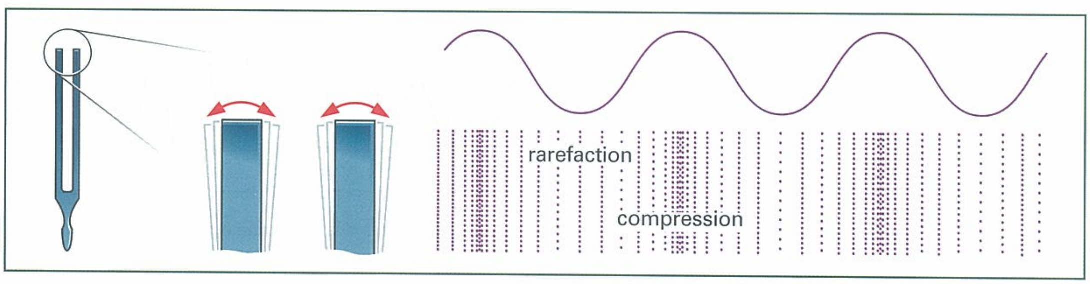


Figure 12.11 A vibrating tuning fork produces a series of compressions and rarefactions as it pushes the air molecules back and forth. This is how a sound travels through the air (or any other material). We can relate this to the wavy trace on an oscilloscope screen.

molecules are merely pushed back and forth. It is the vibrations that travel through the air to our ears.

This picture of how a sound travels also explains why sound cannot travel through a vacuum. There are no molecules or other particles in a vacuum to vibrate back and forth.

Figure **12.11** also shows another way of representing a sound, as a wavy line rather like the trace on an oscilloscope screen. The crests on the wave match the compressions, and the troughs match the rarefactions. It is much easier to represent a sound as an up-and-down wave like this, rather than drawing lots of air molecules pushing each other back and forth.

Here we have used two different **models** to represent sound:

1 vibrations travelling through a material – the particles of the material are alternately compressed together and then rarefied as the sound passes through
2 sound as a wave – a smoothly varying up-and-down line, like the trace on an oscilloscope screen.

The first of these models gives a better picture of what we could see if we could observe the particles of the material through which the sound is passing. The second model is easier to draw. It also explains why we talk about **sound waves**. The wavy line is rather like the shape of waves on the sea. There is much more about sound waves (and other waves) in Chapter **14**.

QUESTIONS

12 Why is it impossible for sounds to travel through a vacuum?

13 How could you convince a small child that, when you speak, it is not necessary for air to travel from your mouth to the ear of a listener?

E

Compression, rarefaction

Look back to Figure **12.11**. The areas of the sound wave where the air molecules are close together are called **compressions**. As the tuning fork vibrates back and forth, compressions are sent out into the air all around it. In between the compressions are **rarefactions**, areas in which the air molecules are less closely packed together, or rarefied.

The sound wave has been drawn so that the crests on the wave match the compressions, and the troughs match the rarefactions. Thus the wave represents the changes in air pressure as the sound travels from its source.

QUESTION

14 What is the difference between a compression and a rarefaction in a sound wave? Illustrate your answer with a sketch.

Summary

Sounds are vibrations that travel through a material, produced by a vibrating source.

An echo is produced when a sound is reflected off a hard surface.

E Sound travels through solids, liquids and gases at speeds of hundreds or thousands of metres per second.

The frequency of a sound is the number of vibrations per second, measured in hertz (Hz).

The greater the frequency of a sound, the higher the pitch.

The greater the amplitude of a sound, the louder it is.

The audible range of sounds is from about 20 Hz to about 20 kHz.

Sounds cannot travel through a vacuum.

E The vibrations of a sound travel through a material in the form of compressions and rarefactions of the particles that make up the material.

End-of-chapter questions

12.1 Sounds are produced by vibrating objects.

a When a wind instrument such as a trumpet produces a sound, what is it that is made to vibrate by the player? [1]

b When a stringed instrument such as a violin is played, what is it that is made to vibrate by the player? [1]

c Describe how the sound from the instrument travels through the air to the listener's ears. [3]

12.2 The vibrations of a sound can be detected using a microphone and then displayed on an oscilloscope screen. Figure 12.12 shows three such traces.

a Which trace shows the loudest sound? Explain your answer. [2]

b Which trace shows the sound with the highest pitch? Explain your answer. [2]

12.3 Describe a method for measuring the speed of sound in air, in the laboratory. What measurements are made, and how is the speed of sound calculated from them? [5]

12.4 **a** In which material does a sound travel faster, a solid or a gas? [1]

b Give **one** piece of evidence that shows that sound can travel through solid materials. [2]

To measure the length of a long metal rod, engineers send a pulse of sound into one end of it. The sound travels to the other end and is reflected back. The engineers detect this echo, and determine the time taken for the sound to travel from one end of the rod to the other.

c When making measurements on a steel rod of length 400 m, they find that the echo returns 0.16 s after the initial pulse. What is the speed of sound in steel? [4]

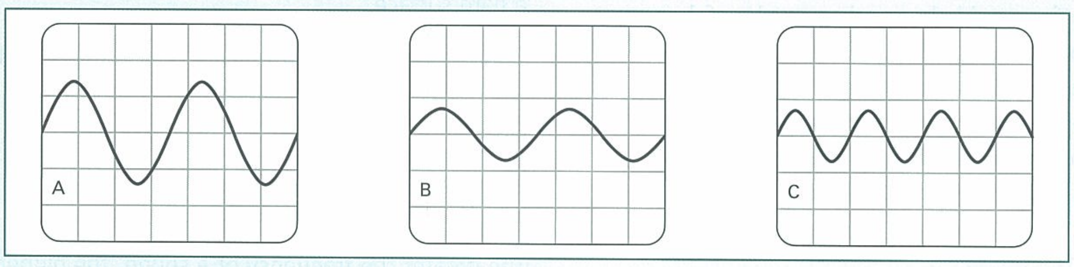


Figure 12.12 For Question 12.2.

13 Light

Core Using the law of reflection of light
Core Describing how a plane mirror forms an image
E Extension Constructing ray diagrams for reflection
Core Describing the refraction of light
E Extension Calculating refractive index and using Snell's law
Core Describing total internal reflection
Core Using ray diagrams to explain how a lens forms a real image
E Extension Explaining how a magnifying glass works

How far to the Moon?

When Apollo astronauts visited the Moon, they left behind reflectors on its surface. These are used to measure the distance from the Earth to the Moon. A laser beam is directed from an observatory on Earth (Figure **13.1**) so that it reflects back from these reflectors left on the lunar surface. The time taken by the light to travel there and back is measured and, because the speed of light is known, the distance can be calculated.

The Moon travels along a slightly elliptical orbit around the Earth, so that its distance varies between 356 500 km and 406 800 km. The laser measurements of its distance are incredibly accurate – to within 30 cm. This means that they are accurate to within one part in a billion. The Moon is gradually slowing down and drifting away from the Earth. With the help of such precise measurements, it is possible to work out just how quickly it is drifting away.

This experiment makes use of two ideas that we will look at in this chapter: the way that light travels in straight lines, and how light is reflected by mirrors.

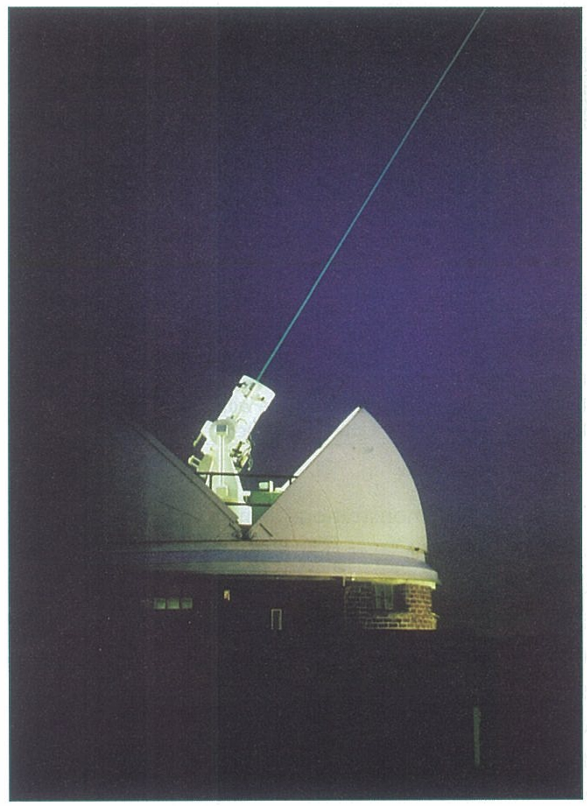


Figure 13.1 A laser beam is directed into space from the Royal Greenwich Observatory (Sussex, UK). The beam reflects off the Moon or a satellite in space. The reflected beam is detected, and the exact distance to the Moon or the satellite can be calculated.

13.1 Reflecting light

Light usually travels in straight lines. It changes direction if it hits a shiny surface, or if it travels from one material into another. This change in direction at a shiny surface such as a mirror is called **reflection**. We look at reflection in this section.

You can see that light travels in a straight line using a **ray box**, as shown in Figure 13.2. A light bulb produces light, which spreads out in all directions. A ray box produces a broad beam. By placing a narrow slit in the path of the beam, you can see a single narrow beam or **ray** of light. The ray shines across a piece of paper. You can record its position by making dots along its length. Laying a ruler along the dots shows that they lie in a straight line.

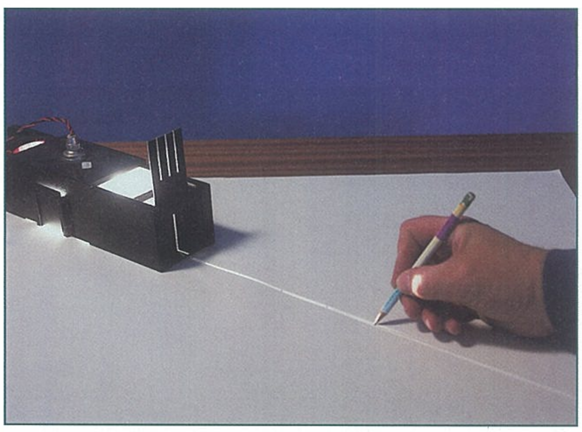


Figure 13.2 A ray box produces a broad beam of light, which can be narrowed down using a metal plate with a slit in it. Marking the line of the ray with dots allows you to record its position.

You may see demonstrations using a different source of light, a **laser**. A laser (Figure 13.3) has the great advantage that all of the light it produces comes out in a narrow beam. All of the energy is concentrated in this beam, rather than spreading out in all directions (as with a light bulb). The total amount of energy coming from the laser is probably much less than that from a bulb, but it is much more concentrated. That is why it is dangerous if a laser beam gets into your eye.

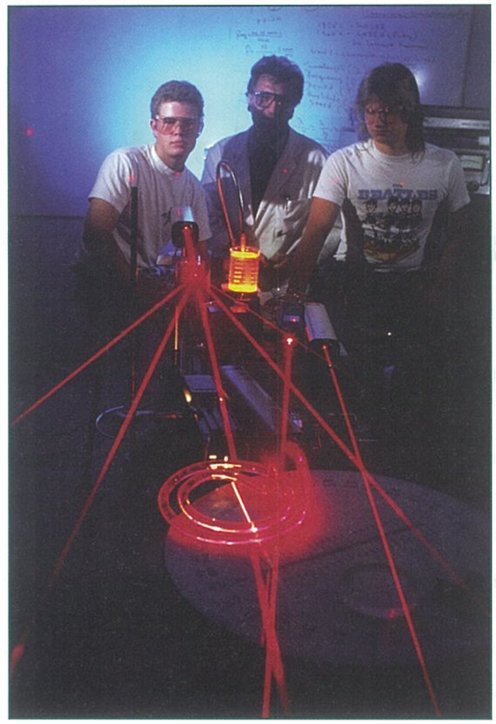


Figure 13.3 Students working with laser beams. They are wearing safety glasses to protect their eyes from stray reflections of the beams.

Looking in the mirror

Most of us look in a mirror at least once a day, to check on our appearance (Figure 13.4). It is important to us to

Figure 13.4 Psychologists use mirrors to test the intelligence of animals. Do they recognise that they are looking at themselves? Apes clearly understand that what they see in the mirror is an image of themselves – they make silly faces at themselves. Other animals, such as cats and dogs, do not – they may even try to attack their own reflection.

know that we are presenting ourselves to the rest of the world in the way we want. Archaeologists have found bronze mirrors over 2000 years old, so the desire to see ourselves clearly has been around for a long time.

Modern mirrors give a very clear image. When you look in a mirror, rays of light from your face reflect off the shiny surface and back to your eyes. You seem to see an image of yourself behind the mirror. To understand why this is, we need to use the law of reflection of light.

When a ray of light reflects off a mirror or other reflecting surface, it follows a path as shown in Figure 13.5. The ray bounces off, rather like a ball bouncing off a wall. The two rays are known as the **incident ray** and the **reflected ray**. The **angle of incidence** i and the **angle of reflection** r are found to be equal to each other. This is the **law of reflection**, which can be written as follows:

> angle of incidence = angle of reflection
>
> $i = r$

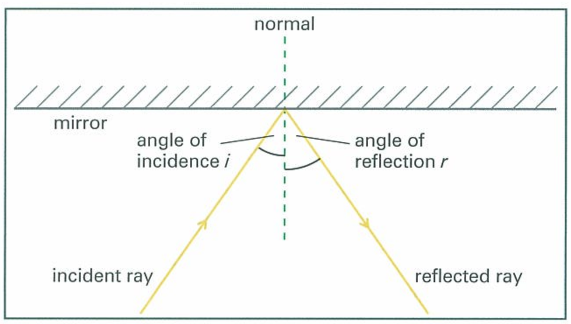


Figure 13.5 The law of reflection of light. The normal is drawn perpendicular to the surface of the mirror. Then the angles are measured relative to the normal. The angle of incidence and the angle of reflection are then equal: $i = r$.

Note that, to find the angles i and r, we have to draw the **normal** to the reflecting surface. This is a line drawn perpendicular (at 90°) to the surface, at the point where the ray strikes it. Of course, the other two angles (between the rays and the flat surface) are also equal. However, we would have trouble measuring these angles if the surface was curved, so we measure the angles relative to the normal. The law of reflection thus also works for curved surfaces, such as concave and convex mirrors.

Activity 13.1 The law of reflection

Check the law of reflection using a ray box and a plane mirror.

The image in a plane mirror

Why do we see such a clear **image** when we look in a plane (flat) mirror? And why does it appear to be behind the mirror?

Figure **13.6** shows how an observer can see an image of a candle in a plane mirror. Light rays from the flame are reflected by the mirror. Some of them enter the

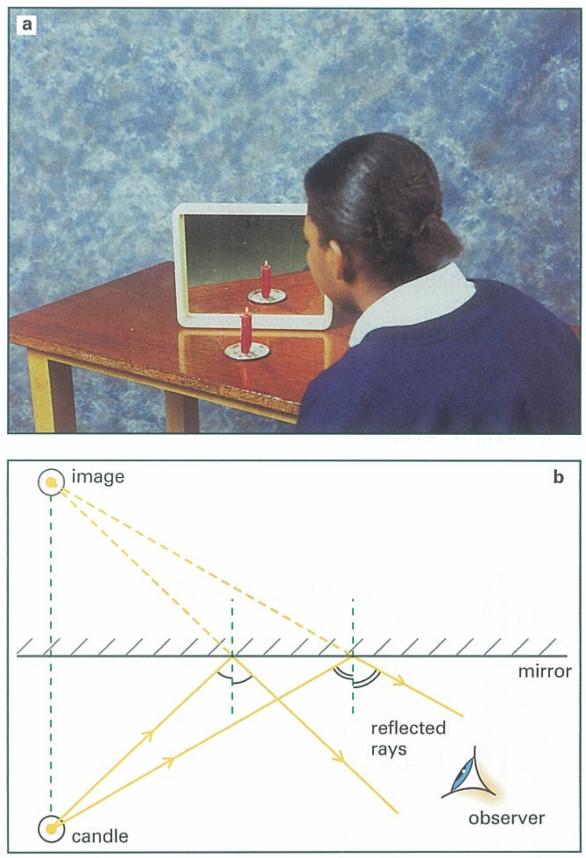


Figure 13.6 **a** Looking in the mirror, the observer sees an image of the candle. The image appears to be behind the mirror. **b** The ray diagram shows how the image is formed. Rays from the candle flame are reflected according to the law of reflection. The dashed lines show that, to the observer, the rays appear to be coming from a point behind the mirror.

observer's eye. In the diagram, the observer has to look forward and slightly to the left to see the image of the candle. Their brain assumes that the image of the candle is in that direction, as shown by the dashed lines behind the mirror. (Our brains assume that light travels in straight lines, even though we know that light is reflected by mirrors.) The dashed lines appear to be coming from a point behind the mirror, at the same distance behind the mirror as the candle is in front of it. You can see this from the symmetry of the diagram.

The image looks as though it is the same size as the candle. Also, it is (of course) a mirror image, that is, it is left–right reversed. You will know this from seeing writing reflected in a mirror.

The image of the candle in the mirror is not a real image. A **real image** is an image that can be formed on a screen. If you place a piece of paper at the position of the image, you will not see a picture of the candle on it, because no rays of light from the candle reach that spot. That is why we drew dashed lines, to show where the rays appear to be coming from. We say that it is a **virtual image**.

To summarise, when an object is reflected in a plane mirror, its image is:

- the **same size** as the object
- the **same distance** behind the mirror as the object is in front of it
- **left–right reversed**
- **virtual**.

QUESTIONS

1 **a** Write the word AMBULANCE as it would appear when reflected in a plane mirror.
  b Why is it sometimes written in this way on the front of an ambulance?
2 **a** Draw a diagram to illustrate the law of reflection.
  b Which **two** angles are equal, according to the law?
3 A ray of light strikes a flat, reflective surface such that its angle of incidence is 30°. What angle does the reflected ray make with the surface?
4 What does it mean to say that a plane mirror produces a **virtual** image?

E

Ray diagrams

Figure **13.6b** on page **135** is an example of a **ray diagram**. Such diagrams are used to predict the position of images in mirrors, or when lenses or other optical devices are being used. The idea is first to draw the positions of things that are known (for example, the candle and the mirror). Then rays of light are drawn. These must be carefully chosen if they are to show up what we want to see. The position of the observer is marked, and then the rays are **extrapolated** back, to show where they appear to be coming from. These are the dashed lines shown in the diagram. This is known as a **construction**, and it allows us to mark the position of the image. Worked example 1 shows the steps in constructing a ray diagram.

E

Worked example 1

A small lamp is placed 5 cm in front of a plane mirror. Draw an accurate scale diagram, and use it to show that the image of the lamp is 5 cm behind the mirror.

The steps needed to draw the ray diagram are listed below and shown in Figure 13.7. (It helps to work on squared paper or graph paper.)

1 Draw a line to represent the mirror, and indicate its reflecting surface, by drawing short lines on the back. Mark the position of the object O.
2 Draw two rays from O to the mirror. Where they strike the mirror, draw in the normal lines.
3 Using a protractor, measure the angle of incidence for each ray. Mark the equal angle of reflection.
4 Draw in the reflected rays, and extend them back behind the mirror. The point where they cross is where the image is formed. Label this point I.

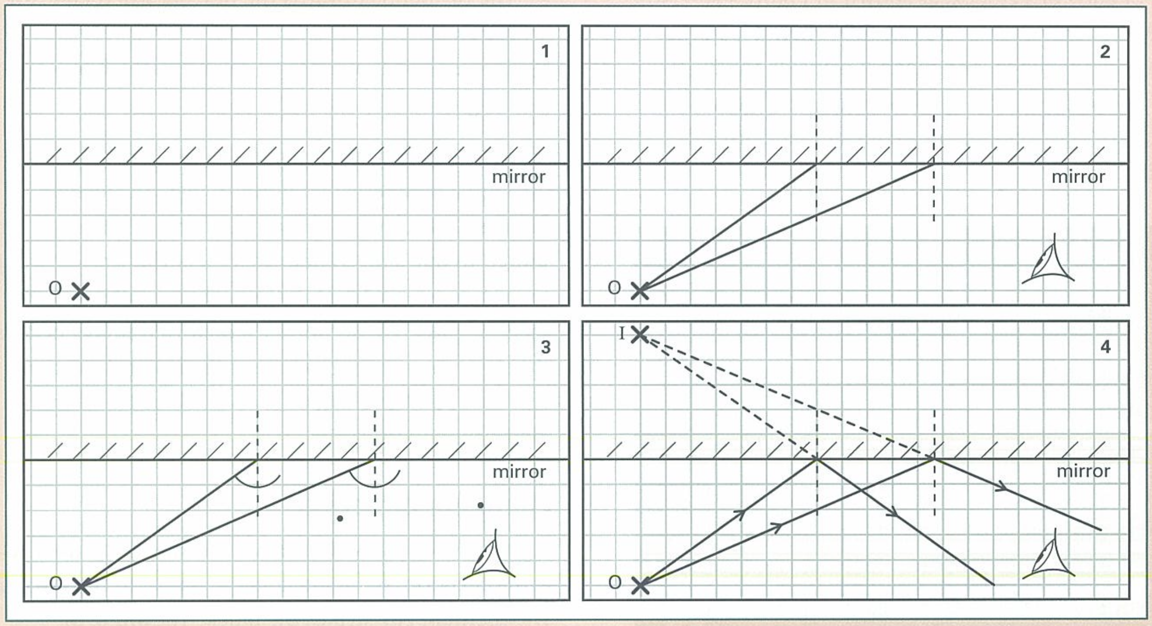


Figure 13.7 The steps in drawing a ray diagram for a plane mirror.

From the diagram for Step 4, it is clear that the image is 5 cm from the mirror, directly opposite the object. The line joining O to I is perpendicular to the mirror.

13.2 Refraction of light

If you look down at the bottom of a swimming pool, you may see patterns of shadowy ripples. The surface of the water is irregular. There are always small disturbances on the water, and these cause the rays of sunlight to change direction. Where the pattern is darker, rays of light have been deflected away, producing a sort of shadow. This bending of rays of light when they travel from one material to another is called **refraction**.

There are many effects caused by the refraction of light. Some examples are the sparkling of diamonds, the way the lens in your eye produces an image of the world around you, and the twinkling of the stars in the night sky. The 'broken stick' effect (Figure **13.8**) is another consequence of refraction. The word 'refraction' is related to the word 'fractured', meaning broken.

Refraction occurs when a ray of light travels from one material into another. The ray of light may change direction. You can investigate this using a ray box and a

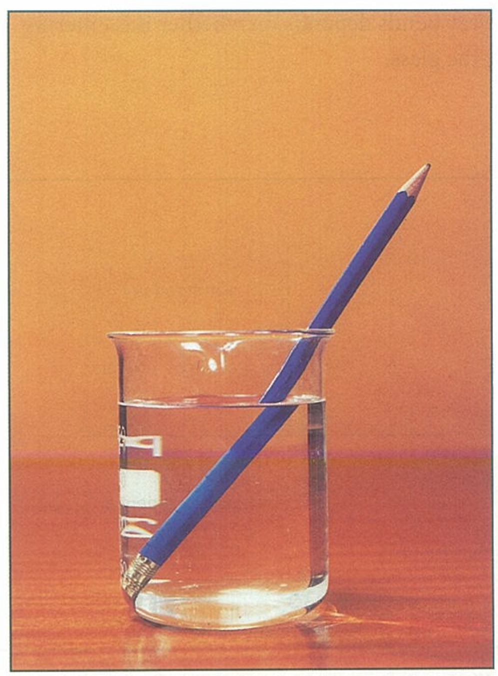


Figure 13.8 The pencil is partly immersed in water. Because of refraction of the light coming from the part of the pencil that is underwater, the pencil appears broken.

block of glass or Perspex, as shown in Figure **13.9**. Note that the ray travels in a straight line when it is in the air outside the block, and when it is inside the block. It only bends at the point where it enters or leaves the block, so it is the **change of material** that causes the bending.

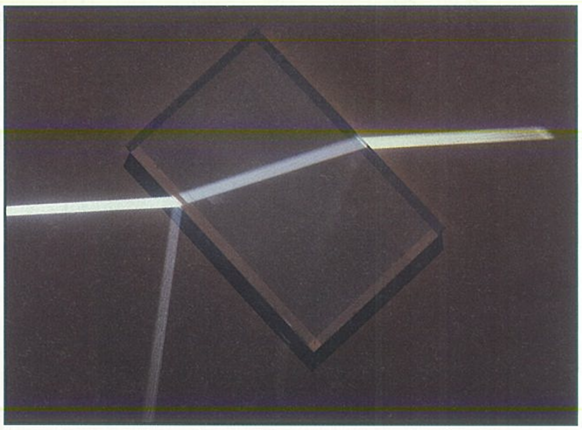


Figure 13.9 Demonstrating the refraction of a ray of light when it passes through a rectangular block of glass or Perspex. The ray bends as it enters the block. As it leaves, it bends back to its original direction.

From Figure **13.9**, you will notice that the direction in which the ray bends depends on whether it is entering or leaving the glass.

- The ray bends towards the normal when entering the glass.
- The ray bends away from the normal when leaving the glass.

One consequence of this is that, when a ray passes through a parallel-sided block of glass or Perspex, it returns to its original direction of travel, although it is shifted to one side. When we look at the world through a window, we are looking through a parallel-sided sheet of glass. We do not see a distorted image because, although the rays of light are shifted slightly as they pass through the glass, they all reach us travelling in their original direction.

Changing direction

Figure **13.10a** shows the terms used for refraction. As with reflection, we define angles relative to the **normal**. The **incident ray** strikes the block. The **angle of incidence** *i* is measured from the ray to the normal. The **refracted ray** travels on at the **angle of refraction** *r*, measured relative to the normal. (Note that, when we discussed reflection, we used *r* for the angle of reflection; here it stands for the angle of refraction.)

A ray of light may strike a surface head-on, so that its angle of incidence is 0°, as shown in Figure **13.10b**. In this case, it does not bend – it simply passes

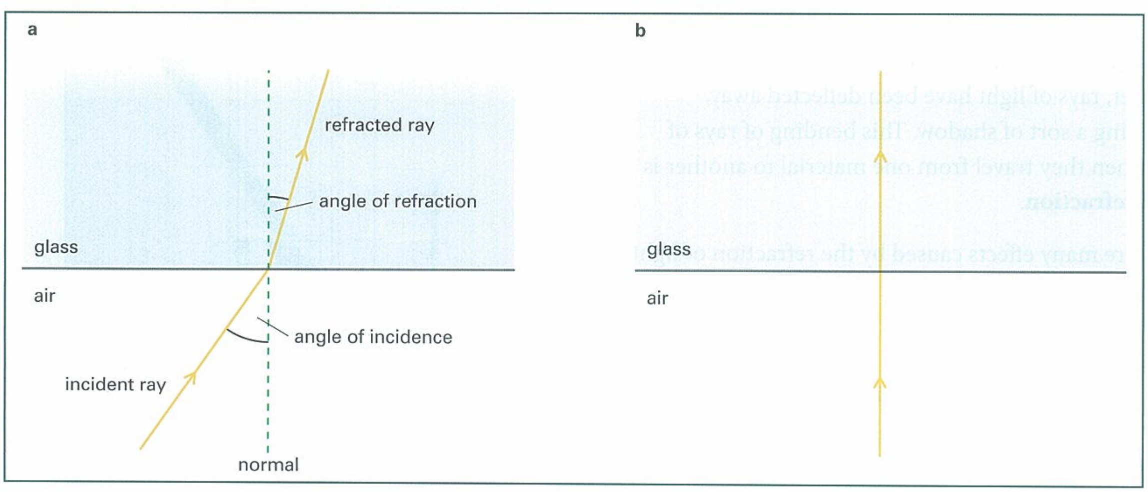


Figure 13.10 **a** Defining the terms used for refraction. The normal is drawn perpendicular to the surface at the point where the ray passes from one material to another. The angles of incidence and refraction are measured relative to the normal. **b** When a ray strikes the glass at 90°, it carries straight on without being deflected.

straight through and carries on in the same direction. Usually we say that refraction is the bending of light when it passes from one material to another. However, we should bear in mind that, when the light is perpendicular to the boundary between the two materials, there is no bending.

Explaining refraction

Why does light change direction when it passes from one material to another? The answer lies in the way its speed changes. Light travels fastest in a vacuum (empty space) and almost as fast in air. It travels more slowly in glass, water and other transparent substances.

One way to explain why a change in speed leads to a change in direction is shown in Figure 13.11. A truck is driving along a road across the desert. The driver is careless, and allows the wheels on the left to drift off the road onto the sand. Here, they spin around, so that the left-hand side of the truck moves more slowly. The right-hand side is still in contact with the road and keeps moving quickly, so that the truck starts to turn to the left.

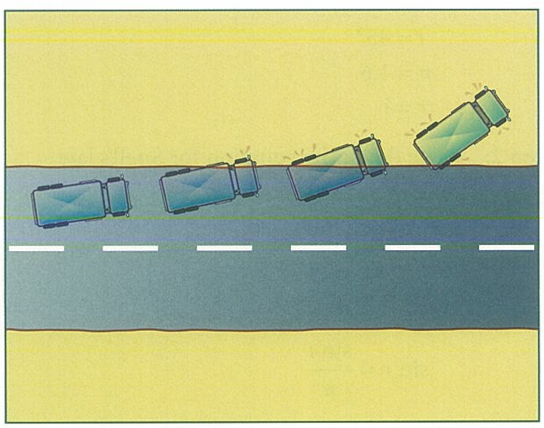


Figure 13.11 To explain why a change in speed explains the bending caused by refraction, we picture a truck whose wheels slip off the road into the sand. The truck veers to the side because it cannot move so quickly through sand.

The boundary between the two materials is the edge of the road. The normal is at right angles to the road. The truck has veered to the left, so its direction has moved towards the normal. Thus we would expect a ray of light to move towards the normal when it enters a material where it moves more slowly. This is indeed what we saw with glass (Figure 13.9). Light travels more slowly in glass than in air, so it bends towards the normal as it enters glass.

Activity 13.2 Investigating refraction

Use a ray box to investigate the refraction of light by a glass or plastic block.

QUESTIONS

5 Draw a diagram to show what we mean by the **angle of incidence** and the **angle of refraction** for a refracted ray of light.

6 A ray of light passes from air into a block of glass. Does it bend **towards** or **away from** the normal?

7 a Draw a diagram to show how a ray of light passes through a parallel-sided block of glass or Perspex.

b What can you say about its final direction of travel?

8 A vertical ray of light strikes the horizontal surface of some water.

a What is its angle of incidence?

b What is its angle of refraction?

9 When a ray of light passes from air to glass, is the angle of refraction greater than, or less than, the angle of incidence?

10 Why do we see a distorted view when we look through a window that is covered with raindrops?

E

Refractive index

Light travels very fast – as far as we know, nothing can travel any faster than light. The **speed of light** as it travels though empty space is exactly:

speed of light = 299 792 458 m/s

This fundamental quantity is given its own symbol, c. For most purposes we can round off the value to:

$c = 300\,000\,000$ m/s or 3×10^8 m/s

When a ray of light passes from air into glass, it slows down and bends towards the normal. The quantity that describes how much light is slowed down is the **refractive index**. If the speed of light is halved when it enters a material, the refractive index is 2, and so on. Hence we can write an equation for the refractive index n of a material:

$$\text{refractive index } n = \frac{\text{speed of light in a vacuum}}{\text{speed of light in the material}}$$

Water has a refractive index $n = 1.33$. This means that light travels 1.33 times as fast in a vacuum, compared to its speed in water.

Table **13.1** shows the speed of light in different materials. The third column shows the factor by which the light is slowed down – in other words, the refractive index of the material.

Material	Speed of light / m/s	$\frac{\text{speed in vacuum}}{\text{speed in material}}$
vacuum	2.998×10^8	1 exactly
air	2.997×10^8	1.0003
water	2.3×10^8	1.33
Perspex	2.0×10^8	1.5
glass	$(1.8–2.0) \times 10^8$	1.5–1.7
diamond	1.25×10^8	2.4

Table 13.1 The speed of light in some transparent materials. (The value for a vacuum is shown, for comparison.) Note that the values are only approximate.

Snell's law

There is a law that relates the size of the angle of refraction r to the angle of incidence i. This is **Snell's law**. It also involves the refractive index, since the greater the refractive index, the more a ray is bent. The law is written in the form of an equation:

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

Worked example **2** shows how to use this equation to find the angle through which a ray is refracted. The equation can also be used to find the value of the refractive index of a material: simply measure values of i and r and substitute them in the equation.

Worked example 2

A ray of light strikes a glass block with an angle of incidence of 45°. The refractive index of the glass is 1.6. What will be the angle of refraction?

The situation is shown in Figure **13.12**.

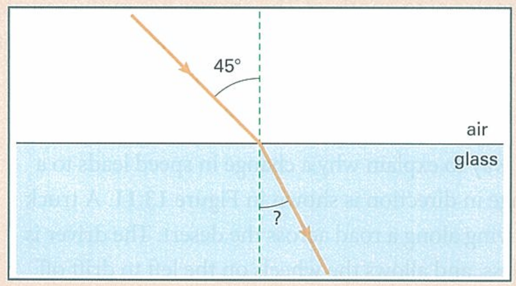


Figure 13.12 See Worked example **2**, on Snell's law.

Step 1: Write down what you know and what you want to know.

$i = 45°$

$n = 1.6$

$r = ?$

Step 2: Write down the equation for Snell's law. Since we want to know r, rearrange it to make $\sin r$ the subject.

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

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

Step 3: Substitute values and calculate $\sin r$.

$$\sin r = \frac{\sin 45°}{1.6} = 0.442$$

Step 4: Use the $\sin^{-1}$ function on your calculator to find r. (This will tell you the angle whose sine is 0.442.)

$$r = \sin^{-1} 0.442 = 26.2°$$

You can see that Snell's law correctly predicts that the ray will be deflected towards the normal.

QUESTIONS

In these questions you will need to use the fact that the speed of light in a vacuum is 3.0×10^8 m/s.

11 Look back at Table **13.1**. What is the value of the refractive index of diamond?

12 Figure **13.13** shows what happens when a ray of light enters blocks of two different materials, A and B.

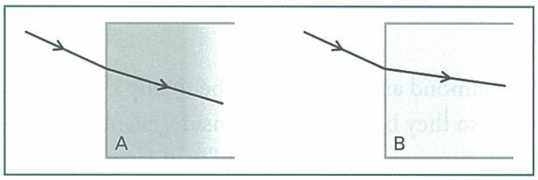


Figure 13.13 For Question **13**.

a In which material does the light travel more slowly, A or B? Explain how you can tell from the diagrams.

b Which material, A or B, has the greater refractive index?

13 Light travels more quickly through water than through glass.

a Which has the greater refractive index, water or glass?

b If a ray passes from glass into water, which way will it bend: towards or away from the normal?

14 The speed of light in a block of glass is found to be 1.9×10^8 m/s. Calculate the refractive index of the glass.

15 A solution of sugar in water is found to have a refractive index of 1.38. Calculate the speed of light in the solution.

16 Perspex is a form of transparent plastic. It has a refractive index $n = 1.5$. A ray of light strikes the flat surface of a Perspex block with an angle of incidence of 40°. What will be the angle of refraction?

13.3 Total internal reflection

If you have carried out a careful investigation of refraction using a ray box and a transparent block, you may have noticed something extra that happens when a ray strikes a block. A reflected ray also appears, in addition to the ray that is refracted. You can see this in Figure **13.9**, but it was ignored in Figure **13.10**. When the ray strikes the block, some of the light passes into the block and is refracted, and some is reflected. When it leaves the block, again some leaves the block and is refracted, and some is reflected. These reflected rays obey the law of reflection:

angle of incidence = angle of reflection

These reflected rays can be a nuisance. If you try to look downwards into a pond or river to see if there are any fish there, your view may be spoilt by light reflected from the surface of the water. You see a reflected image of the sky, or of yourself, rather than what is in the water. On a sunny day, reflected light from windows or water can be a hazard to drivers.

To see how we can make use of reflected rays, you can use the apparatus shown in Figure **13.14**. A ray box shines a ray of light at a semicircular glass block. The ray is always directed at the curved edge of the block, along the radius. This means that it enters the block along the normal, so that it is not bent by refraction. Inside the glass, the ray strikes the midpoint of the flat side, which we call point X.

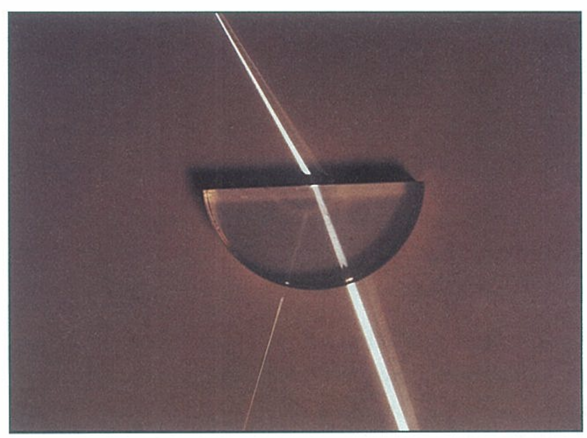


Figure 13.14 Using a ray box to investigate reflection when a ray of light strikes a glass or Perspex block. The ray enters the block without bending, because it is directed along the radius of the block.

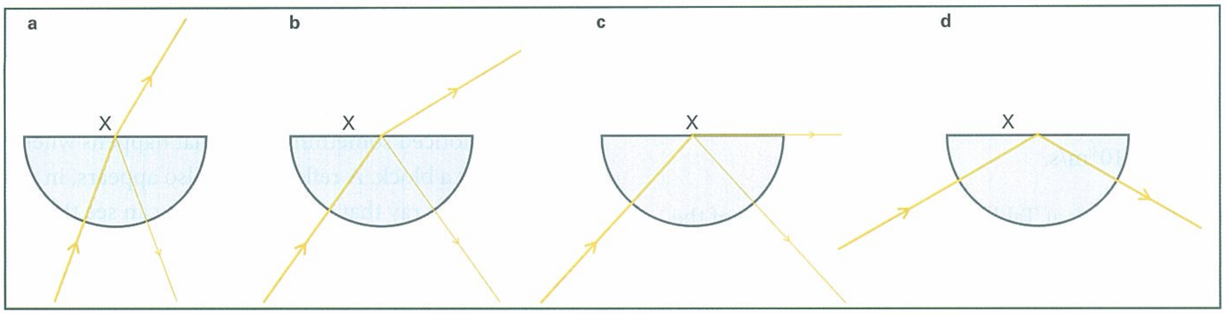


Figure 13.15 How a ray of light is reflected or refracted inside a glass block depends on the angle of incidence. **a, b** For angles less than a certain angle, called the critical angle, some of the light is reflected and some is refracted. **c** At the critical angle, the angle of refraction is 90°. **d** At angles of incidence greater than the critical angle, the light is totally internally reflected – there is no refracted ray.

What happens next? This depends on the angle of incidence of the ray at point X. The various possibilities are listed below and shown above in Figure **13.15**.

a If the angle of incidence is small, most of the light emerges from the block. There is a faint reflected ray inside the glass block. The refracted ray bends away from the normal.

b If the angle of incidence is increased, more light is reflected inside the block. The refracted ray bends even further away from the normal.

c Eventually, at one particular angle, the refracted ray emerges along and parallel to the surface of the block. Most of the light is reflected inside the block.

d Now, at an even greater angle of incidence, all of the light is reflected inside the block. No refracted ray emerges from point X.

We have been looking at how light is reflected inside a glass block. We have seen that, if the angle of incidence is greater than a particular value, known as the **critical angle**, the light is entirely reflected inside the glass. This phenomenon is known as **total internal reflection** (**TIR**):

- **total**, because 100% of the light is reflected
- **internal**, because it happens inside the glass
- **reflection**, because the ray is entirely reflected.

For total internal reflection to happen, the angle of incidence of the ray must be greater than the critical angle. The critical angle depends on the material being used. For glass, it is about 42° (though this depends on the composition of the glass). For water, the critical angle is greater, about 49°. For diamond, the critical angle is small, about 25°. Hence rays of light that enter a diamond are very likely to be totally internally reflected, so they bounce around inside, eventually emerging from one of the diamond's cut faces. That explains why diamonds are such sparkly jewels.

Activity 13.3 Total internal reflection

Use a ray box and a semicircular block to observe total internal reflection.

QUESTIONS

17 Explain the meaning of the words **total** and **internal** in the expression 'total internal reflection'.

18 The critical angle for water is 49°. If a ray of light strikes the upper surface of a pond at an angle of incidence of 45°, will it be totally internally reflected? Explain your answer.

E

Optical fibres

A revolution in telecommunications has been made possible by the invention of fibre optics. Telephone messages and other electronic signals such as Internet computer messages or cable TV signals are passed along fine glass fibres in the form of flashing laser light – a digital signal. Figure **13.16a** shows just how fine these fibres can be. Each of these fibres is capable of carrying thousands of telephone calls simultaneously.

E

Inside a fibre, light travels along by total internal reflection (see Figure **13.16b**). It bounces along inside the fibre because, each time it strikes the inside of the fibre, its angle of incidence is greater than the critical angle. Thus no light is lost as it is reflected. The fibre can follow a curved path and the light bounces along inside it, following the curve. For signals to travel over long distances, the glass used must be of a very high purity, so that it does not absorb the light.

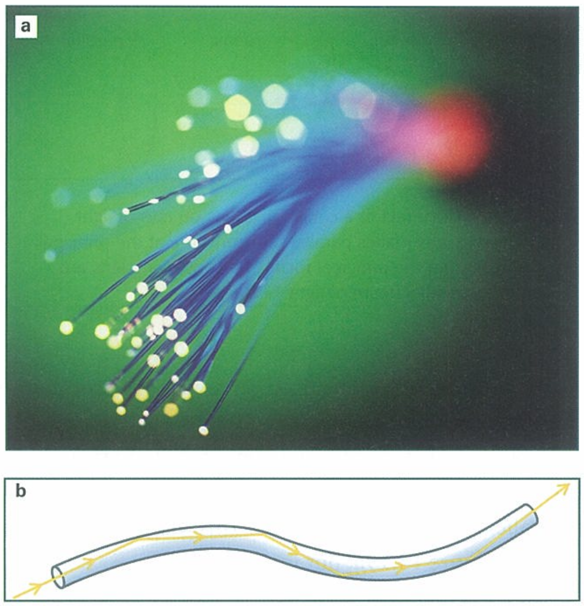


Figure 13.16 The use of fibre optics has greatly increased the capacity and speed of the world's telecommunications networks. Without this technology, cable television and the Internet would not be possible. **a** Each of these very fine fibres of high-purity glass can carry many telephone messages simultaneously. **b** Light travels along a fibre by total internal reflection. Because the reflection is total, and the glass is so pure, the light can travel many kilometres along a single fibre.

Optical fibres are also used in medicine. An endoscope is a device that can be used by doctors to see inside a patient's body – for example, to see inside the stomach. One bundle of fibres carries light down into the body (it is dark in there), while another bundle carries an image back up to the user. The endoscope may also have a small probe or cutting tool built in, so that minor operations can be performed without the need for major surgery.

E

QUESTIONS

19 Sketch a diagram to show how a ray of light can travel along a curved glass fibre. Indicate the points where total internal reflection occurs.

20 Why must high-purity glass be used for optical fibres used in telecommunications?

13.4 Lenses

We are all familiar with lenses in everyday life – in spectacles and cameras, for example. The development of high-quality lenses has had a profound effect on science. In 1609, using the newly invented telescope, Galileo discovered the moons of Jupiter and triggered a revolution in astronomy. In those days, scientists had to grind their own lenses starting from blocks of glass, and Galileo's skill at this was a major factor in his discovery.

Later in the 17th century, a Dutch merchant called Anton van Leeuwenhoek managed to make microscope lenses that gave a magnification of 200 times. He used these to look at the natural world around him. He was amazed to find a wealth of tiny microorganisms, including bacteria, that were invisible to the naked eye (Figure 13.17). This provided the clue to how infectious diseases might be spread. Previously people thought infections were carried by smells or by mysterious vapours. A revolution in medicine had begun.

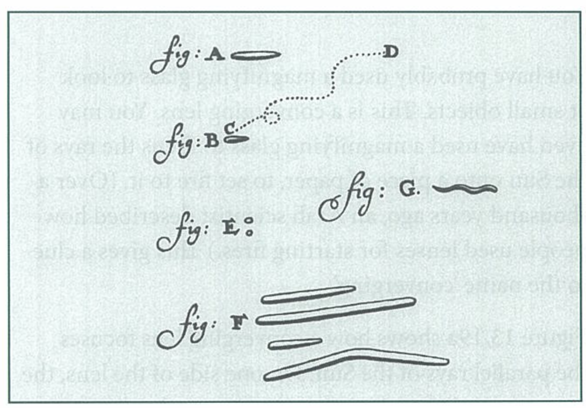


Figure 13.17 Bacteria cannot be seen with the naked eye. These drawings were made by Anton van Leeuwenhoek in 1683 using an early microscope. They show bacteria he obtained by scraping material from between his teeth.

Converging and diverging lenses

Lenses can be divided into two types, according to their shape (Figure **13.18**):

- **converging lenses** are fatter in the middle than at the edges
- **diverging lenses** are thinner in the middle than at the edges.

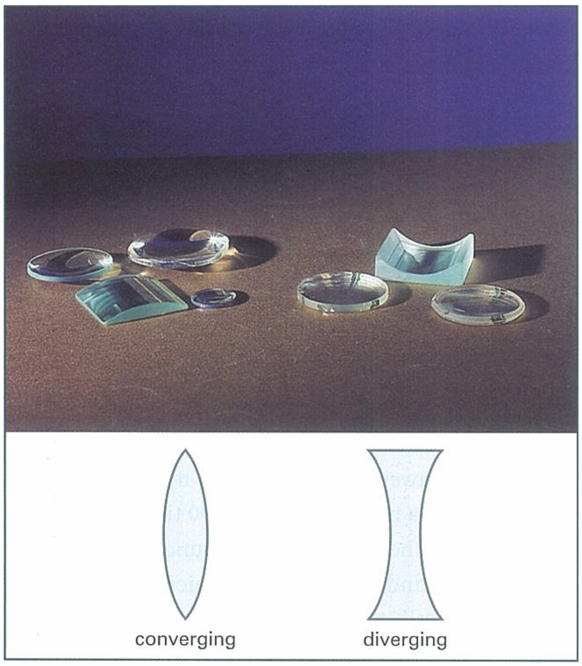


Figure 13.18 The lenses on the left are converging lenses, which are fattest at the middle. On the right are diverging lenses, which are thinnest at the middle. They are given these names because of their effect on parallel rays of light. Usually we simply draw the cross-section of the lens, to indicate which type we are considering.

You have probably used a magnifying glass to look at small objects. This is a converging lens. You may even have used a magnifying glass to focus the rays of the Sun onto a piece of paper, to set fire to it. (Over a thousand years ago, an Arab scientist described how people used lenses for starting fires.) This gives a clue to the name 'converging'.

Figure **13.19a** shows how a converging lens focuses the parallel rays of the Sun. On one side of the lens, the rays are parallel to the **axis** of the lens. After they pass through the lens, they converge on a single point, the **principal focus** or **focal point**. After they have passed through the principal focus, they spread out again.

So a converging lens is so-called because it makes parallel rays of light converge. The principal focus is the point where the rays are concentrated together, and where a piece of paper needs to be placed if it is to be burned. The distance from the centre of the lens to the principal focus is called the **focal length** of the lens. The fatter the lens, the closer the principal focus is to the lens. A fat lens has a shorter focal length than a thin lens.

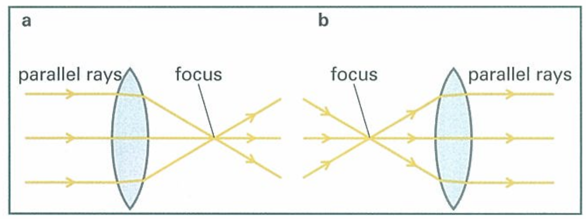


Figure 13.19 The effect of a converging lens on rays of light. **a** A converging lens makes parallel rays converge at the principal focus. **b** Rays from the principal focus of a converging lens are turned into a parallel beam of light.

A converging lens can be used 'in reverse' to produce a beam of parallel rays. A source of light, such as a small light bulb, is placed at the principal focus. As they pass through the lens, the rays are bent so that they become a parallel beam (Figure **13.19b**). This diagram is the same as Figure **13.19a**, but in reverse.

Lenses work by refracting light. When a ray strikes the surface of the lens, it is refracted towards the normal. When it leaves the glass of the lens, it bends away from the normal. The clever thing about the shape of a converging lens is that it bends all rays just enough for them to meet at the principal focus.

Forming a real image

When the Sun's rays are focused onto a piece of paper, a tiny image of the Sun is created. It is easier to see how a converging lens makes an image by focusing an image of a light bulb or a distant window onto a piece of white paper. The paper acts as a screen to catch the image. Figure **13.20** shows an experiment in which an image of a light bulb (the object) is formed by a converging lens.

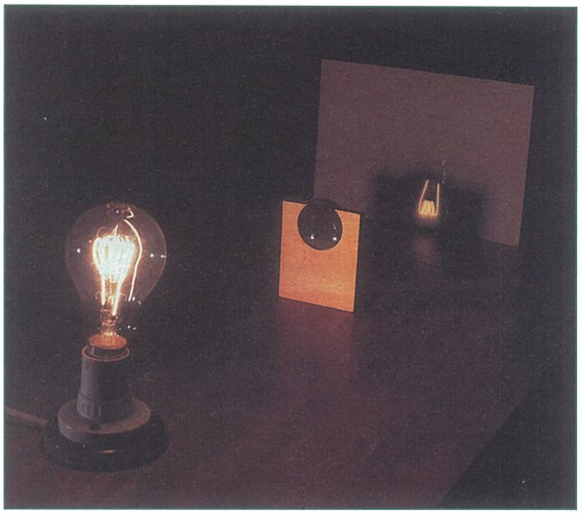


Figure 13.20 Forming a real image of a light bulb using a converging lens. The image is upside down on the screen at the back right.

There are some things to note. In this experiment, the image is:

- **inverted** (upside down)
- **reduced** (smaller than the object)
- **nearer to** the lens than the object
- **real.**

We say that the image is real, because light really does fall on the screen to make the image. If light only appeared to be coming from the image, we would say that the image was virtual. The size of the image depends on how fat or thin the lens is.

We can explain the formation of this real image using a **ray diagram**. The steps needed to draw an accurate ray diagram are listed below and shown in Figure **13.21**. (It helps to work on squared paper or graph paper.)

1. Draw the lens – a simple outline shape will do – with a horizontal axis through the middle of it.
2. Mark the positions of the principal focuses F on either side, at equal distances from the lens. Mark the position of the object O, an arrow standing on the axis.
3. Draw ray 1, a straight line from the top of the arrow and passing undeflected through the middle of the lens.
4. Draw ray 2, from the top of the arrow parallel to the axis. As it passes through the lens, it is deflected down through the principal focus. Look for the point where the two rays cross. This is the position of the top of the image I.

With an accurately drawn ray diagram, you can see that the image is inverted, reduced and real. Note that we do not bother to draw ray 2 bending twice, at the two surfaces of the lens. It is easier to show it bending once, in the middle of the lens, though this is not a correct representation of what really happens.

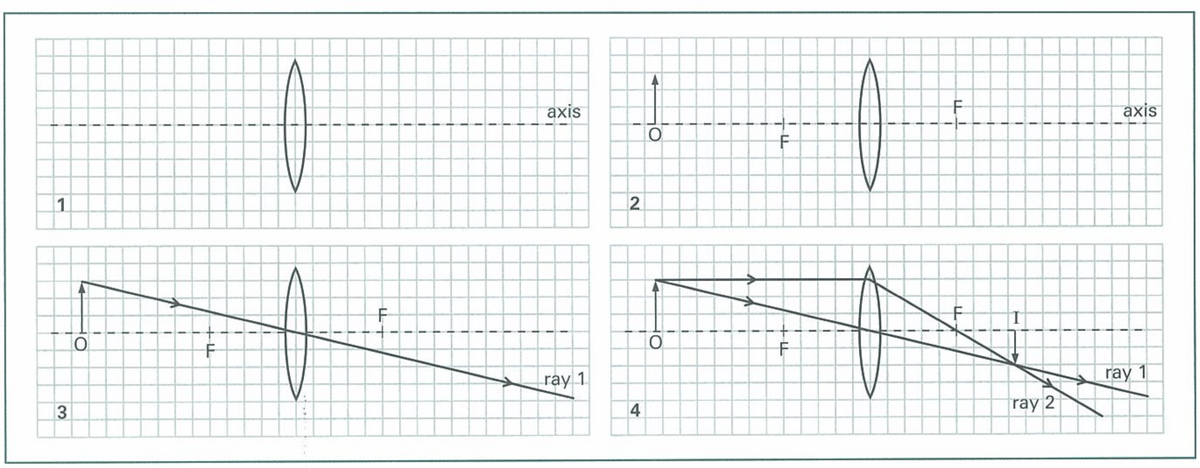


Figure 13.21 A ray diagram can be used to show how an image is formed by a converging lens. The steps are given in the text.

So, to construct a ray diagram like this, draw two rays starting from the top of the object:

- ray 1, undeflected through the centre of the lens
- ray 2, parallel to the axis and then deflected through the principal focus.

Activity 13.4 Investigating converging lenses

Measure the focal length of a lens and draw an accurate ray diagram.

QUESTIONS

21 Draw a diagram to show the difference in shape between a converging lens and a diverging lens.

22 Draw a ray diagram to show how a converging lens focuses parallel rays of light.

23 How would you alter your diagram in question 22 to show how a converging lens can produce a beam of parallel rays of light?

24 What is meant by the principal focus (or focal point) of a converging lens?

25 What is the difference between a real image and a virtual image?

26 Look at the ray diagram shown in Figure 13.21. How does it show that the image formed by a converging lens is inverted?

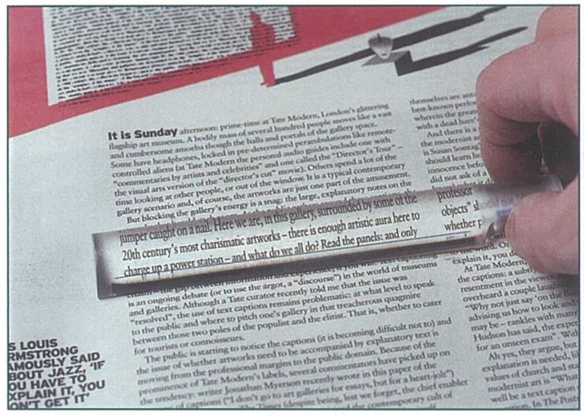


Figure 13.22 This long converging lens is designed to help people to read. It produces a magnified image of a line of print. The user simply slides it down the page.

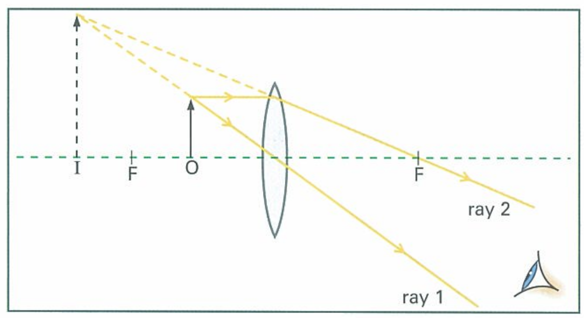


Figure 13.23 A ray diagram to show how a magnifying glass works. The object is between the lens and the focus. The image produced is virtual. To find its position, the rays have to be extended back (dashed lines) to the point where they cross.

Magnifying glasses

A magnifying glass is a converging lens. You hold it close to a small object and peer through it to see a magnified image. Figure 13.22 shows how a magnifying glass can help to magnify print for someone with poor eyesight.

The object viewed by a magnifying glass is closer to the lens than the principal focus. This allows us to draw the ray diagram shown in Figure 13.23. In the same way as in Figure 13.21, we draw two rays from the top of the object O, rays 1 and 2:

- ray 1 is undeflected, as it passes through the centre of the lens
- ray 2 starts off parallel to the axis and is deflected by the lens so that it passes through the principal focus.

Rays 1 and 2 do not cross over each other. They are diverging (spreading apart) after they have passed through the lens. However, by extending the rays backwards, as shown by the dashed lines, we can see that they both appear to be coming from a point behind the object. This is the position of the image I. We draw dashed lines because light does not actually travel along these parts of the rays. This tells us that the image formed is virtual. We cannot catch the image on a screen, because there is no light there.

From the ray diagram (Figure **13.23**), we can see the following features of the image produced by a magnifying glass. The image is:

- **upright** (the right way up, not inverted)
- **magnified** (bigger than the object)
- **further from** the lens than the object
- **virtual** (not real).

So, if you read a page of a book using a magnifying glass, the image you are looking at is behind the page that you are reading.

QUESTIONS

27 Look at Figure 13.23. How can you tell from the diagram that the object formed by the magnifying glass is a virtual image?

28 **a** A converging lens has focal length 5 cm. An object is placed 3 cm from the centre of the lens, on the principal axis. Draw an accurate ray diagram to represent this.

b Use your diagram to determine the distance of the virtual image formed from the lens.

Summary

The law of reflection:

angle of incidence = angle of reflection

$$i = r$$

Angles are measured relative to the normal to the surface.

The image formed by a plane mirror is the same size as the object, as far behind the mirror as the object is in front of it, left–right reversed, and virtual.

A light ray changes direction when it meets the boundary between two different materials (unless it meets the boundary at right angles). This bending is known as refraction.

Refractive index:

$$n = \frac{\text{speed of light in a vacuum}}{\text{speed of light in the material}}$$

Snell's law:

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

A ray is totally internally reflected when it strikes a boundary at an angle greater than the critical angle.

Total internal reflection is used in optical fibres for telecommunications.

A converging lens makes rays of light parallel to the axis converge at the principal focus.

A magnifying glass is a converging lens, with the object closer than the principal focus. It produces a magnified, virtual image.

End-of-chapter questions

13.1 The law of reflection says that: 'When a ray of light is reflected at a surface, the **angle of incidence** is equal to the **angle of reflection**.'

Draw a diagram to indicate how a ray of light is reflected by a flat mirror, and mark the **two** angles mentioned in the law. [4]

13.2 Windows usually have a flat sheet of glass, so that we can see clearly through them. Frosted glass has an irregular surface, so that we do not see a clear image through it.

a Draw a ray diagram to show how a ray of light passes through a parallel-sided glass block if it hits the glass at 90° (that is, perpendicular to the glass). [2]

b Draw a ray diagram to show how a ray of light passes through a parallel-sided glass block if it hits the glass at an angle other than 90° (that is, obliquely to the glass). [3]

c Explain why we can see clearly through a flat sheet of glass, even though light is refracted as it passes through. [1]

13.3 Figure 13.24 shows two blocks of a material whose critical angle is 40°. In block A, the ray strikes the inner surface with an angle of incidence of 30°. In block B, the ray's angle of incidence is 50°.

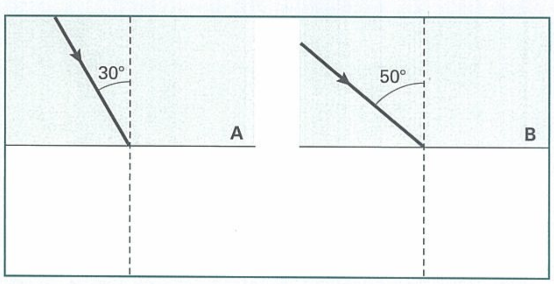


Figure 13.24 For Question **13.3**.

a Copy and complete each diagram to show what happens when the ray strikes the surface. [4]

b Use the diagrams to explain what is meant by **total internal reflection**. [3]

E

13.4 A small lamp is placed at a distance of 4 cm from a plane mirror.

a Draw an accurate ray diagram to show where the image of the lamp in the mirror is formed. [4]

b Explain how you have used the law of reflection in drawing your diagram. [2]

c What does it means to say that the image of the lamp is a **virtual** image? [2]

13.5 Figure 13.25 shows an incomplete ray diagram, which represents the following situation.

A converging lens has a focal length of 4 cm. Its principal focuses are marked F. An object O is placed at a distance of 10 cm from the lens. Ray 1 passes through the centre of the lens. Ray 2 is parallel to the axis of the lens.

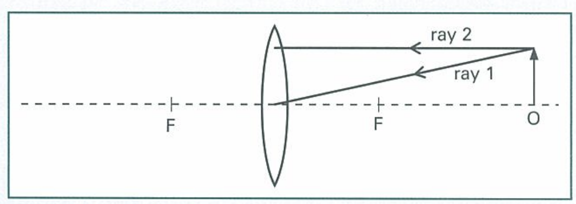


Figure 13.25 For Question **13.5**.

a Copy and complete the ray diagram, on squared paper or graph paper, to find the position of the image formed by the lens. [4]

b Explain whether the diagram shows that the image is real or virtual. [2]

c Explain whether the diagram shows that the image is magnified or diminished (smaller than the object). [2]

d Explain whether the diagram shows that the image is upright or inverted. [1]

14 Properties of waves

- **Core** Describing transverse and longitudinal waves
- **Core** Explaining speed, amplitude, frequency and wavelength
- E **Extension** Calculating wave speed
- **Core** Describing reflection, refraction and diffraction of waves
- E **Extension** Explaining reflection, refraction and diffraction of waves

All at sea!

It cannot be much fun to be adrift in a small boat on a rough sea, being tossed up and down. For some birds, this is a regular experience. Many seabirds spend the whole winter on the open sea, at a time when the sea is at its roughest (Figure **14.1**). The waves may be 20 m high, enough to dwarf a two-storey house, but the birds feel safer here than they would on the cliffs, where they nest in the spring. Guillemots, for example, cluster together in 'rafts', carried up and down by the waves. It is this up-and-down motion that is liable to make *you* feel sea-sick if you are on board a ship in stormy weather.

When waves reach the beach, they start to break. The bottom of the wave drags on the seabed and slows down. The top of the wave carries on and gradually tips over to form a breaker. Breaking waves like this are the natural home of the surfer (Figure **14.2**).

Physicists talk about light waves, sound waves, electromagnetic waves, and so on. The idea of a wave is a very useful model in physics. It is not obvious that light and sound are similar to waves on the sea. In this chapter we will see how water waves *can* act as a good model for both light and sound. The water waves that we will be thinking of are more like those on the open sea than breakers on a beach.

Figure 14.1 Many seabirds such as guillemots spend the whole of the winter on the open ocean. They gather together in 'rafts' and spend their days and nights riding up and down on the waves.

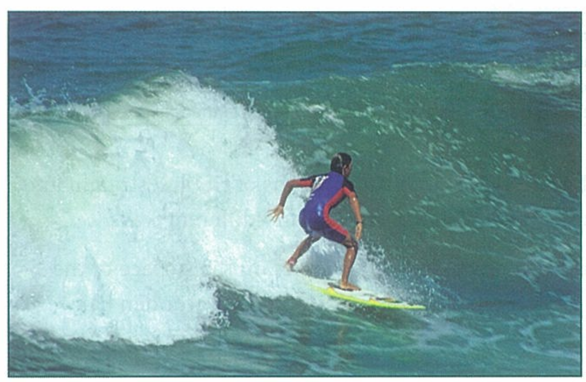


Figure 14.2 Surfers look out for waves that are beginning to break. The top of the wave is tipping over, and this provides the push they need to start them moving along with the crest of the wave.

14.1 Describing waves

Physicists use waves as a **model** to explain the behaviour of light, sound and other phenomena. Waves are what we see on the sea or a lake, but physicists have a more specialised idea of waves. We can begin to understand this model in the laboratory using a **ripple tank** (Figure 14.3). A ripple tank is a shallow glass-bottomed tank containing a small amount of water. A light shining downwards through the water casts a shadow of the **ripples** on the floor below, showing up the pattern that they make.

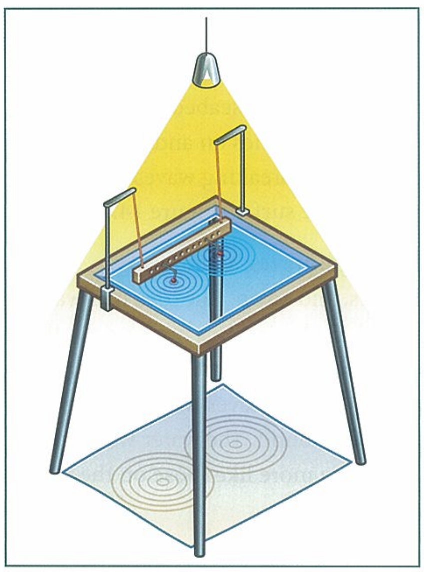
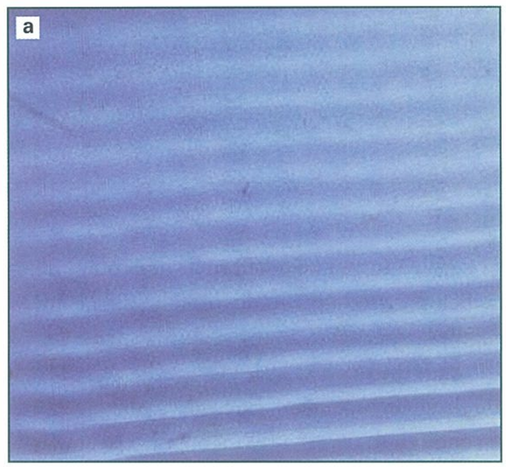


Figure 14.3 The ripples on the surface of the water in this ripple tank are produced by the spherical dippers attached to the bar, which vibrates up and down. The pattern of the ripples is seen easily by shining a light downwards through the water. This casts a shadow of the ripples on the floor beneath the tank.

Figure **14.4** shows two patterns of ripples, straight and circular, which are produced in different ways.

a One way of making ripples on the surface of the water in a ripple tank is to have a wooden bar that just touches the surface of the water. The bar vibrates up and down at a steady rate. This sends equally spaced straight ripples across the surface of the water.

b A spherical dipper can produce a different pattern of ripples. The dipper just touches the surface of the water. As it vibrates up and down, equally spaced circular ripples spread out across the surface of the water.



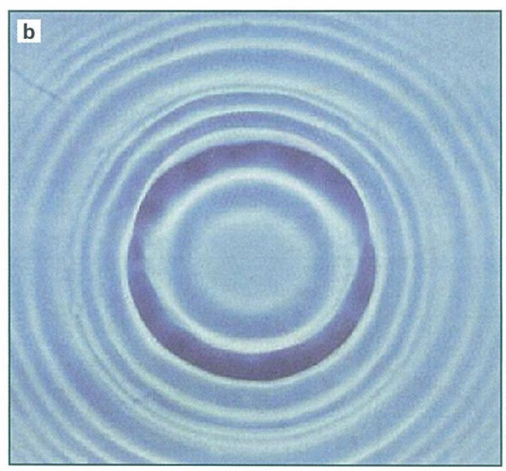


Figure 14.4 Two patterns of ripples on water. **a** Straight ripples are a model for a broad beam of light. **b** Circular ripples are a model for light spreading out from a lamp.

In each case, the ripples are produced by something vibrating up and down **vertically**, but the ripples move out **horizontally**. The vibrating bar or dipper pushes water molecules up and down. Each molecule drags its neighbours up and down. These then start their neighbours moving, and so on. This may make you think of the seabirds we discussed, floating on the rough sea. The waves go past the birds. The birds simply float up and down on the surface of the water.

How can these patterns of ripples be a model for the behaviour of light? The straight ripples are like a beam of light, perhaps coming from the Sun. The ripples move straight across the surface of the water, just as light from the Sun travels in straight lines. The circular ripples spreading out from a vibrating dipper are like light spreading out from a lamp. (The dipper is the lamp.) Throughout this chapter, we will gradually build up the idea of how ripples on the surface of water can be a model for the behaviour of light, other electromagnetic waves and sound.

Wavelength and amplitude

A more familiar way of representing a wave is as a wavy line, as shown in Figure **14.5**. We have already used this idea for sound waves (in Chapter **12**) and we will do so again for electromagnetic waves (in Chapter **15**). This wavy line is like a downward slice though the ripples in the ripple tank. It shows up the succession of **crests** and **troughs** of which the ripples are made.

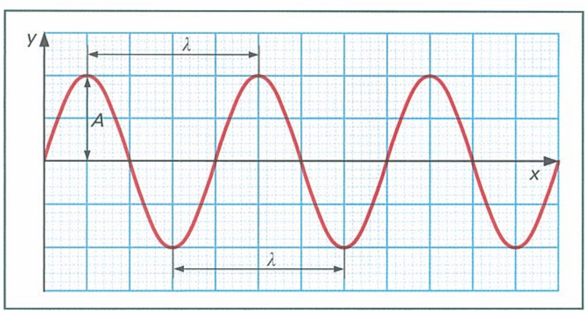


Figure 14.5 Representing a wave as a smoothly varying wavy line. This shape is known as a sine graph. If you have a graphics calculator, you can use it to display a graph of $y = \sin x$, which will look like this graph.

The graph in Figure **14.5** shows a wave travelling from left to right. The horizontal axis (x-axis) shows the distance x travelled horizontally by the wave. The vertical axis (y-axis) shows how far (distance y) the surface of the water has been displaced from its normal level. Hence we can think of the x-axis as the level of the surface of the water when it is undisturbed. The line of the graph shows how far the surface of the water has been displaced from its undisturbed level.

From the representation of the wave in Figure **14.5**, we can define two quantities for waves in general:

- The **wavelength** λ of a wave is the distance from one crest of the wave to the next (or from one trough to the next). Since the wavelength is a distance, it is measured in metres, m. Its symbol is λ, the Greek letter 'lambda'.
- The **amplitude** A of a wave is the maximum distance that the surface of the water is displaced from its undisturbed level – in other words, the height of a crest. For ripples on the surface of water, the amplitude is a distance, measured in metres, m. Its symbol is A.

Note that the amplitude is measured from the undisturbed level up to the crest. It is not measured from trough to crest. For ripples in a ripple tank, the wavelength might be a few millimetres and the amplitude a millimetre or two. Waves on the open sea are much bigger, with wavelengths of tens of metres, and amplitudes varying from a few centimetres up to several metres.

Frequency and period

As the bar in the ripple tank vibrates, it sends out ripples. Each up-and-down movement sends out a single ripple. The more times the bar vibrates each second, the more ripples it sends out. This is shown in the graph of Figure **14.6**. Take care! This looks very similar to the previous wave graph (Figure **14.5**), but here the horizontal axis shows time t, not distance x. This graph shows how the surface of the water at a particular point moves up and down as time passes.

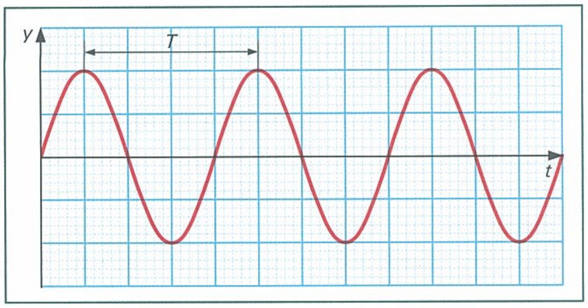


Figure 14.6 A graph to show the period of a wave. Notice that this graph has time t on its horizontal axis.

From the representation of the wave in Figure **14.6**, we can define two quantities for waves in general:

- The **frequency** f of a wave is the number of waves sent out each second. Frequency is measured in hertz, Hz. One hertz (1 Hz) is one complete wave or ripple per second.
- The **period** T of a wave is the time taken for one complete wave to pass a point. The period is measured in seconds, s.

We have already discussed the frequency and period of a sound wave in Chapter **12**. It is important always to check whether a wave graph has time t or distance x on its horizontal axis.

The frequency of a wave is the number of waves sent out or passing a point per second. Its period is the number of seconds for each wave to pass a point. Hence frequency f and period T are obviously related to each other. Waves with a short period have a high frequency.

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

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

Waves on the sea might have a period of 10 s. Their frequency is therefore about 0.1 Hz. A sound wave might have a frequency of 1 000 Hz. Its period is therefore 1/1 000 s, which means that a wave arrives every 1 ms (one millisecond).

Wave speed

The **wave speed** is the rate at which the crest of a wave travels along. For example, it could be the speed of the crest of a ripple travelling over the surface of the water. Speed is measured in metres per second (m/s).

Waves can have very different speeds. Ripples in a ripple tank travel a few centimetres per second. Sound waves travel at 330 m/s through air. Light waves travel at 300 000 000 m/s through air.

Transverse and longitudinal waves

Ripples in a ripple tank are one way of looking at the behaviour of waves. You can demonstrate waves in other ways. As shown in Figure **14.7a**, a stretched 'slinky' spring can show waves. Fix one end of the spring and move the other end from side to side. You will see that a wave travels along the spring. (You may also notice it reflecting from the fixed end of the spring.) You can demonstrate the same sort of wave using a stretched rope or piece of elastic.

A second type of wave can also be demonstrated with a stretched 'slinky' spring. Instead of moving the free

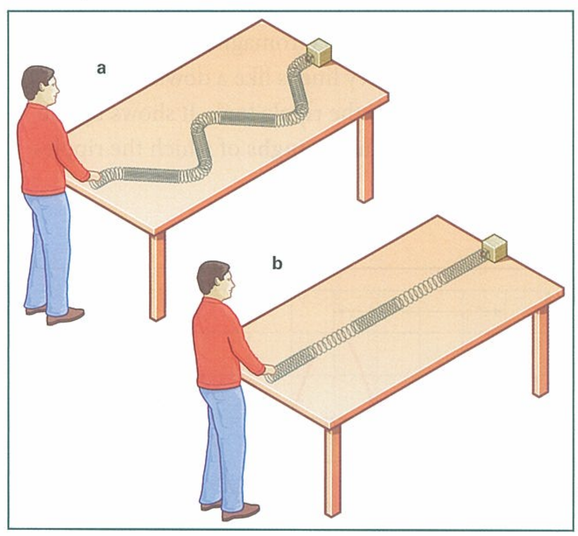


Figure 14.7 Waves along a stretched spring. **a** A transverse wave, made by moving the free end from side to side. **b** A longitudinal wave, made by pushing the free end back and forth, along the length of the spring.

end from side to side, move it back and forth (Figure **14.7b**). A series of compressions travels along the spring, regions in which the segments of the spring are compressed together. In between are rarefactions, regions where the segments of the spring are further apart. This type of wave cannot be demonstrated on a stretched rope.

These demonstrations in Figure **14.7** show two different types of wave:

- **transverse waves**, in which the particles carrying the wave move from side to side, at right angles to the direction in which the wave is moving
- **longitudinal waves**, in which the particles carrying the wave move back and forth, along the direction in which the wave is moving.

A ripple on the surface of water is an example of a transverse wave. The particles of the water move up and down as the wave travels horizontally.

A sound wave is an example of a longitudinal wave. As a sound travels through air, the air molecules move back and forth as the wave travels. Compare Figure **14.7b** with Figure **12.11** on page **130** to see the similarity. Table **14.1** lists examples of transverse and longitudinal waves.

Transverse waves	Longitudinal waves
ripples on water	sound
light and all other electromagnetic waves	

Table 14.1 Transverse and longitudinal waves.

Activity 14.1 Observing waves

Carry out some experiments to observe transverse and longitudinal waves.

QUESTIONS

1 Describe the motion of molecules of water as a ripple moves across the surface of water in a ripple tank.
2 The two graphs shown in Figures **14.5** and **14.6** are very similar to each other. What is the important difference between them?
3 Draw a diagram to show what is meant by the amplitude of a wave.
4 How could you find the wavelength of the ripples shown in Figure **14.4**?
5 If 10 waves occupy 15 cm, what is their wavelength?
6 **a** If 100 sound waves reach your ear each second, what is their frequency?
  b What is their period?
7 Are sound waves transverse or longitudinal?

E

14.2 Speed, frequency and wavelength

How fast do waves travel across the surface of the sea? If you stand on the end of a pier, you may be able to answer this question. Suppose that the pier is 60 m long, and that you notice that exactly five waves fit into this length (Figure **14.8**). From this information, you can deduce that their wavelength is:

$$\text{wavelength} = \frac{60\,\text{m}}{5} = 12\,\text{m}$$

Now you time the waves arriving. The interval between crests as they pass the end of the pier is 4 s. How fast

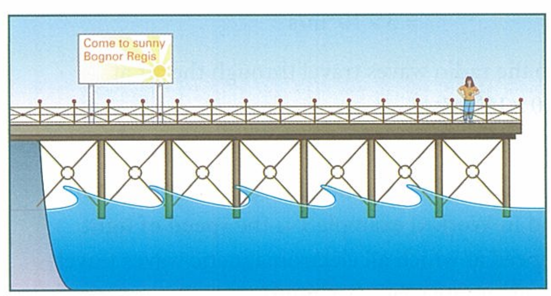


Figure 14.8 By timing waves and measuring their wavelength, you can find the speed of waves.

E are the waves moving? One wavelength (12 m) passes in 4 s. So the speed of the waves is:

$$\text{speed} = \frac{12\,\text{m}}{4\,\text{s}} = 3\,\text{m/s}$$

Hence the speed v, frequency f and wavelength λ of a wave are connected. We can write the connection in the form of an equation:

$$\text{speed (m/s)} = \text{frequency (Hz)} \times \text{wavelength (m)}$$
$$v = f\lambda$$

Another way to think of this is to say that the speed is the number of waves passing per second times the length of each wave. If 100 waves pass each second ($f = 100\,\text{Hz}$), and each is 4 m long ($\lambda = 4\,\text{m}$), then 400 m of waves pass each second. The speed of the waves is 400 m/s.

Worked example 1

An FM radio station broadcasts signals of wavelength 3.0 m and frequency 100 MHz. What is their speed?

Step 1: Write down what you know, and what you want to know.

$f = 100\,\text{MHz} = 100\,000\,000\,\text{Hz} = 10^8\,\text{Hz}$
$\lambda = 3.0\,\text{m}$
$v = ?$

Step 2: Write down the equation for wave speed. Substitute values and calculate the answer.

$v = f\lambda$
$v = 10^8\,\text{Hz} \times 3.0\,\text{m}$
$= 3 \times 10^8\,\text{m/s}$

So the radio waves travel through the air at $3.0 \times 10^8\,\text{m/s}$.

You should recognise that the value of $3.0 \times 10^8\,\text{m/s}$ found in Worked example **1** is the **speed of light**, the speed at which all electromagnetic waves travel through empty space (vacuum).

E

Worked example 2

A pianist plays the note middle C, whose frequency is 264 Hz. What is the wavelength of the sound waves produced? (Speed of sound in air = 330 m/s.)

Step 1: Write down what you know, and what you want to know.

$f = 264\,\text{Hz}$
$\lambda = ?$
$v = 330\,\text{m/s}$

Step 2: Write down the equation for wave speed. Rearrange it to make wavelength λ the subject.

$v = f\lambda$

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

Step 3: Substitute values and calculate the answer.

$\lambda = \frac{330\,\text{m/s}}{264\,\text{Hz}} = 1.25\,\text{m}$

So the wavelength of the note middle C in air is 1.25 m.

Changing material, changing speed

When waves travel from one material into another, they usually change speed. Light travels more slowly in glass than in air. Sound travels faster in steel than in air. When this happens, the frequency of the waves remains unchanged. As a consequence, their wavelength must change. This is illustrated in Figure **14.9**, which shows light waves travelling quickly through air. They reach some glass and slow down, and their wavelength decreases. When they leave the glass again, they speed up, and their wavelength increases again.

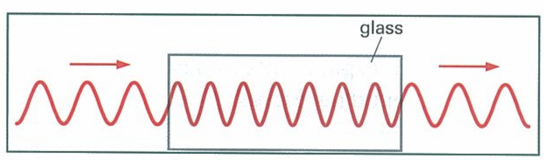


Figure 14.9 Waves change their wavelength when their speed changes. Their frequency remains constant. Here, light waves slow down when they enter glass and speed up when they return to the air.

E

QUESTIONS

8 Write down an equation relating speed, frequency and wavelength of a wave. Indicate the SI units of each quantity.

9 If 10 waves pass a point each second and their wavelength is 30 m, what is their speed?

10 All sound waves travel with the same speed in air. Which has the higher frequency, a sound wave of wavelength 2 m or one with wavelength 1 m?

11 Which have the longer wavelength, radio waves of frequency 90 MHz or 100 MHz?

12 Light slows down when it enters water from air.
  a What happens to its speed?
  b What happens to its wavelength?
  c What happens to its frequency?

14.3 Reflection and refraction of waves

If we look at ripples on the surface of water in a ripple tank, we can begin to see why physicists say that light behaves as if it were a form of wave. The ripples are much more regular and uniform than waves on the sea, so they are a good **model** system to look at.

Reflection of ripples

Figure **14.10** shows what happens when a flat metal barrier is placed in the ripple tank. The photograph in Figure **14.10a** shows the pattern of the ripples observed, and Figure **14.10b** shows how the ripples are produced. Straight ripples ('plane waves') are reflected when they strike the flat surface of the barrier. The metal barrier acts like a mirror, and the ripples bounce off it. This shows an important thing about how waves behave. They pass through each other when they overlap.

In Figure **14.10c**, you can see the same pattern, this time as a drawing. This is an 'aerial view' of the ripples. The blue lines represent the tops of the ripples. These lines are known as **wavefronts**. The separation of the wavefronts is equal to the wavelength of the ripples. Figure **14.10c** also shows lines (the red arrows) to indicate how the direction of travel of the ripples changes. This diagram should remind you of the ray diagram for the law of reflection of light (Figure **13.5** on page 135). The ripples are reflected by the metal barrier so that the angle of incidence equals the angle of reflection.

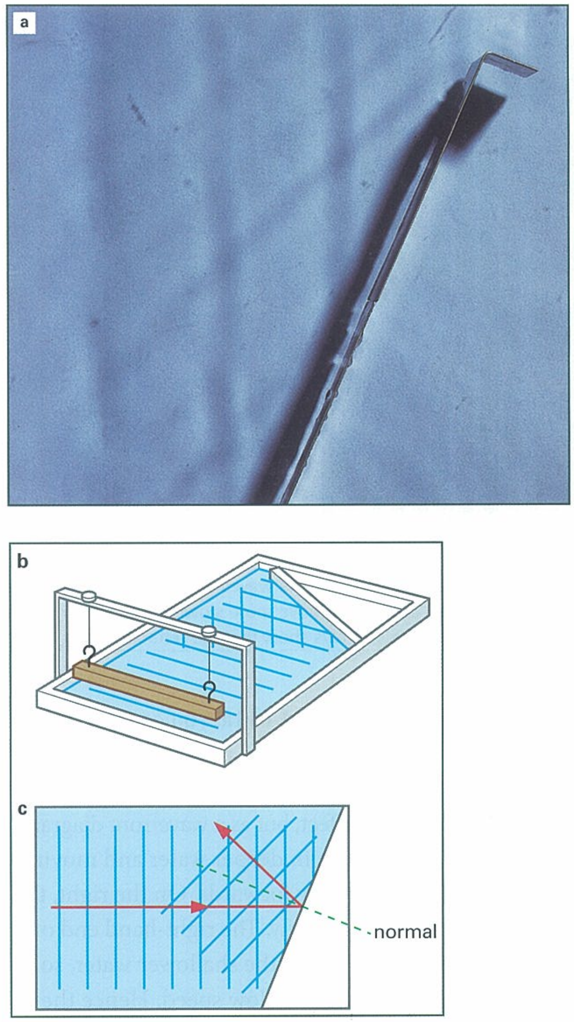
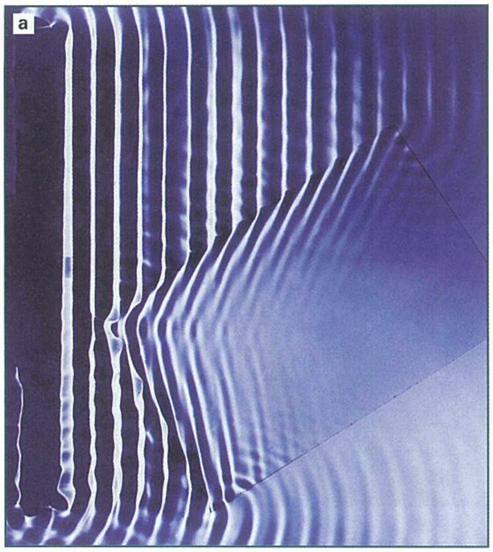


Figure 14.10 The reflection of plane waves by a flat metal barrier in a ripple tank. **a** This criss-cross pattern is observed as the reflected ripples pass through the incoming ripples. **b** How the ripples are produced. **c** The arrows show how the direction of the ripples changes when they are reflected. The angle of incidence is equal to the angle of reflection, just as in the law of reflection of light.

Refraction of ripples

Refraction occurs when the speed of light changes. We can see the same effect for ripples in a ripple tank (Figure **14.11**). A glass plate is immersed in the water, to make the water shallower in that part of the tank. There, the ripples move more slowly because they drag on the bottom of the tank (which is now actually the upper surface of the submerged glass plate).



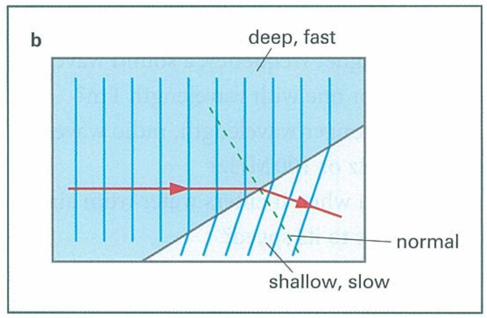


Figure 14.11 The refraction of plane waves by a flat glass plate in a ripple tank. **a** A submerged glass plate makes the water shallower on the right. In this region, the ripples move more slowly, so that they lag behind the ripples in the deeper water. **b** This wavefront diagram shows the same pattern of ripples. The rays show that the refracted ray is closer to the normal, just as when light slows down on entering glass.

In the photograph in Figure **14.11a**, you can see that these ripples lag behind the faster-moving ripples in the deeper water. Their direction of travel has changed. Figure **14.11b** shows the same effect, but as a wavefront diagram. On the left, the ripples are in deeper water and moving faster. They advance steadily forwards. On the right, the ripples are moving more slowly. The right-hand end of a ripple is the first part to enter the shallower water, so it has spent longest moving at a slow speed. Hence the right-hand end of each ripple lags furthest behind.

The rays (the red arrows) marked on Figure **14.11b** show the direction in which the ripples are moving. They are always at right angles to the ripples. They emphasise how the ripples turn so their direction is closer to the normal as they slow down, just as we saw with the refraction of light (Figure **13.10** on page **138**).

Activity 14.2 Ripple tank

Observe reflection and refraction of ripples in a ripple tank.

QUESTIONS

13 Draw a diagram to show what happens to plane waves when they strike a flat reflector placed at 45° to their direction of travel.

14 How can the speed of ripples in a ripple tank be changed?

E

Explaining reflection and refraction

The law of reflection of light **describes** how a ray of light behaves when it strikes a flat surface. However, it does not **explain** how light is reflected. We need the wave theory of light to provide an explanation.

We have seen that waves are reflected when they strike a surface. If we picture light as a form of wave, then we can predict that it will be reflected in the same way that ripples on the surface of water are reflected.

We have also seen that ripples are refracted when their speed changes. We know that the speed of light changes as light passes from one material to another. So the wave theory of light allows us to predict that light will be refracted.

If you study physics to a higher level, you will learn more about how light, sound and other phenomena can be described and explained using wave theory. Here, we will conclude this chapter by looking at another aspect of wave theory: the behaviour of waves when they pass through a gap or around an obstacle in their path.

14.4 Diffraction of waves

We can see an interesting phenomenon when we look at how ripples behave when they go through a gap in a barrier. Figure **14.12** shows what happens. As ripples pass through a gap in a barrier, they spread out into the space beyond the barrier.

This is an example of a phenomenon called **diffraction**. The effect is biggest when the gap is similar in size to the wavelength of the ripples (see Figure **14.13**).

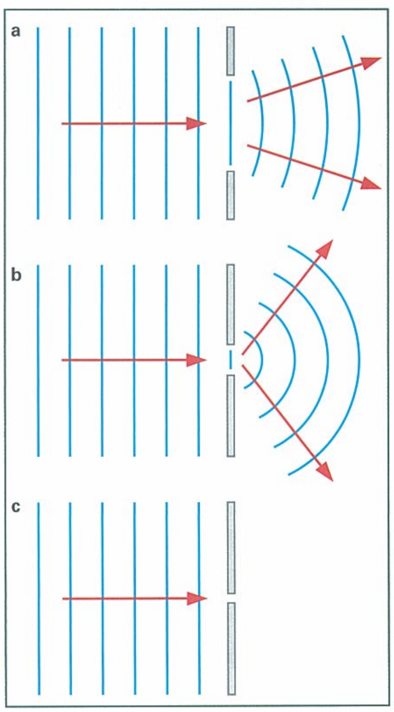


Figure 14.13 Diffraction is greatest when the width of the gap is similar to the wavelength of the waves being diffracted. When the gap is much smaller than the wavelength, the waves do not pass through at all.

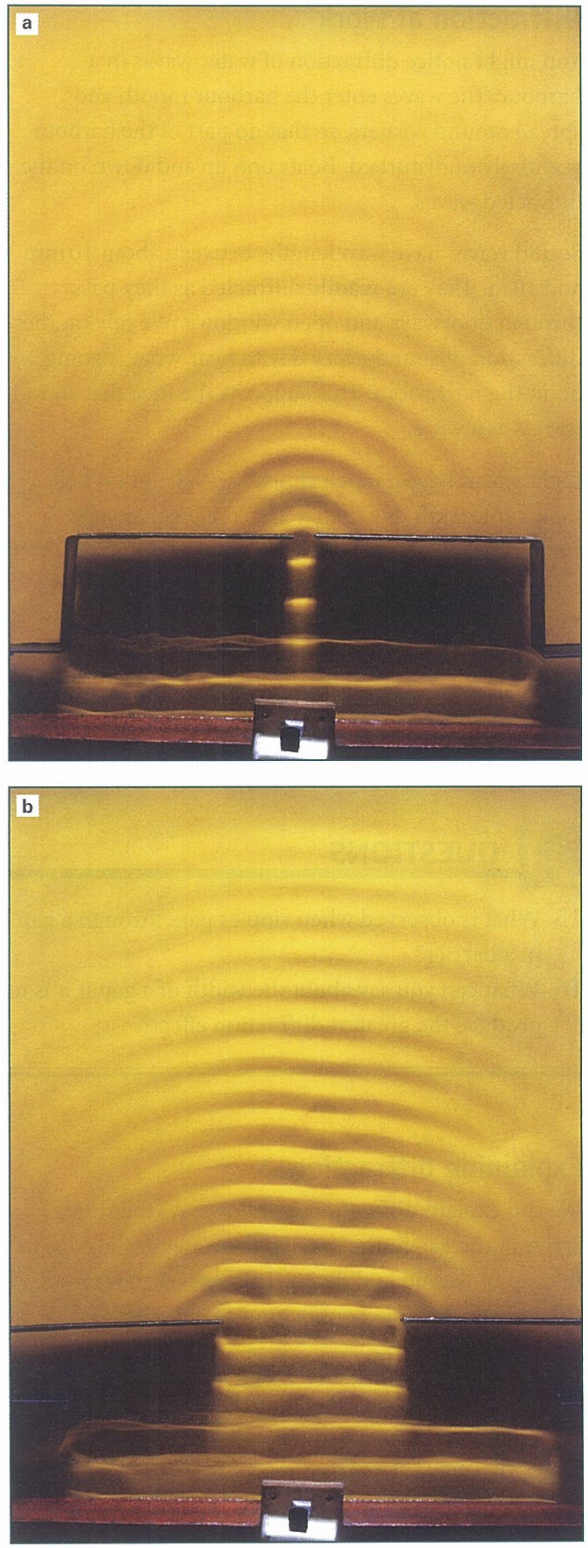


Figure 14.12 Ripples are diffracted as they pass through a gap in a barrier – they spread into the space behind the barrier. The effect is greater in **a** than in **b** because the gap is narrower in **a**.

Diffraction at work

You might notice diffraction of water waves in a harbour. The waves enter the harbour mouth and spread around corners, so that no part of the harbour is entirely undisturbed. Boats bob up and down on the diffracted waves.

Sound waves have wavelengths between about 10 mm and 10 m. They are readily diffracted as they pass through doorways and open windows. We rely on the diffraction of sound every day to hear what is going on in the next room. This supports the idea that sound travels as a wave.

Light waves have a much shorter wavelength – less than a millionth of a metre. This means that very small gaps are needed to see light being diffracted. You might notice that, on a foggy night, street lamps and car headlights appear to be surrounded by a 'halo' of light. This is because their light is diffracted by the tiny droplets of water in the air. The same effect can also sometimes be seen around the Sun during the day (see Figure **14.14**).

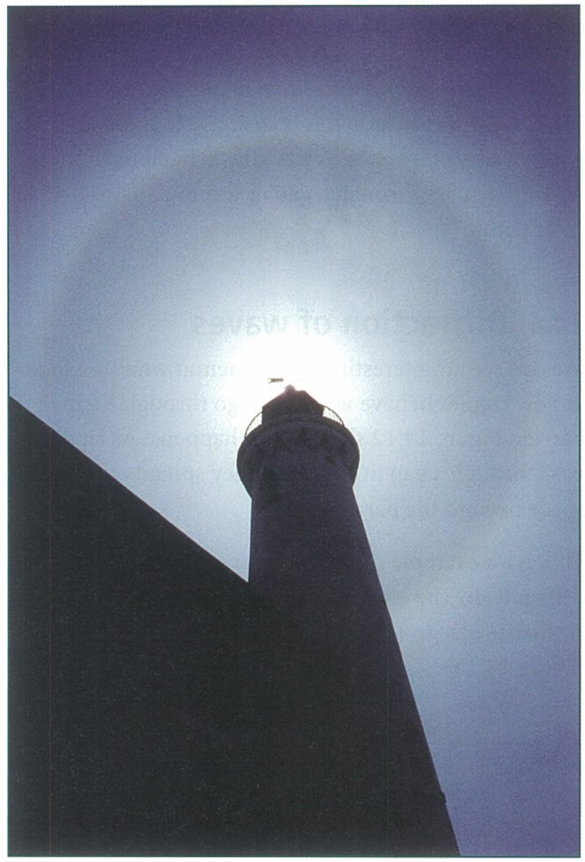


Figure 14.14 Light from the Sun is diffracted as it passes through foggy air (which is full of tiny droplets of water), producing a halo of light.

QUESTIONS

15 What is observed when ripples pass through a gap in a barrier?

16 What can you say about the width of a gap if it is to produce the greatest diffraction effect?

E

Explaining diffraction

We can explain diffraction as follows. As the ripples arrive at the gap in the barrier, the water at the edge of the gap moves up and down. This sets off new circular ripples, which spread out behind the barrier.

If you look at the diffracted ripples in Figure **14.12b**, you will see that the central part of the ripple remains straight after it has passed through the gap. At the edges, the ripples have the shape of an arc of a circle.

E

QUESTION

17 Draw a diagram to show how a series of parallel, straight wavefronts are altered as they pass through a gap whose width is equal to the wavelength of the waves.

Summary

A wave is a regularly varying disturbance that travels from place to place.

Ripples on water can act as a model for the way in which waves travel.

In transverse waves, the disturbance varies from side to side, at right angles to the direction in which the wave is travelling.

In longitudinal waves, the disturbance is back and forth, along the direction of travel.

Wave speed, frequency and wavelength are related by

speed = frequency × wavelength.

Waves can be reflected, when they reach a boundary between two different materials.

Waves can be refracted, when their speed changes.

Waves can be diffracted, when they pass through a gap.

Reflection, refraction and diffraction can be explained using the wave model.

End-of-chapter questions

14.1 Look at the wave shown in Figure **14.15**.

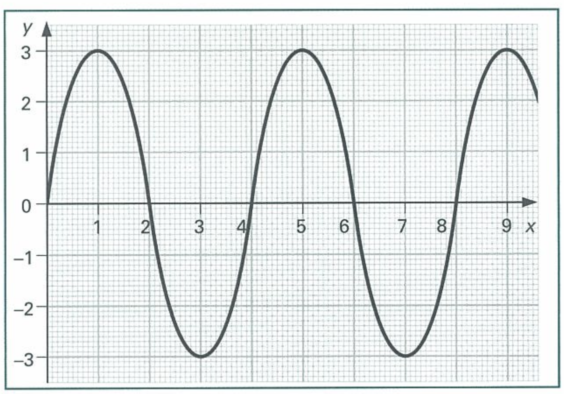


Figure 14.15 For Question **14.1**. The horizontal and vertical scales are in cm.

a What is its wavelength? [1]

b What is its amplitude? [1]

c If this wave is moving at a speed of 10 cm/s, what is its frequency? [3]

d On graph paper, with the same labelled and numbered axes as here, sketch a wave having **half** this amplitude and **twice** this wavelength. [2]

14.2 Copy and complete the diagrams in Figure **14.16** to show how the following effects appear in a ripple tank.

a Plane waves are reflected by a straight barrier. [2]

b Plane waves are diffracted as they pass through a narrow gap. [2]

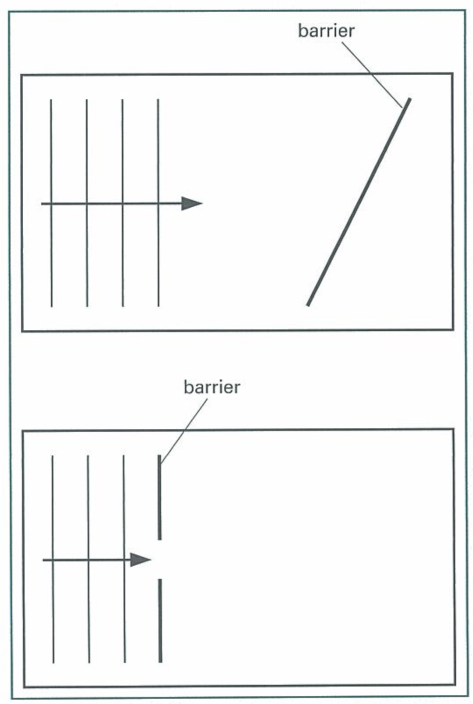


Figure 14.16 For Question **14.2**.

E

14.3 When light passes from air into glass, do the following quantities increase, decrease, or stay the same?

a speed [1]

b frequency [1]

c wavelength [1]

E

14.4 a Give an equation that relates the speed, frequency and wavelength of a wave. [1]

b Light waves of frequency 6×10^{14} Hz have a wavelength of 3.75×10^{-7} m in water. What is their speed in water? [2]

15 Spectra

Core Describing the dispersion of light by a prism
Core Describing the main features of the electromagnetic spectrum
Core Stating that all electromagnetic waves travel at the same speed in vacuum
E Extension Stating the value of the speed of electromagnetic waves

Light and colour

Diamonds are attractive because they sparkle. As you turn a cut diamond, light flashes from its different internal surfaces. As we have seen in Chapter **13**, this is a result of total internal reflection of light within the diamond. You may also notice that you can see all sorts of colours in the diamond, even though the diamond itself is likely to be colourless. (Some diamonds are slightly yellow, because they contain impurities.) Where do these varying colours come from?

Cut glass is a lot cheaper than diamonds, and has many more uses (Figure **15.1**). It is used for chandeliers, which move gently in the air. It is also used for glass ornaments. Your eye is caught by the changing colours as you walk past. Again, the glass itself is colourless, so where do these colours come from?

The underlying principle is shown in Figure **15.2**. A ray of white light is shone at a prism. It refracts as it enters and leaves the glass. At the same time, it is split into a **spectrum** of colours. You should notice that the colours merge into one another, and they are not all of equal widths in the spectrum.

Traditionally, we say that there are seven colours in the spectrum. The number seven was chosen because it had a mystical significance in the 17th century. It is very hard to distinguish between indigo and violet at the end of the spectrum, so you might say that there are really only six colours. Alternatively, you might suggest that there are many shades of red present, and of each of the other colours, so the spectrum shows many more than seven colours.

Figure 15.1 Cut glass is used for ornaments and chandeliers, because it shows all the colours of the rainbow as it moves in the light.

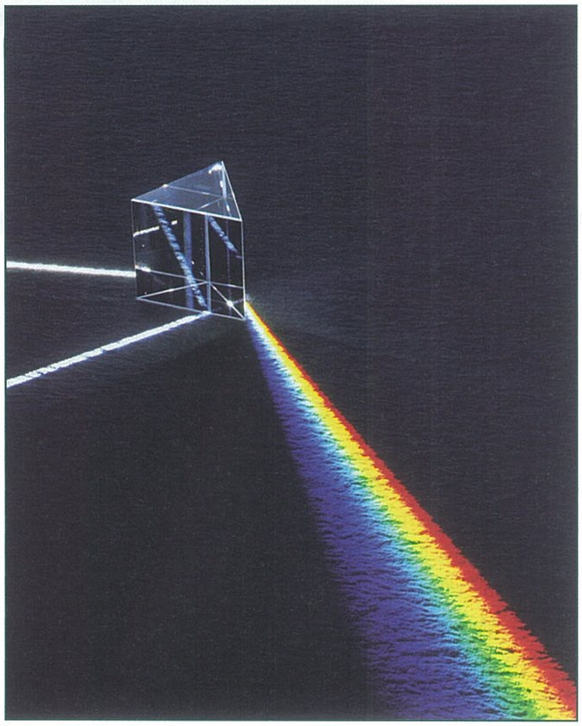


Figure 15.2 A spectrum can be produced by shining a ray of white light through a glass prism. The light is split up into a spectrum.

The standard list is as follows:

red orange yellow green blue indigo violet

There are different ways of remembering this list. One simple way is to remember the sequence of initial letters in the form of someone's name: Roy G Biv.

A rainbow is a naturally occurring spectrum. White light from the Sun is dispersed as it enters and leaves droplets of water in the air. It is also reflected back to the viewer by total internal reflection, which is why you must have the Sun behind you to observe a rainbow.

15.1 Dispersion of light

This splitting up of white light into a spectrum is known as **dispersion** ('spreading out'). Isaac Newton set out to explain how it happens. It had been suggested that light is coloured by passing it through a prism. Newton showed that this was the wrong idea by arranging for the spectrum to be passed back through another prism. The colours recombined to form white light again. He concluded that white light is a mixture of all the different colours of the spectrum.

So what happens in a prism to produce a spectrum? As the white light enters the prism, it slows down. We say that it is refracted and, as we have seen, its direction changes. Dispersion occurs because each colour is refracted by a different amount. Violet light slows down the most, and so it is refracted the most. Red light is least affected (Figure 15.3).

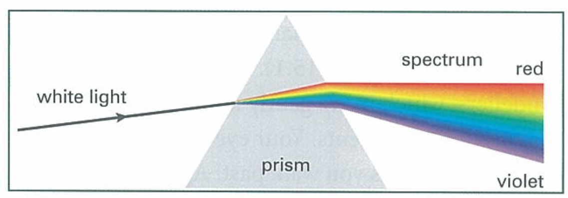


Figure 15.3 Violet light is dispersed more than red light as it passes through a prism.

Activity 15.1 Making spectra

Make a spectrum of white light by passing it through a prism.

Then make a spectrum using a diffraction grating.

E

Laser light is not dispersed by a prism. It is refracted so that it changes direction, but it is not split up into a spectrum. This is because it is light of a single colour, and is described as **monochromatic** ('mono' = one, 'chromatic' = coloured).

QUESTIONS

1 What colours are next to green in the spectrum?
2 Draw a diagram to show how white light can be dispersed into a spectrum using a glass prism.
3 Why are some colours of light more strongly refracted than others when they enter glass?

15.2 The electromagnetic spectrum

In 1799, William Herschel was examining the spectrum of light from the Sun. He was an astronomer, German by birth but working at Slough, near London. He knew that the Sun was a star and wondered what he might find out about the Sun by looking at its spectrum. He shone the Sun's light through a prism to produce a spectrum, then placed a thermometer at different points in the spectrum, as shown in Figure **15.4**. The reading on the thermometer rose, because objects get warm when they absorb light. Herschel noticed an interesting effect – the thermometer reading grew higher as he moved towards the red end of the spectrum. What would happen if he moved just beyond the end? To his surprise, he found that the reading was higher still. There was nothing to be seen beyond the red, but there was definitely something there. A little further, and the mercury in the thermometer rose higher still. Further still, and it started to fall.

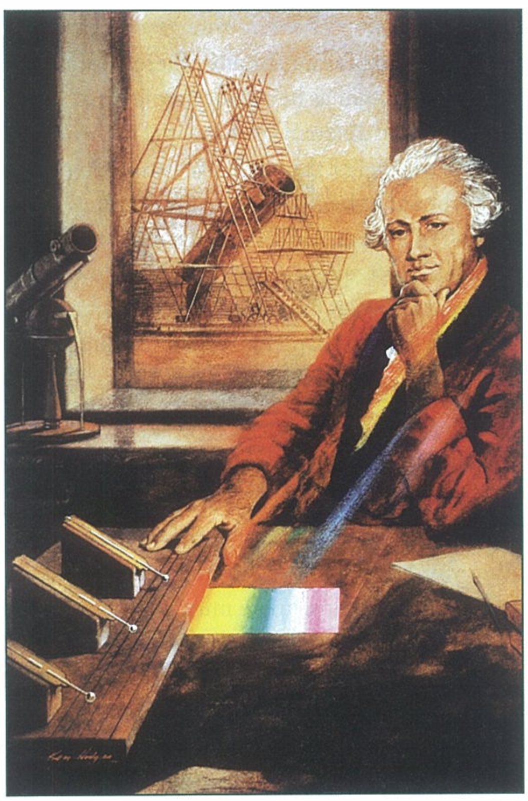


Figure 15.4 William Herschel, together with the apparatus he used to discover infrared radiation.

Herschel had discovered an invisible form of radiation, which he called **infrared radiation** ('infra' means 'below' or 'lower down'). You can experience infrared radiation for yourself, using a kettle that has recently boiled. With great care, hold the back of your hand near to the kettle. You feel the warmth of the kettle as it is absorbed by your skin. The kettle is emitting infrared radiation. (We sometimes call this 'heat radiation' – see Chapter **11** – but 'infrared radiation' is a better term.)

It is not surprising to learn that we receive heat from the Sun. However, what is surprising is that this radiation behaves in such a similar way to light. It is as if it is just an extension of the spectrum of visible light.

Beyond the violet

The discovery of radiation beyond the red end of the spectrum encouraged people to look beyond the violet end. In 1801, a German scientist called Johan Ritter used silver chloride to look for 'invisible rays'. Silver salts are blackened by exposure to sunlight (this is the basis of photography), so he directed a spectrum of sunlight onto paper soaked in silver chloride solution. The paper became blackened and, to his surprise, the effect was strongest beyond the violet end of the visible spectrum. He had discovered another extension of the spectrum, which came to be called **ultraviolet radiation** ('ultra' means 'beyond'). Although our eyes cannot detect ultraviolet radiation, sensitive photographic film can (see Figure **15.5**).

Both infrared and ultraviolet radiations were discovered by looking at the spectrum of light from the Sun. However, they do not have to be produced by an object like the Sun. Imagine a lump of iron that you heat in a Bunsen flame. At first, it looks dull and black. Take it from the flame and you will find that it is emitting infrared radiation. Put it back in the flame and heat it more. It begins to glow, first a dull red colour, then more yellow, and eventually white hot. It is emitting visible light. When its temperature reaches about 1000 °C, it will also be emitting appreciable amounts of ultraviolet radiation.

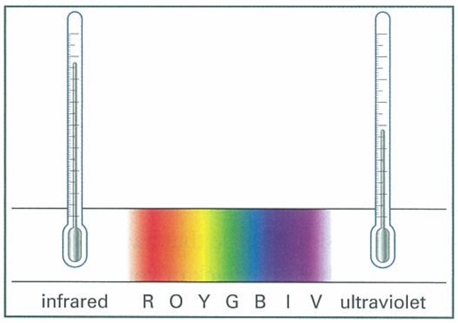


Figure 15.5 The spectrum of light from the Sun extends beyond the visible region, from infrared to ultraviolet.

This experiment should suggest to you that there is a connection between infrared, visible and ultraviolet radiations. A cool object emits only radiation at the cool end of the spectrum. The hotter the object, the more radiation it emits from the hotter end.

The Sun is a very hot object (Figure 15.6). Its surface temperature is about 7000 °C, so it emits a lot of ultraviolet radiation. Most of this is absorbed in the atmosphere, particularly by the ozone layer. A small amount of ultraviolet radiation does get through to us. The thinning of the ozone layer by chemicals released by human activity means that this amount is increasing. This increased exposure is disturbing because it increases the risk of skin cancer.

Electromagnetic waves

In section 15.1, we saw that a spectrum is formed when light passes through a prism because some colours are refracted more than others. The violet end of the spectrum is refracted most. Now we can deduce that ultraviolet radiation is refracted even more than violet light, and that infrared radiation is refracted less than red light.

To explain the spectrum, and other features of light, physicists developed the **wave model** of light. Just as sound can be thought of as vibrations or waves

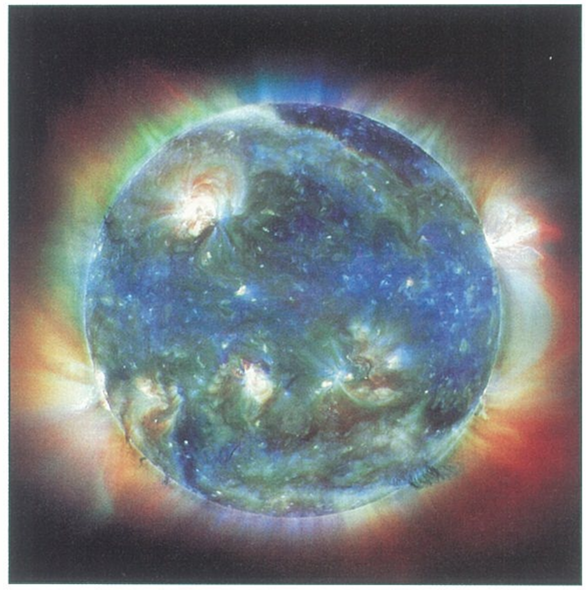


Figure 15.6 The Sun is examined by several satellite observatories. This image was produced by the SOHO satellite using a camera that detects the ultraviolet radiation given off by the Sun. You can see some detail of the Sun's surface, including giant prominences looping out into space. The different colours indicate variations in the temperature across the Sun's surface.

travelling through the air (or any other material), so we can think of light as being another form of wave. Sounds can have different pitches – the higher the frequency, the higher the pitch. We can think of a piano keyboard as being a 'spectrum' of sounds of different frequencies. Light can have different colours, according to its frequency. Red light has a lower frequency than violet light. Visible light occurs as a spectrum of colours, depending on its frequency.

A Scottish physicist, James Clerk Maxwell, eventually showed in 1860 that light was in fact small oscillations in electric and magnetic fields, or **electromagnetic waves.** His theory allowed him to predict that they could have any value of frequency. In other words, beyond the infrared and ultraviolet regions of the spectrum, there must be even more types of electromagnetic wave. By the early years of the 20th century, physicists had discovered or artificially produced several other types of electromagnetic wave (see Table 15.1), to complete the **electromagnetic spectrum.** Maxwell also predicted that all electromagnetic waves travel at the same speed through empty space, the speed of light (almost 300 000 000 m/s).

Type of electromagnetic wave	Discoverer	Date
infrared	William Herschel	1799
ultraviolet	Johan Wilhelm Ritter	1801
radio waves	Heinrich Hertz	1887
X-rays	Wilhelm Röntgen	1895
gamma (γ) rays	Henri Becquerel	1896

Table 15.1 Discoverers of electromagnetic waves.

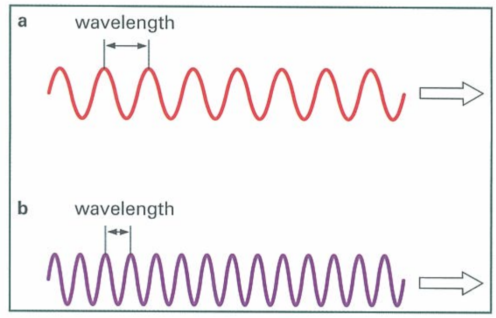


Figure 15.7 Comparing red and violet light waves. Both travel at the same speed, but red light has a longer wavelength because its frequency is less. The wavelength is the distance from one crest to the next (or from one trough to the next). Think of red light waves as long, lazy waves; violet light is made up of shorter, more rapidly vibrating waves.

The speed of electromagnetic waves

All types of electromagnetic wave have one thing in common: they travel at the same speed in a vacuum. They travel at the speed of light, whose value is close to 300 000 000 m/s (3×10^8 m/s). Like light, the speed of electromagnetic waves depends on the material through which they are travelling. They travel fastest through a vacuum.

Wavelength and frequency

We can represent light as a wave, just as we represented the small changes in air pressure as a sound wave (page 130). Figure 15.7 compares red light with violet light. Red light has a greater wavelength than violet light – that is, there is a greater distance from one wave crest to the next. This is because both red light and violet light travel at the same speed (as predicted by Maxwell), but violet light has a greater frequency, so it goes up and down more often in the same length.

The waves that make up visible light have very high frequencies – over one hundred million million hertz, or 10^{14} Hz. Their wavelengths are very small, from 400 nm for violet light to 700 nm for red light. (One nanometre (1 nm) is one-billionth (one-thousand-millionth, 1/1 000 000 000th) of a metre, so 400 nm = 400×10^{-9} m.) So more than one million waves of visible light fit into a metre.

Figure 15.8 shows the complete electromagnetic spectrum, with the wavelengths and frequencies of each region. In fact, we cannot be very precise about where each region starts and stops. Even the ends of the visible light section are uncertain, because different

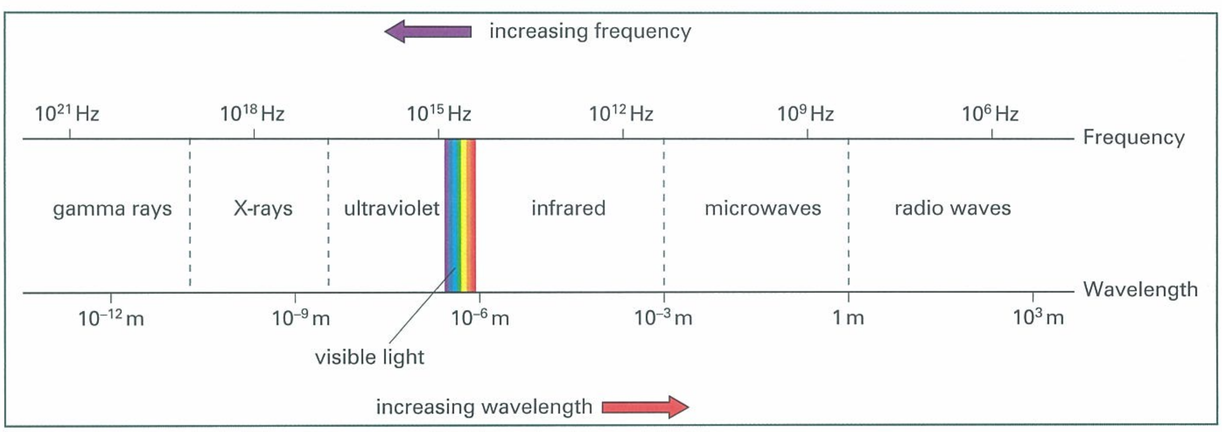


Figure 15.8 The electromagnetic spectrum. The scale of frequencies increases along one side. The scale of wavelengths increases in the opposite direction.

people can see slightly different ranges of wavelengths, just as they can hear different ranges of sound frequencies.

QUESTIONS

4 a Which has the longer wavelength, red light or violet light?
  b Which has the greater frequency?
5 a Which has the longer wavelength, red light or infrared radiation?
  b Which has the greater frequency?
6 Look at the spectrum shown in Figure **15.8**.
  a Which waves have the shortest wavelength?
  b Which have the lowest frequency?
7 a Which travels faster in empty space, violet light or red light?
  b Which travels faster in glass?

Uses of electromagnetic waves

Since the different regions of the electromagnetic spectrum were discovered, we have found many ways to make use of these waves. Here are some important examples.

Radio waves are used to broadcast radio and television signals. These are sent out from an aerial (a transmitter) a few kilometres away, to be captured by an aerial on the roof of a house.

Microwaves are used in satellite television broadcasting, because microwaves pass easily through the Earth's atmosphere as they travel up to a broadcasting satellite, thousands of kilometres away in space. Then they are sent back down to subscribers on Earth. Microwaves are also used to transmit mobile phone (cellphone) signals between masts, which may be up to 20 km apart.

Infrared radiation is used in remote controls for devices such as televisions and video recorders. A beam of radiation from the remote control carries a coded signal to the appliance, which then changes channel, starts to record, or whatever. You may be able to use a digital camera to observe this radiation, which would otherwise be invisible to our eyes. Grills and toasters also use infrared radiation, because it is thermal (heat) energy 'on the move'. Security alarms send out beams of infrared and detect changes in the reflected radiation – these may indicate the presence of an intruder.

X-rays can penetrate solid materials and so they are used in security scanners at airports (see Figure **15.9**). They are also used in hospitals and clinics to see inside patients without having to perform surgery.

Figure 15.9 Two uses of electromagnetic radiation at the airport security check: X-rays are used to see inside the passengers' hand baggage, while radio waves detect metal objects as passengers walk through the arch.

Electromagnetic hazards

All types of radiation can be hazardous – even bright light shone into your eyes can blind you. So people who work with electromagnetic radiation must be careful and take appropriate precautions.

Microwaves are used to cook food in microwave ovens. This shows that they have a heating effect when absorbed. Telephone engineers, for example, must take care not to expose themselves to microwaves when they are working on the masts of a mobile phone (cellphone) network. Domestic microwave ovens must be checked to ensure that no radiation is leaking out.

People who work with X-rays must minimise their exposure. They can do this by standing well away when a patient is being examined, or by enclosing the equipment in a metal case, which will absorb X-rays.

QUESTIONS

8 Name **two** types of electromagnetic radiation that can be used for cooking food.

9 Explain how radio waves, microwaves and infrared radiation might all play a part when you watch a television show.

Activity 15.2 Using electromagnetic waves

Divide into groups and allocate a region of the electromagnetic spectrum to each group. Research uses of your region of the spectrum and stage a debate to decide whose region is the most useful.

Summary

White light can be dispersed by a prism to form a spectrum.

The electromagnetic spectrum extends to wavelengths and frequencies beyond those of the visible light spectrum.

Electromagnetic waves are varying electric and magnetic fields that travel through empty space at the speed of light.

Electromagnetic radiation has many uses. Care must be taken to ensure that the user does not come to any harm.

E The speed of light in vacuum is approximately 300 000 000 m/s.

Laser light is light of a single wavelength, that is, it is monochromatic.

End-of-chapter questions

15.1 A glass prism can be used to show the dispersion of white light to form a spectrum.

- **a** Draw a diagram to show how a ray of white light is dispersed as it passes through a prism. [2]
- **b** Which colour of light is most strongly dispersed (deflected) as it passes through the prism? [1]
- **c** Explain why some colours of light are more strongly dispersed than others. [2]

15.2

- **a** Put the following regions of the electromagnetic spectrum in order, starting with the waves that have the greatest wavelength. [4]

  visible light infrared radio waves
  gamma rays ultraviolet microwaves
  X-rays

- **b** Which of these waves have the greatest frequency? [1]
- **c** Which of these waves have the greatest speed in empty space (in vacuum)? [1]

E

15.3 At what speed do electromagnetic waves travel through a vacuum? [1]

15.4 Explain why white light is dispersed to form a spectrum when it passes through a glass prism but laser light is not. [3]