Chapter 13: Light Waves

We see objects because they emit or reflect light. In this chapter you will learn how light behaves when it reflects from different surfaces, and what happens when light travels from one transparent material to another.

Seeing the light

The patient shown in Figure 13.1 has a cataract. The front of one of his eyes has become so cloudy that he is unable to see. Nowadays it is possible to remove this damaged part of the eye and replace it with a clear plastic that will again allow light to enter the eye.

Figure 13.1 *Cataracts mean that light cannot enter the eye correctly.*

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

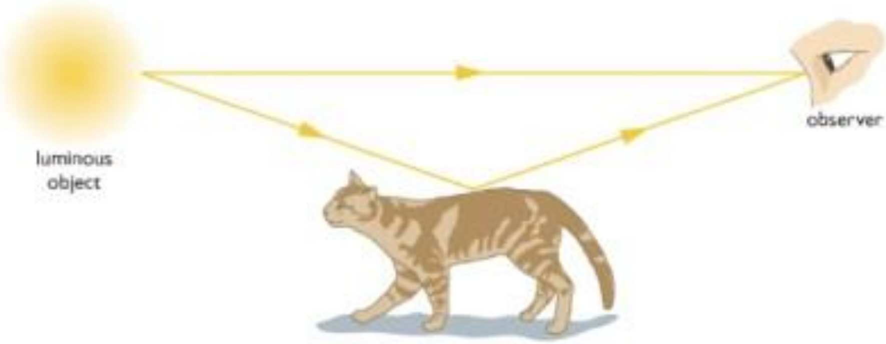

Figure 13.2 *Luminous objects, such as the Sun, give out light. Non-luminous objects only reflect light.*

Light waves are transverse waves and, like all waves, can be reflected, refracted and diffracted.

Reflection

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

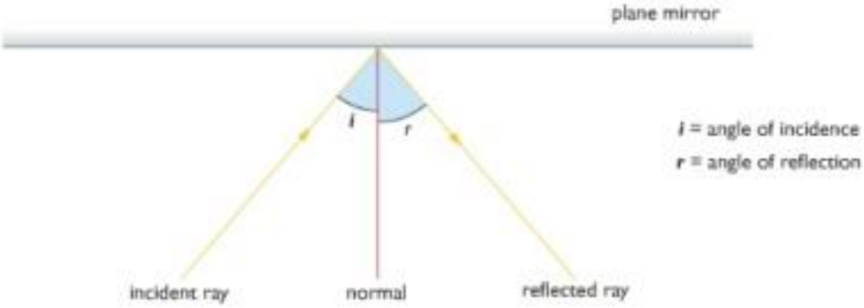

Figure 13.3 *Light is reflected from a plane mirror. The angle of incidence is equal to the angle of reflection. The normal is a line at right angles to the mirror.*

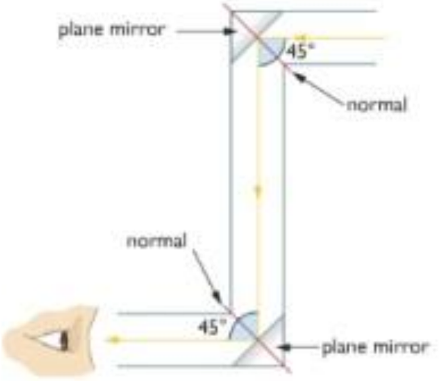

Figure 13.4 *A periscope is used to see over or around objects.*

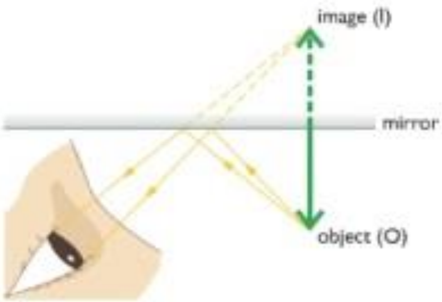

Figure 13.5 *Virtual images look like they are behind the surface of the mirror.*

If you can produce an image on a screen, it is real.

Figure 13.7 *Some emergency vehicles have mirror writing on their bonnets so that drivers in front can read the name when they look in their mirrors.*

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

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

Images created by a plane mirror

When you look into a plane mirror, you see images of the room that appear to be behind the mirror. These images are created by rays of light from objects inside the room striking the mirror and being reflected into your eyes. Figure 13.5 shows how these images are created.

Because rays of light normally travel in straight lines, your brain interprets the rays as having come from **I** (that is, an image of the object is seen at **I**). Images like these, through which rays of light do not actually pass, are called **virtual images**. Images created with rays of light actually passing through them (for example, on a cinema screen) are called **real images**.

Figure 13.6 *Real images are produced when light passes through them.*

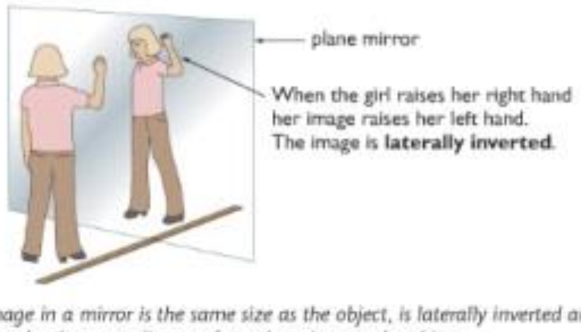

Figure 13.8 *The image in a mirror is the same size as the object, is laterally inverted and is virtual. The image also appears to be the same distance from the mirror as the object.*

Properties of an image in a plane mirror

- The image is as far behind the mirror as the object is in front.
- The image is the same size as the object.
- The image is virtual – that is, it cannot be produced on a screen.
- The image is **laterally inverted** – that is, the left side and right side of the image appear to be interchanged.

Refraction

Figure 13.9 *This rainbow is caused by refraction.*

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

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

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

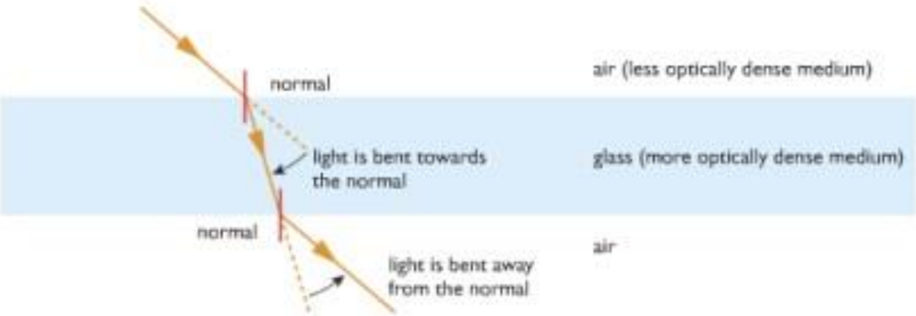

Figure 13.10 *Light rays bend as they travel from air into glass and out again. This is called refraction.*

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

If the ray strikes the boundary between the two media at 90°, the ray continues without change of direction (Figure 13.11).

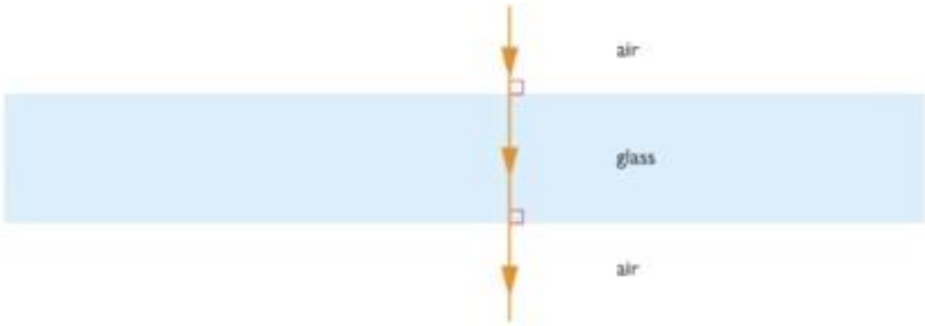

Figure 13.11 *If the light hits the boundary at 90° the ray does not bend.*

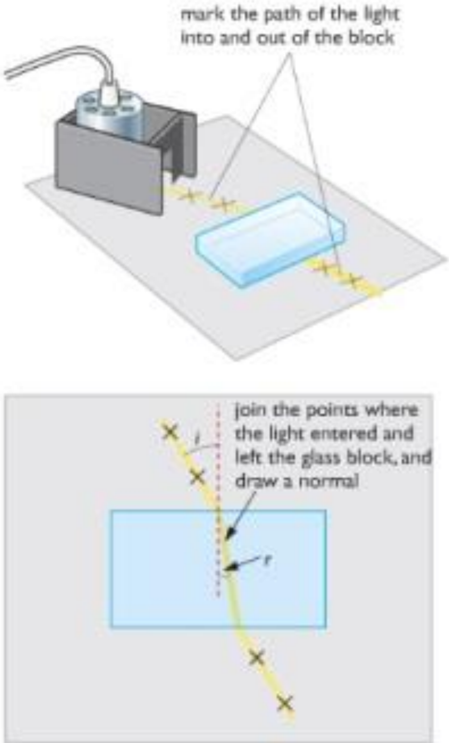

Figure 13.12 *How to investigate refraction using a rectangular glass block.*

Refractive index

You can investigate refraction in glass using a rectangular glass block. By tracing the rays of light on a piece of paper, you can measure the angles of incidence (i) and refraction (r).

If you carry out the procedure shown in Figure 13.12 for a range of different angles of incidence, you would find that the ratio between the sine of the angle of incidence and the sine of the angle of refraction is constant. This ratio is called the **refractive index** of the material, and is given the letter n. As it is a ratio, it has no units.

The angles of incidence and refraction and the refractive index are related by the following equation:

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

Worked example

Example 1

In an experiment similar to the one shown in Figure 13.12, the angle of incidence was measured as 30° and the angle of refraction as 19°. Calculate the refractive index of the glass block.

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

$$n = \frac{\sin 30}{\sin 19.5}$$

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

$$n = 1.51$$

Total internal reflection

'Optical density' describes how much light slows down when it enters a material. It is not the same as density (mass per unit volume; see page 162).

When a ray of light passes from an optically more dense medium into an optically less dense medium – for example, from glass into air – the majority of the light is refracted away from the normal but there is a small amount that is reflected from the boundary.

You can investigate total internal reflection in the laboratory using a semi-circular glass block. As shown in Figure 13.13, a ray of light is directed at the centre of the straight side of the block, through the curved side. The incident ray always hits the edge of the glass block at 90°, so there are no refraction effects to take into account as the light goes into the block.

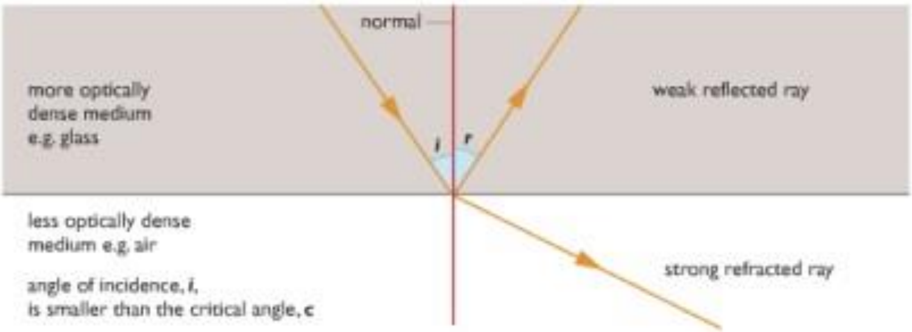

Figure 13.14 *A ray of light is refracted as it passes from a more dense to a less dense medium, but a little ray of light is reflected.*

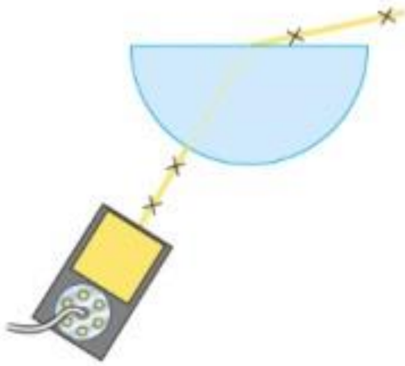

Figure 13.13 *A semi-circular glass block used to demonstrate total internal reflection.*

As the angle of incidence in the more dense medium increases the angle of refraction also increases until, at a special angle called the **critical angle**, the angle of refraction is 90°.

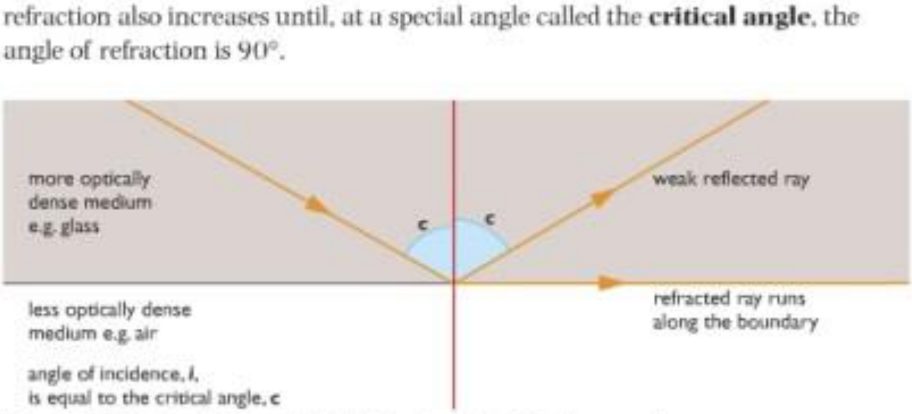

Figure 13.15 *At the critical angle the light is refracted at 90° to the normal.*

If the angle of incidence in the glass is further increased, *all* of the light is reflected from the boundary. The ray is said to have undergone **total internal reflection.**

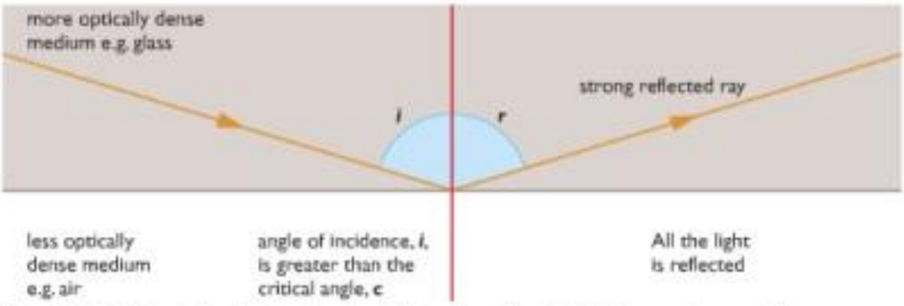

Figure 13.16 *Above the critical angle, the light is reflected back into the more dense medium.*

The value of the critical angle depends upon the media on either side of the boundary. Assuming that the less dense medium is air, then the critical angle for glass is typically 42° and the critical angle for water is 49°.

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

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

Worked example

Example 2

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

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

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

$$\sin c = 0.69$$

$$c = 43.6°$$

Using total internal reflection

If we look carefully at the image of an object created by a plane mirror we may see several faint images around the main central image. These multiple images are due to several partial internal reflections at the non-silvered glass surface of the mirror.

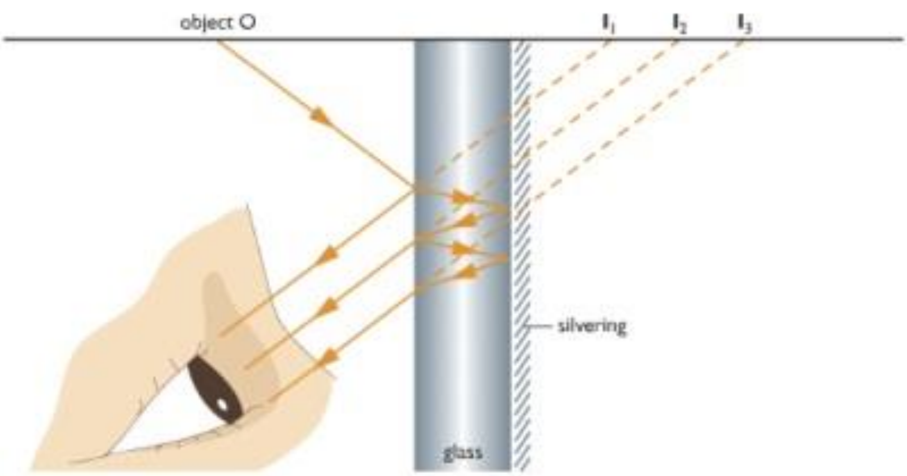

Figure 13.17 *The faint multiple images we can sometimes see in a mirror are caused when some of the light is reflected at the non-silvered surface of the mirror.*

To avoid this problem, particularly when high quality images are required, glass prisms are often used to alter the direction of the light rather than mirrors.

The prismatic periscope

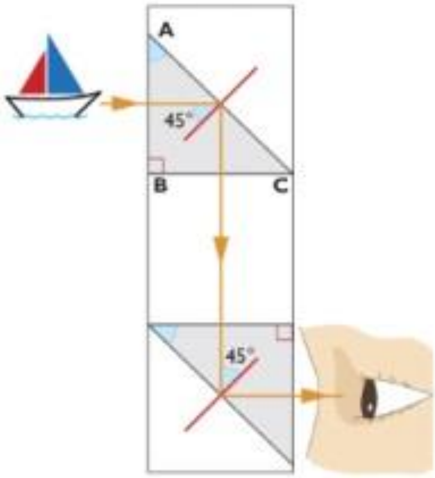

Figure 13.18 *Prisms can be used in periscopes instead of plane mirrors.*

Light passes normally through the surface AB of the first prism (that is, it enters the prism at 90°) and so is undeviated. It then strikes the surface AC of the prism at an angle of 45°. The critical angle for glass is 42° so the ray is totally internally reflected and is turned through 90°. On emerging from the first prism the light travels to a second prism which is positioned such that the ray is again totally internally reflected. The ray emerges parallel to the direction in which it was originally travelling.

The final image created by this type of periscope is likely to be sharper and brighter than that produced by a periscope that uses two mirrors, as no multiple images are created.

Reflectors

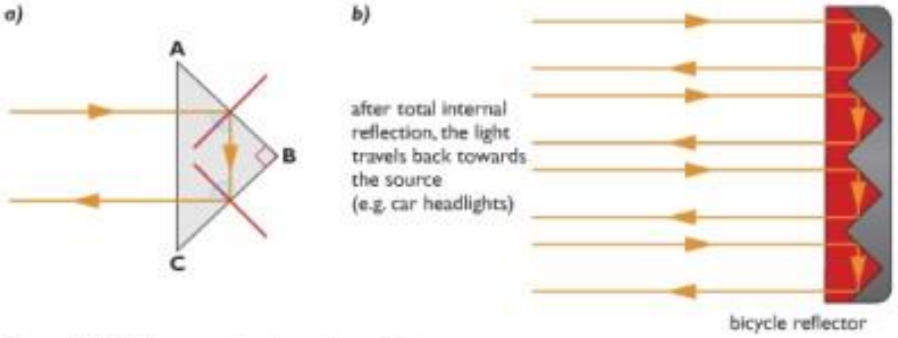

Figure 13.19 *Prisms can also be used as reflectors.*

Light entering the prism in Figure 13.19 undergoes total internal reflection twice. It emerges from the prism travelling back in the direction from which it originally came. This arrangement is used in bicycle reflectors and binoculars.

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

Optical fibres

One of the most important applications for total internal reflection is the **optical fibre**. This is a very thin strand composed of two different types of glass. There is a central core of optically dense glass (high refractive index) around which is a "cladding" or "coat" of optically less dense glass.

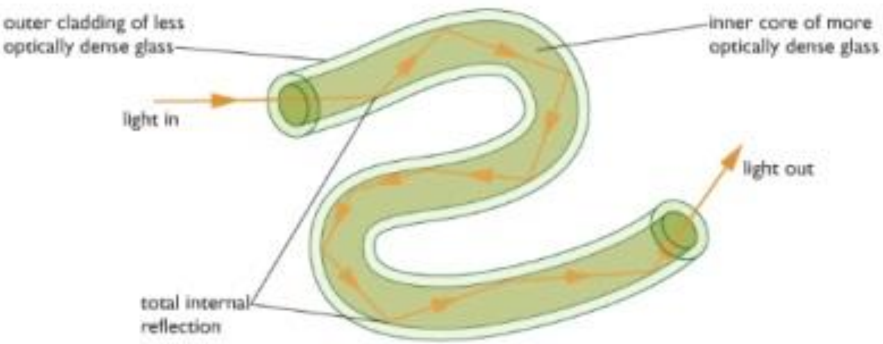

Figure 13.20 *In an optical fibre, light undergoes total internal reflection.*

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

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

Figure 13.21 *Optical fibres*

Using optical fibres to see what they are doing, surgeons can carry out operations through small holes made in the body, rather than making large incisions. This is called "keyhole surgery". It causes less distress to patients and usually leads to a more rapid recovery.

Figure 13.22 shows optical fibres in an endoscope. The endoscope is used by doctors to see the inside the body – for example, to examine the inside of the stomach. Endoscopes can also be used by engineers to see inaccessible parts of machinery.

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

Optical fibres in telecommunications

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

The endoscope

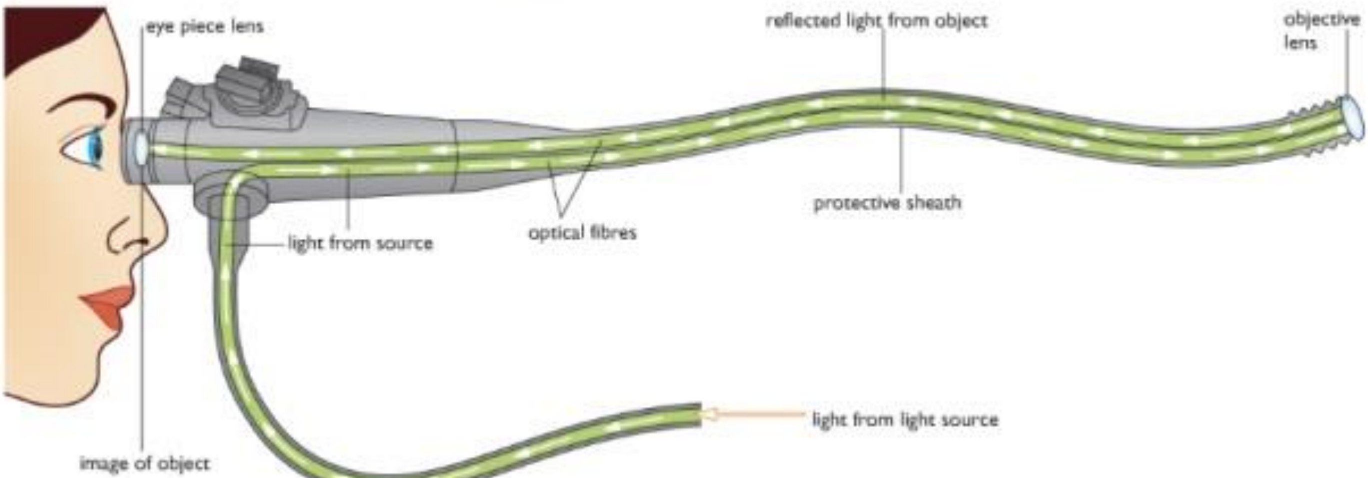

Figure 13.22 *Optical fibres are used in endoscopes to see inside the body.*

Dispersion

You can investigate refraction using glass blocks of different shapes. When white light passes through a prism (Figure 13.23), it emerges as a band of colours called a **spectrum**. The spectrum is formed because white light is a mixture of colours and each colour travels through the prism at a slightly different speed, so each colour is refracted by a different angle. The prism has a different refractive index for each colour. Because of this, each of the colours emerges from the prism travelling in a slightly different direction. The process is called **dispersion**. The speed of red light is changed least and so red has the smallest deviation. The speed of violet light is changed the most and so violet has the largest deviation.

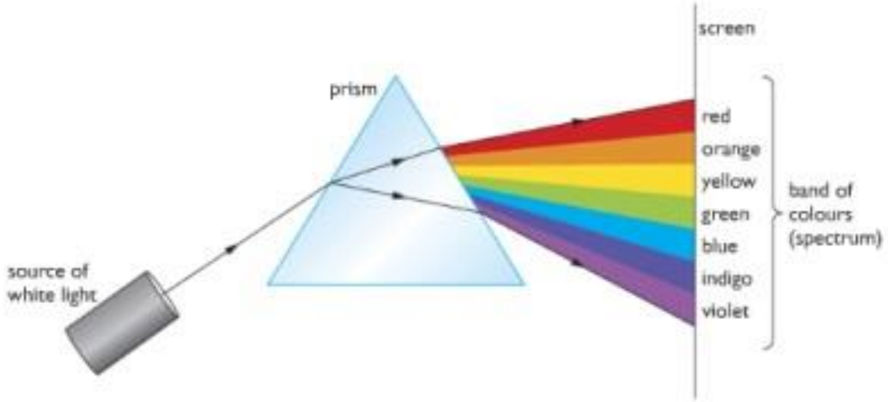

Figure 13.23 *A prism separates white light into its colours because the prism has a slightly different refractive index for each of the colours.*

End of Chapter Checklist

You will need to be able to do the following:

- ✓ recall that light waves are transverse waves that can be reflected, refracted and diffracted
- ✓ describe how light is reflected from a plane surface so that the angle of incidence is equal to the angle of reflection
- ✓ draw ray diagrams to show how an image is created in a plane mirror
- ✓ recall that light bends towards the normal as it enters an optically denser medium, and bends away from the normal when it enters an optically less dense medium
- ✓ recall and use the equation
  $n = \frac{\sin i}{\sin r}$
- ✓ recall the conditions under which total internal reflection takes place
- ✓ recall and use the equation
  $\sin c = \frac{1}{n}$
- ✓ describe experiments to investigate the refraction of light, including finding the refractive index and the critical angle
- ✓ describe several applications of total internal reflection, including optical fibres and prisms.

Questions

More questions on refraction can be found at the end of Section C on page 126.

1 Draw a ray diagram to show how a ray of light can be turned through 180° using three plane mirrors. Mark on your diagram a value for the angle of incidence at each of the mirrors.

2 *a)* Draw an accurate diagram to show how a plane mirror creates an image of an object.

b) State five properties of an image created in a plane mirror.

c) A man stands 5 m in front of a plane mirror. How far is he from his image?

d) The man walks towards the mirror at a speed of 1 m/s. At what speed are the man and his image approaching each other?

3 *a)* Draw a diagram to show the path of a ray of light travelling from air into a rectangular glass block at an angle of about 45°.

b) Show the path of the ray as it emerges from the block.

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

d) Draw a second diagram showing a ray that travels through the block without being deviated.

4 In an experiment to measure the refractive index of a type of glass, the angle of refraction was found to be 31° when the angle of incidence was 55°.

a) Calculate the refractive index of the glass.

b) What would the angle of refraction be for a ray with an angle of incidence of 45°?

c) Calculate the critical angle for the glass.

5 *a)* Draw a diagram to show how a prism can cause dispersion.

b) Explain why the white light is dispersed.

6 Draw three ray diagrams to show what happens to a ray of light travelling in a more dense medium if it strikes the boundary with a less dense medium at an angle:

a) less than the critical angle

b) equal to the critical angle

c) greater than the critical angle.

7 ***a)*** What is meant by "total internal reflection of light" and under what conditions does it occur?

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

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

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

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

b) What would happen to a ray of light inside an optical fibre if the outer glass had a higher optical density than the inner glass?

c) Explain how doctors use optical fibres to see inside the body.