CHAPTER 18

Refraction

18.1 INTRODUCTION

Refraction is a property of waves that has been with us since time began. The refraction of light waves and radio waves through the universe has gone on since the beginning of the universe. Early hunters and spearfishermen used the refractive properties of water to accurately spear fish. However, the use of refraction, particularly in the fields of communication and medicine, has increased beyond belief over the past two decades. The development of optical fibres has revolutionised the way we receive telephone calls and TV programs (pay TV), and has reduced the time we spend in hospital with exploratory surgery.

- But what is refraction?
- How do optical fibres rely on refraction?
- Why are optical fibres in so much demand today?
- There are many uses made of optical fibres — can you name a few?

Questions related to everyday phenomena and which can be explained by refraction include these:

- Why do swimming pools or clear mountain streams seem shallower than they are?
- What causes mirages?
- Did you know a rainbow can only be observed when the rain is in front of you and the Sun is behind you?
- Did you know that the 'glass frogs' of Central America, whose bodies are so transparent you can see their insides, use refraction to vanish from sight when they slip into the water?

These questions and many more odd characteristics of the way light travels can be answered by a study of the refraction of light. By the end of this chapter many interesting phenomena will be able to be discussed with a knowledge of refraction.

18.2 REFRACTION

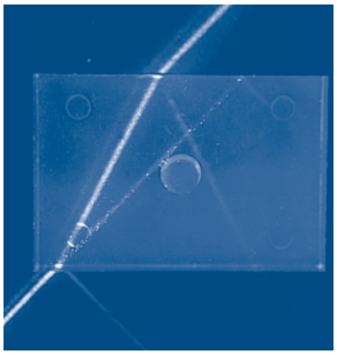
Recall the definition of refraction — it is the changing in direction of waves as they go from one medium to another. For water waves this meant that the direction of propagation of waves changed when they travelled from one depth of water to another. For light, refraction occurs when light passes from one medium to another, such as when light rays pass from air to water, from air to glass or from glass to water. This direction change can be easily observed in the case of light — the light rays themselves bend at the boundary between the media. A definition of refraction for light thus becomes:

> *Refraction is the bending of light rays at the boundary or interface, as they go from one medium to another.*

EI Activity 18.1 REFRACTION

1. Use a light box with a narrow aperture to produce a single light ray.
2. Shine this ray at an angle other than 90° onto a block of glass.
3. What happens to the ray as it goes from air to glass?

Photo 18.1
The refraction of light as it passes through a block of glass.



You should have noticed that the ray bent as it entered the glass and bent again on exiting from the other side. (See Photo 18.1.) It has been refracted twice. If the normal had been drawn to the surface of the glass at the point the ray entered the glass, it would have also been noticed that the ray bent closer to the normal in the glass on entering and further from the normal on exiting.

We call the ray that strikes the glass **the incident ray**, and the ray that bends in the glass the **refracted ray**. The angle between the incident ray and the normal is **the angle of incidence** (**i**) and the angle between the refracted ray and the normal is **the angle of refraction** (**r**) (Figure 18.1).

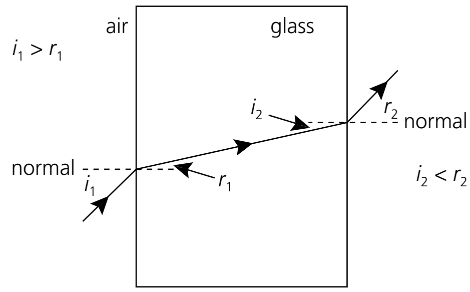


Figure 18.1
Light is refracted as it passes through glass, bending towards the normal in the more dense medium, and away in the less dense medium.

At the second surface, the surface where the ray passes from glass to air, the ray in the air is the refracted ray and the ray in the glass is the incident ray.

If Perspex is used instead of glass, similar refraction occurs except that for the same angle of incidence the angle of refraction will be different.

Similar effects are observed using any transparent material. The refracted ray bends towards the normal when the light travels from air to the material. The amount the rays bend depends on the **optical density** of the material. Optical density has nothing to do with physical density — mass, volume, etc. — but with the ability of light to pass through it.

A general rule is that **light rays bend toward the normal when they go from a less optically dense medium to a more optically dense medium**. The reverse is also true — **light rays bend away from the normal as they pass from a more optically dense medium to a less optically dense medium**. This illustrates the reversibility properties of light rays through a refractive system.

The amount of refraction that occurs results from the changing speed of light as it goes from air to the medium. (This was shown, using water waves, in Chapter 14.) Light travels faster in a vacuum or in air than in glass, water, etc. This is shown in Table 18.1.

PHYSICS FACT

Diamonds have one of the highest refractive indices of all substances. The pioneer in making fake diamonds was teenager Carroll Chatham, who in 1926 dissolved some graphite in molten iron and dropped the fiery solution into a vat of liquid nitrogen (−196°C). Instead of getting diamonds, the explosion blew out the windows in his San Francisco home. Later he had success and his son Tom now produces synthetic diamonds that have similar RI to the real ones.

Table 18.1 THE VELOCITY OF LIGHT IN VARIOUS MEDIA OF DIFFERENT REFRACTIVE INDICES

MEDIUM	VELOCITY OF LIGHT IN THE MEDIUM, v (10^8 m s^{-1})	ABSOLUTE REFRACTIVE INDEX OF THE MATERIAL, n
Air	3.00	1.00
Ice	2.31	1.30
Water	2.26	1.33
Ethyl alcohol	2.21	1.36
Fused quartz	2.05	1.46
Perspex	2.00	1.49
Benzene	2.00	1.50
Crown glass	1.97	1.52
Light flint glass	1.90	1.58
Heavy flint glass	1.82	1.65
Zircon	1.58	1.90
Diamond	1.24	2.42

The effect can be explained by use of the analogy of a car hitting a flooded section of a road. As one of the car's front wheels hits the water it slows down while the other wheel keeps going at the original speed. Therefore the direction of the car changes (if allowed). It bends into the water. (See Figure 18.2.) The car's direction changes. The new direction of the car will be closer to the normal and it will slow down.

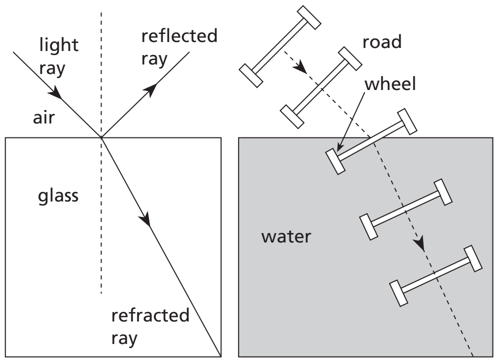


Figure 18.2
As the wheels of the car enter the water they slow down and swerve towards the normal.

The ratio of the velocity of light in air to the velocity of light in a different medium — water, glass, etc. — is constant. This constant is called the **absolute refractive index** of the material and is denoted by the symbol n. That is:

$$\frac{v_a}{v_m} = n$$

where v_a is the velocity of light in air; v_m is the velocity of light in the medium.

The refractive indices of several common materials are shown in Table 18.1. Notice that since n is a ratio it has no units.

Questions

1. Use Table 18.1 to see if you obtain the correct refractive index of the material by dividing the velocity of light in air by the velocity of light in the material.
2. Calculate the index of refraction for light going from air to a material in which its speed is **(a)** 2.6×10^8 m s^{-1}; **(b)** 1.8×10^8 m s^{-1}; **(c)** 3.4×10^8 m s^{-1}. (Is answer **(c)** possible? Explain!)
3. Calculate the speed of light in a medium whose refractive index is **(a)** 1.5; **(b)** 2.4; **(c)** 1.3.

18.3 SNELL'S LAW

In 1621 a Dutch mathematician, **Willebrod Snell** (1591–1626), discovered that the refractive index of a substance can be found using the angles of incidence and refraction. He found that if the angle of incidence was changed, the angle of refraction also changed in such a way that the ratio of the sine of the angle of incidence to the sine of the angle of refraction is always a constant for a particular material. This constant is the absolute refractive index of the material.

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

This is known as **Snell's law**.

For example, for a ray of light entering a block of glass, the ratio $\frac{\sin i}{\sin r} = 1.5$ for all values of i. Therefore the refractive index of glass $n_{a\text{-}g}$ or just $n_g = 1.5$.

The refractive indices given in Table 18.1 are the **absolute refractive indices**. They are the refractive indices obtained when a light ray travels from air to the material. Knowing the value of the absolute refractive index and the angle of incidence, the angle of refraction can be determined.

Example

Light from a light box is shone onto a block of Perspex at an angle of 30° to the normal. Determine the angle of refraction.

Solution

- $n_{\text{Perspex}} = 1.4$

$$\frac{\sin i}{\sin r} = n = 1.4$$

$$\sin r = \frac{\sin i}{1.4}$$

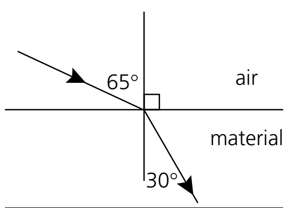
$$= \frac{\sin 30°}{1.4}$$

$$= 0.357$$

$$r = 21°$$

Questions

Figure 18.3 For question 4.



4 Use Figure 18.3 to calculate the refractive index of the material.

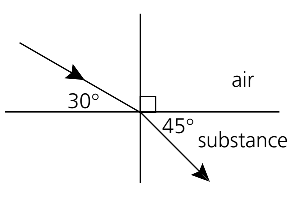
5 Complete Table 18.2 for light rays passing from air to a different medium.

Table 18.2

	A	B	C	D
Angle of incidence, i (degrees)	30	60		0
Angle of refraction, r (degrees)	20		40	
Refractive index, n		1.8	1.4	

(Had a problem with D?)

Figure 18.4 For question 6.



6 A light ray travels from air to a substance as shown in Figure 18.4. Find the refractive index of the substance.

7 Students conducting experiments to find the absolute refractive index of a piece of Perspex obtained the results shown in Table 18.3 for the angles of incidence and refraction.

Table 18.3

Angle of incidence, i (degrees)	10	20	30	40	50	60
Angle of refraction, r (degrees)	6.0	13	19	25	30	35

(a) Plot a graph of $\sin i$ against $\sin r$.
(b) From the shape of the graph what is the relationship between $\sin i$ and $\sin r$?
(c) What is the refractive index of the Perspex?
(d) What is the angle of refraction if the angle of incidence is 54°?

The absolute refractive indices in Table 18.1 are for light going from air to the material, that is $n_{a \to g}$. But what is the refractive index of light passing from glass to air $n_{g \to a}$ as shown at the second surface in Figure 18.1?

Because of the reversible nature of light, angle r_1 = angle i_2 and angle i_1 = angle r_2. Therefore at surface 2:

$$\begin{aligned} n_{g \to a} &= \frac{\sin i_2}{\sin r_2} \\ &= \frac{1}{\dfrac{\sin r_2}{\sin i_2}} \\ &= \frac{1}{\dfrac{\sin i_1}{\sin r_1}} \\ n_{g \to a} &= \frac{1}{n_{a \to g}} \end{aligned}$$

This is called the 'reciprocal law'.

In general, the refractive index of light going from a material to air is the reciprocal of the absolute refractive index of the material:

$$n_{m \to a} = \frac{1}{n_{a \to m}} = \frac{1}{n_m}$$

Example

Find the refractive index of light going from glass to air.

Solution

$$\begin{aligned} n_{g \to a} &= \frac{1}{n_{a \to g}} \\ &= \frac{1}{1.50} \\ &= 0.67 \end{aligned}$$

If a ray of light passes from one medium to another, for example from water to glass, it is found that the ratio of the sine of the angle of incidence in water (θ_w) to the sine of the angle of refraction in glass (θ_g) is also a constant, n_{w-g}:

$$\frac{\sin \theta_w}{\sin \theta_g} = n_{w-g}$$

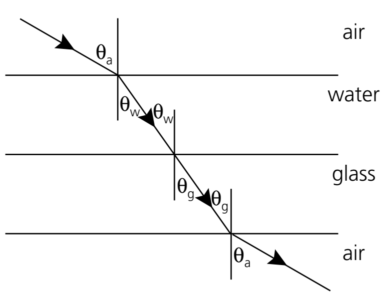


Figure 18.5
How much light rays bend depends on the optical density of the medium. They bend more in glass than in water.

From Figure 18.5:

$$\frac{\sin \theta_a}{\sin \theta_w} = n_w$$

$$\therefore \sin \theta_w = \frac{\sin \theta_a}{n_w}$$

$$\frac{\sin \theta_g}{\sin \theta_a} = \frac{1}{n_g}$$

$$\therefore \sin \theta_g = \frac{\sin \theta_a}{n_g}$$

$$\therefore \frac{\sin \theta_w}{\sin \theta_g} = \frac{\frac{\sin \theta_a}{n_w}}{\frac{\sin \theta_a}{n_g}}$$

$$\therefore \frac{\sin \theta_w}{\sin \theta_g} = \frac{n_g}{n_w} = n_{w-g}$$

In general, the **relative refractive index** for light passing from medium 1 to medium 2 is given by the formula:

$$n_{1\rightarrow 2} = \frac{n_2}{n_1}$$

where $n_{1\rightarrow 2}$ is the relative refractive index for light going from medium 1 to medium 2; n_2 is the absolute refractive index for medium 2; n_1 is the absolute refractive index for medium 1.

This results in a more general form of Snell's law, which can be used for light passing between any two media:

$$\frac{\sin \theta_1}{\sin \theta_2} = n_{1,2} = \frac{n_2}{n_1}$$

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

Example

Find the angle of refraction for a ray of light passing from water to glass when the angle of incidence in water is 25°.

Solution

$$n_w \sin \theta_w = n_g \sin \theta_g$$

$$1.33 \sin 25° = 1.5 \sin \theta_g$$

$$\frac{1.33 \sin 25°}{1.5} = \sin \theta_g$$

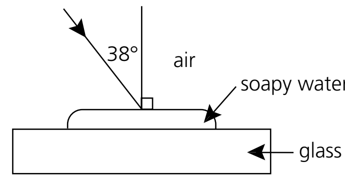
$$\theta_g = 22°$$

Questions

8 See if you obtain the same result for the relative refractive index for light passing from water to crown glass using $n_{w-g} = v_w/v_g$ and n_g/n_w.

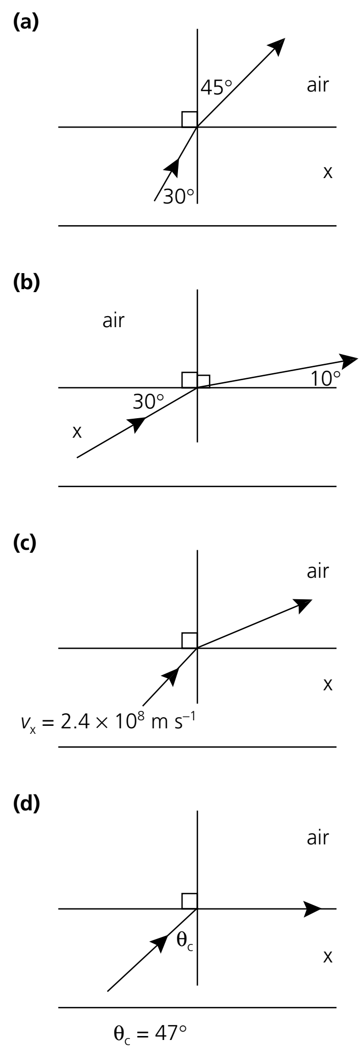
9 A drop of soapy water ($n_{\text{soapy water}}$ = 1.38) was placed onto a block of glass (n_g = 1.5), as shown in Figure 18.6. A ray from a laser was shone onto the water at an angle of 38°. Calculate:
(a) the angle of refraction in the soapy water;
(b) the angle of refraction in the glass;
(c) the angle at which the ray exited from the glass;
(d) the relative refractive index of light going from soapy water to glass.

Figure 18.6
For question 9.



10 In each of the cases shown in Figure 18.7 a light ray travels from a substance, X, to air. Find the refractive index of the substance.

Figure 18.7
For question 10.



11 A layer of water (n_w = 1.33) is placed on a block of glass (n_g = 1.52), as shown in Figure 18.8. Calculate the angles θ_w and θ_g.

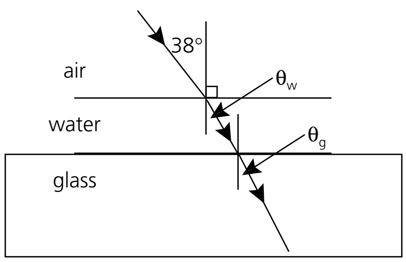


Figure 18.8
For question 11.

12 In which of the following will rays of light bend towards the normal?
(a) Glass to water.
(b) Glass to diamond.
(c) Alcohol to water.
(d) Perspex to heavy flint glass.

Colours

Refraction is due to the velocity of light changing as it goes from one medium to another:

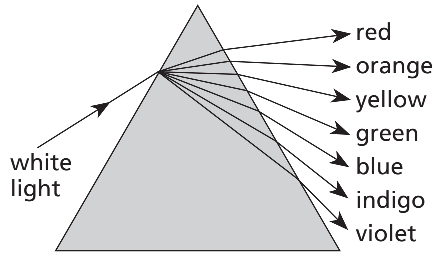
$$n_m = \frac{v_a}{v_m}$$

where v_a is the velocity of light in air; v_m is the velocity of light in the material.

Since $v = f\lambda$ and the frequency of waves does not change as they go from one medium to another, then:

$$n_m = \frac{v_a}{v_m} = \frac{f\lambda_a}{f\lambda_m} = \frac{\lambda_a}{\lambda_m}$$

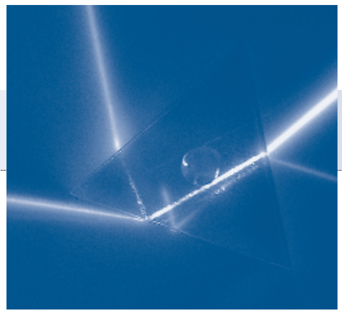
This results in each colour of light having a slightly different absolute refractive index. This means that if white light is shone on the surface of a block of glass, for example, the angle of refraction for each colour will be slightly different. The colours will separate slightly. If this occurs at a second surface, such as the second surface of a prism as shown in Figure 18.9, the effect is increased, resulting in a very visible separation of the colours of light. This phenomenon is known as **dispersion**. (See Photo 18.2 and colour section.) The colour pattern formed is called a **spectrum**. Notice that violet light is refracted the most and red the least.



$n_{red} = 1.515$
$n_{yellow} = 1.517$
$n_{blue} = 1.523$
$n_{violet} = 1.533$

Figure 18.9
Because the different colours of light have different refractive indices they separate when passing through a prism, creating a spectrum (see also colour section).

Photo 18.2
A continuous spectrum produced by the refraction of white light by a prism (see also colour section).



In summary:

$$\frac{\sin \theta_1}{\sin \theta_2} = n_{1,2} = \frac{n_2}{n_1} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$$

EXAMPLES OF REFRACTION 18.4

A fish eye view To a fish or underwater diver, a tree on the shore would appear to be up in the air and objects would appear to be in different positions from where they actually are because of refraction. However, certain fish have overcome these apparent positional changes to still be able to shoot down insects by squirting a high pressure jet of water from their mouths toward their prey, which can be up to 3 m above the surface. These fish must take account of refraction with a great deal of precision to enable them to aim from under the water to make a 'hit' on an insect. Once hit, the insect falls to the water, where it becomes a meal for these incredible marksmen.

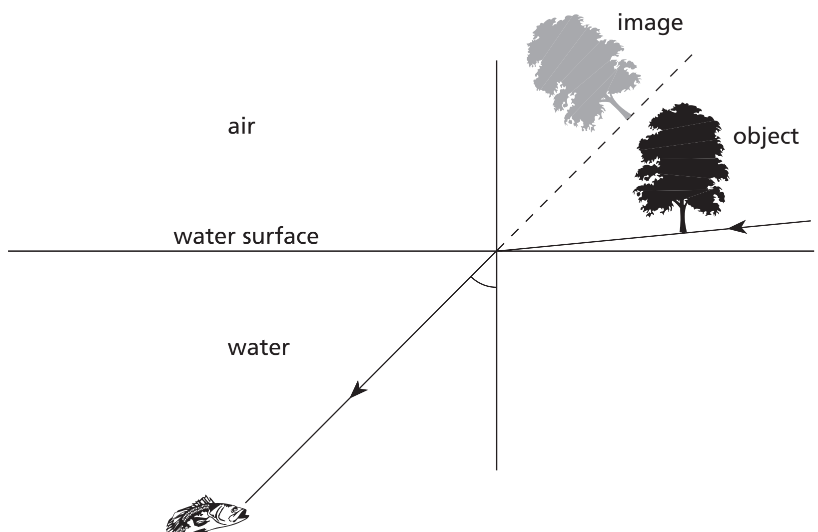
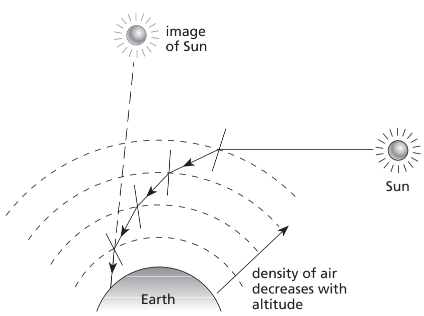


Figure 18.10
Because of refraction, fish see objects at positions that differ from their true positions.

Figure 18.11
Light entering our atmosphere is refracted by layers of differing density, producing an apparent shift in the position of the stars.



Astronomers Like the water-squirting fish, astronomers have to make allowances for refraction when observing stars. Light from the stars travels in straight lines through the vacuum of space until it enters the Earth's atmosphere where it is refracted. The atmosphere of Earth is a more dense medium than the vacuum of space. Stars appear to be at different positions in the sky from where they actually are.

This occurs with light from our Sun. However, since the refractive index for light travelling from space to our atmosphere is only 1.000 29, Figure 18.11 has been exaggerated. The observed position of the Sun is only about 0.5° or one Sun's diameter higher in the sky than its real position. Since it takes the Earth about 2 minutes to rotate through 0.5° we gain approximately 4 minutes of extra sunlight a day due to refraction at sunrise and sunset.

Apparent depth The refraction of light results in objects in different media appearing to be closer than they are. For example, a toy at the bottom of a pool will appear to be closer to the surface than it really is, to an observer standing above the pool. (See Figure 18.12.)

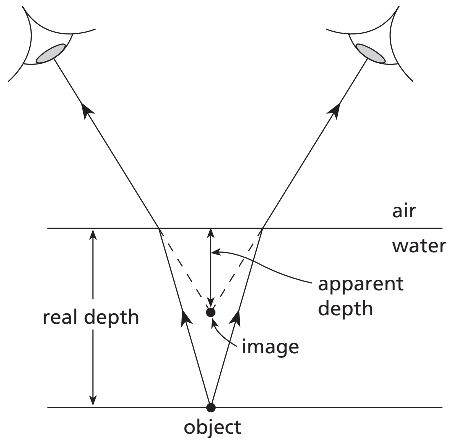


Figure 18.12
Because of refraction objects appear closer to the surface of a pool than they actually are.

Light rays travelling from the toy to your eyes are refracted away from the normal at the water's surface. To your eyes and brain, which trace these rays back to where they appear to meet, the object appears to be closer to the surface than it actually is. This depth is called the **apparent depth**. It can be derived that:

$$\frac{\text{true depth}}{\text{apparent depth}} = n$$

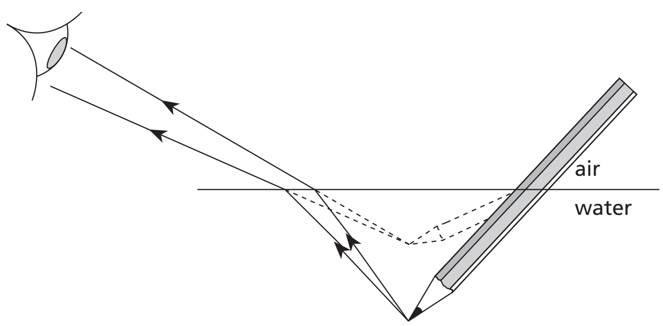


Figure 18.13
The pencil appears bent because the parts of the pencil under water appear closer to the surface.

This is why a pencil placed in water appears to be bent. (See Figure 18.13.)

Rays from the tip of the pencil are refracted away from the normal at the surface of the water. On tracing them back they appear to come from the image of the tip of the pencil, which is closer to the surface.

Example

A stone at the bottom of a pool in a creek appears to be 1.2 m from the surface. What is the true depth of the pool? (n_w = 1.33)

Solution

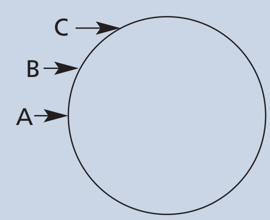
$$\frac{\text{true depth}}{\text{apparent depth}} = n$$

$$\frac{\text{true depth}}{1.2} = 1.33$$

$$\text{true depth} = 1.6 \text{ m}$$

NOVEL CHALLENGE

In 1621, French scientist Rene Descartes published a diagram showing the refraction and total internal reflection of light in a raindrop. Redraw a big circle like the one in the diagram and show the path of the parallel sunlight rays A, B and C that strike the drop at the 9, 10 and 11 o'clock positions. Assume n_{glass} = 1.5.



Questions

13 A student on a biology field trip dropped a coin in a creek. The depth of the water appeared to be 75 cm so he rolled up his sleeves to retrieve the money. What would be the consequences of such an action? Explain! (The refractive index of water is 1.33.)

TOTAL INTERNAL REFLECTION 18.5

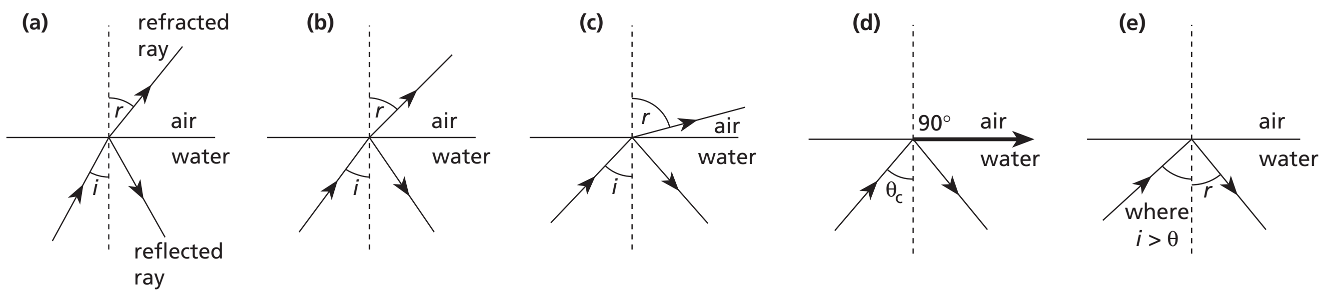


Figure 18.14
When light passes from a more dense to a less dense medium it bends away from the normal. However, after the refracted ray = 90° the incident ray is totally reflected, producing total internal reflection.

As previously discussed a ray of light bends toward the normal when going from a less dense to a more dense medium. The opposite is also true. Rays will bend away from the normal when going from a more dense to a less dense medium, as was shown in Figure 18.1. This results in an odd situation as the angle of incidence increases as shown in Figure 18.14. There comes a stage where the angle of refraction is 90° (Figure 18.14**(d)**). The angle of incidence that produces this is called the **critical angle** (θ_c). If the angle of incidence is further increased the ray of light is entirely reflected from the surface at an angle equal to the angle of incidence. This is called **total internal reflection** and occurs when light travels from a more optically dense medium to a less optically dense medium and the angle of incidence is greater that the critical angle.

For a ray of light going from water to air:

$$\frac{\sin \theta_w}{\sin \theta_a} = n_{wa} = \frac{1}{n_w}$$

When the angle of incidence θ_w is equal to the critical angle θ_c, the refracted angle $\theta_a = 90°$, and sin 90° = 1, then:

$$\sin \theta_c = \frac{1}{n_w}$$

Example

Find the critical angle for a light ray passing from light flint glass to **(a)** air; **(b)** water.

Solution

(a)

$$\sin \theta_c = \frac{1}{n_g} = \frac{1}{1.58}$$
$$\theta_c = 39°$$

(b)

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$
$$1.58 \sin \theta_c = 1.33 \sin 90°$$
$$\sin \theta_c = \frac{1.33 \times \sin 90°}{1.58}$$
$$\theta_c = 57.3°$$

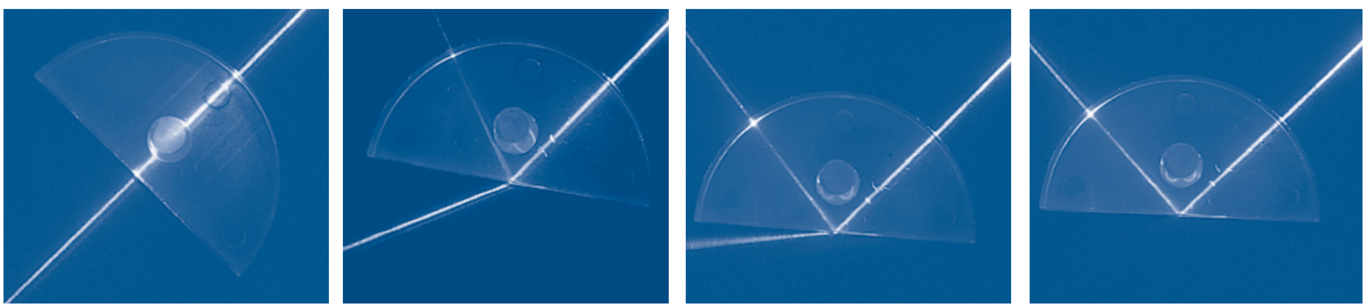
Total internal reflection can be demonstrated easily by using a semicircular block of glass and a light box. (See the Photo 18.3.)

The block is placed on a sheet of white paper and a ray from a light box is directed onto the centre of the semicircular block; the ray entering the glass, as it is along a radius, is then perpendicular to the surface. Therefore no refraction occurs at the first surface. However, refraction occurs at the second surface and the ray bends away from the normal. As the angle of incidence at this surface is increased, the angle of refraction also increases. (Notice that you will start to see a faint reflected beam from this surface as light is both reflected and refracted from transparent surfaces.) When the angle of incidence is approximately 42°, the refracted beam will be along the straight surface of the block of glass; that is, the angle of refraction is 90°. If the angle of incidence is made slightly greater, the refracted beam disappears as the light beam is reflected back inside the block of glass at an angle equal to the angle of incidence. (See the Photo 18.3.) This is total internal reflection.

NOVEL CHALLENGE

When you squeeze the air out of a plastic soft-drink bottle while it is under water, bubbles rise to the surface. Predict what they would look like when observed from the water's surface. Think about air lenses and total internal reflection. You'd be very surprised!

Photo 18.3
Total internal reflection produced by light passing from glass to air. This occurs when the angle of incidence is greater than the critical angle. The refraction of light through a semicircular block of glass showing total internal reflection.



Questions

14 In each of the following situations where a light ray passes from one medium to another state whether it is possible for total internal reflection to take place. Explain.
- **(a)** Air to glass.
- **(b)** Diamond to air.
- **(c)** Water to glass.
- **(d)** Flint glass to air.
- **(e)** Ice to a vacuum.
- **(f)** Crown glass to Perspex.

15 A block of ice is placed on top of a semicircular block of crown glass (Figure 18.15). At what minimum angle would all light incident on the boundary between the two surfaces be reflected?

16 A ray of light travels from one medium to another. It is found that total internal reflection occurs when the incident angle is greater than 54°. If the refractive index of the first medium is 1.49, calculate the refractive index of the second medium.

17 Students investigating total internal reflection using a semicircular block of glass notice that before total internal reflection occurs there is a faint reflected beam. Comment on the intensity of beams **(i)**, **(ii)** and **(iii)** in Figure 18.16 as the angle of incidence increases.

Figure 18.15
For question 15.

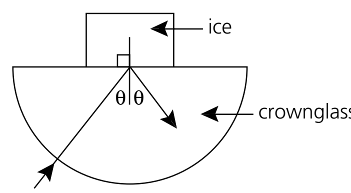


Figure 18.16
For question 17.

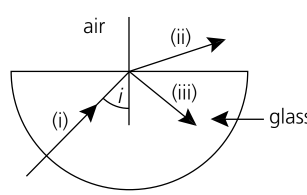


Figure 18.17
Because of total internal reflection prisms are capable of bending light rays through 90°.

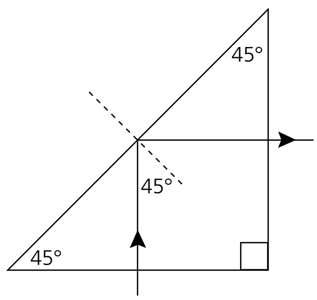


Figure 18.18
Periscopes use total internal reflection in prisms.

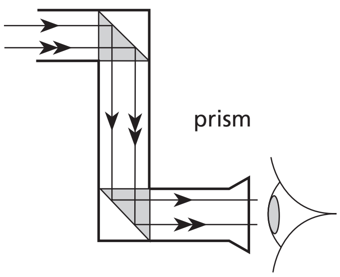


Figure 18.19
Quality periscopes use prisms rather than mirrors because mirrors produce multiple images if thick glass is used.

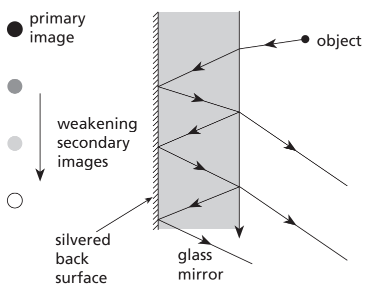
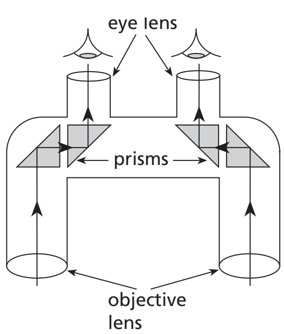


Figure 18.20
A schematic diagram of binoculars using glass prisms.



Activity 18.2 UNDERWATER BUBBLES

1 Hold an empty plastic soft drink bottle upside-down in a bucket of water, an aquarium, or a swimming pool.
2 Squeeze the bottle and watch the air bubbles rise. They look shiny.
3 Why is this?

USES OF TOTAL INTERNAL REFLECTION 18.6

Prisms

A glass 45°/45° prism as shown in Figure 18.17 can be used for total internal reflection and has many uses.

Light striking one surface of the prism at right angles makes an angle of 45° with the second surface. The angle of incidence is greater than the critical angle of 42° and the light is therefore reflected from this surface. It then strikes the third surface at right angles. The rays have thus made right-angled turns.

This makes them useful in quality periscopes (Figure 18.18). They have an advantage over mirrors because mirrors produce multiple images as light is reflected from the back and front surfaces a number of times (Figure 18.19). The coating on mirrors can also flake, reducing the reflected light intensity.

Prisms are also used in prism binoculars, making these pieces of equipment much more compact than older telescopes (Figure 18.20). In single lens reflex cameras a pentaprism is used to reflect the incoming light back to the viewfinder as well as invert it so that the photographer is actually seeing the light which is entering the camera lens used to form the image on the film.

If light is incident at right angles onto the hypotenuse of the prism it is reflected back the way it came (Figure 18.21). This property of prisms makes them useful for reflectors on bicycles and 'cats'-eyes' on roads. Notice, however, that the rays of light are inverted.

Diamonds are cut in similar ways to reflect light incident on them to produce many internal reflections and thus to sparkle.

Optical fibres

One of the major developing uses of total internal reflection is in optical fibres. Fibre optics is a branch of optics dealing with the transmission of light through fibres or thin rods of glass or some other transparent material of high refractive index. If light is admitted at one end of a fibre, it can travel through the fibre with very low loss, even if the fibre is curved.

Optical fibres have been around for decades. You might remember, or have seen, those stringy plastic lights (Fantasy lights) that were the rage back in the 1970s. These consisted of basic optical fibres. (See Photo 18.4.)

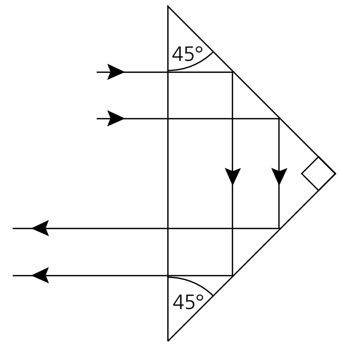
However, the number of medical and communication uses of optical fibres has exploded over the past decade.

An optical fibre consists of a very pure glass fibre as thin as a hair 0.125 mm with a layer of cladding around the outside (Figure 18.22), to protect it from damage and moisture.

The outside layer has a lower refractive index than the inside material, thus creating a situation where light propagating in the central layer is travelling in a more dense material than in the outside layer. This means the light is totally internally reflected if it strikes the boundary between the two media at an angle greater then the critical angle. Thus light is reflected and reflected and reflected along the length of the fibre, which can be bent into any shape as long as it is not kinked. Once kinked, surface cracks allow light to refract out. In underwater cables the glow at the kink attracts fish, which can eat and sever the cable.

Optical fibres can be made as either step index type where the refractive index changes rapidly at the boundary between the core and the cladding, or graded index where there is a more gradual change of refractive index from the centre to outside.

Figure 18.21
45°/45° prisms can also cause light rays to bend through 180° when the light is incident on the hypotenuse.

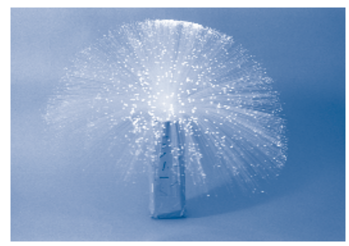


Communication

One of the first large commercial users of optical fibres was the telecommunications industry. Optical fibres were first used in the USA in the 1960s and are now replacing copper conductors in telephone and cable TV and data systems worldwide. Digital electrical signals are converted into light pulses and transmitted over optical fibre cable by switching light-emitting or laser diodes on and off. At the other end, these optical digital pulses are converted back into electrical signals by photo-transistors. Optical fibres are thinner, cheaper and lighter than equivalent copper conductors and can carry much more information. One particular fibre optic cable laid from New Jersey to Britain and France can carry 50 000 simultaneous voice conversations as well as other information, such as ten channels for cable TV and Internet data. There is no cross-talk between voice conversations and they are almost impossible to 'bug'.

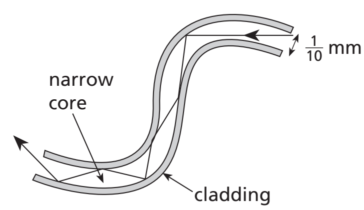
It is suggested that Australia has an international fibre optic cable capacity of over one terabit per second (1.0 Tb s^{-1}). Bandwidth capacity is forecast to increase to over 4 Tb s^{-1} by 2004. The new Australia–Japan cable connects the east coast of Australia with Japan and North America. It has doubled existing broadband capacity to the west coast of the United States and increased the capacity to North Asia 15-fold. Australian domestic networks consist of fibre-optic, wireless, satellite and microwave systems; but fibre optic is now the predominant technology. Major fibre optic networks provided by companies such as Telstra, SingTel-Optus, PowerTel, Uecomm and NextGen connect Sydney and the major east-coast cities. Total bandwidth capacity of satellites covering Australia is estimated to be 4 Gb s^{-1}.

Photo 18.4
An optical fibre lamp.



The installation of asymmetric ADSL (asymmetric digital subscriber line) technology into local telephone exchanges is connecting businesses and residential homes into a high-speed digital broadband network. SingTel-Optus uses a fibre optic cable network (CABLE) which is supported on the local powerline distribution grid. With data speeds from 256 kb s^{-1} to over 2 Mb s^{-1}, everyone will have access to Internet speeds 30–50 times faster than the standard dial-up service. New South Wales carries the majority of Australia's Internet traffic. Over 500 Internet service providers in Australia use Internet Protocol (IP) technology, which mixes voice, data and video transfer over the same networks.

Figure 18.22
An optical fibre consists of a thin glass fibre of higher refractive index than the outside cladding layer. Thus total internal reflection is used to reflect light pulses along the length of the fibre.



Activity 18.3 INTERNET CONNECTIONS

Compare and contrast ADSL, cable and the standard 56K V90 modem. In your discussion discuss the upload and download speeds of ADSL, cable and dial-up, as well as the pricing plan for the major Internet service providers in your local area. Are there any other factors that you need to consider when thinking about installing an Internet connection into your home and computer system?

Medical

The medical profession was the first to make use of optical fibres. Surgeons use bundles of fibres to look inside a person's stomach and lungs without surgery. A bundle of fibres is introduced into the stomach via the throat. Light is shone down some of the fibres and reflected light from the stomach is transmitted back via other fibres. If, for example, an ulcer is discovered, a laser beam is transmitted down the fibres to burn and seal the ulcer. These devices are commonly called 'endoscopes'. Most recently fibre optic endoscopes have been used coupled with colour video cameras and external video monitors to increase ease of viewing. (The word endoscope comes from the Greek *endo skopion* meaning 'within' and 'to see'.)

Other effects of total internal reflection

Mirages

Mirages result from refraction and total internal reflection. On a hot day imaginary pools of water appear on the road or the desert. As rays of light from the sky reach the ground they undergo gradual refraction in the layers of hot air above the road. The rays end up hitting the hot layer just above the ground at an angle greater than the critical angle and thus are reflected from this layer to the observer who sees the layer as a pool of water. In fact, it is the reflection of the sky (Figure 18.23).

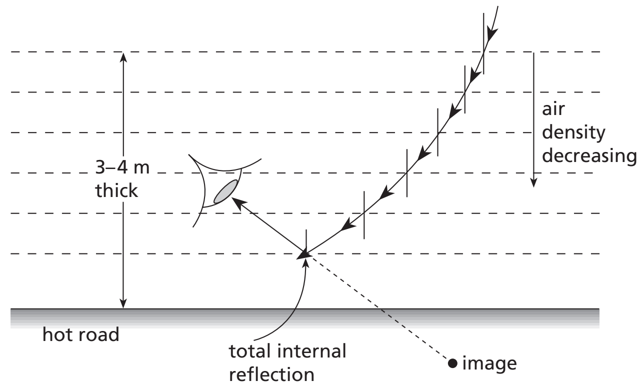


Figure 18.23
A mirage is formed when light from the sky is refracted as it passes through the different density layers of air above a hot surface. It is reflected from the bottom hot layer.

Rainbows

A rainbow forms when water droplets in the rain refract the sunlight. The process actually involves two refractions and a total internal reflection (Figure 18.24).

When sunlight from behind the observer strikes rain droplets in front of the observer the light is refracted on entering the droplet, totally internally reflected, and refracted on leaving. Red light is refracted the least and violet the most, therefore a person on the ground sees red light from high in the sky and the other colours from raindrops closer to the ground.

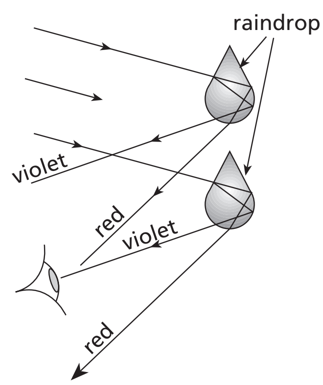


Figure 18.24
A rainbow is formed when sunlight undergoes refraction and reflection inside raindrops.

INVESTIGATING

A 'blue sky' is due to the scattering of sunlight. But so is a 'red sky'.
How can you resolve this anomaly?

Questions

18 Optical fibres have a less optically dense layer surrounding the fibre so as to produce total internal reflection. If the fibre has a refractive index of 1.70 and the outside cladding layer has a refractive index of 1.48:

(a) calculate the minimum angle at which light incident on the junction is totally internally reflected;

(b) find the speed of light in the fibre.

19 A scuba diver working in the ocean looks up to notice the Sun setting on the horizon. At what angle to the normal to the surface will he need to look? ($n_{\text{salt water}}$ = 1.38.)

Activity 18.4 RESEARCH QUESTIONS

Write a short report on one of the following topics:

Diamonds Why do real diamonds sparkle more than counterfeit ones? In your answer describe the 'brilliant cut' — one of the most common styles of faceting a diamond. How many separate facets are there in the 'brilliant cut' and who invented it?

Endoscopy Fibre optics endoscopy is used for examining the oesophagus, pancreas and bladder, among other organs, to detect the presence of cancer. Name two other medical conditions endoscopy is used for, and say how the endoscope is inserted, and how the doctor views the image.

Phone cables Find out the following about fibre optic phone cables:

1. What is the distance between boosters?
2. How is the cable joined?
3. What is the diameter of a single fibre?
4. How far underground is the cable buried?
5. What is multiplexing?

Glass fibre Early trials of optic fibres in medicine were unsuccessful but in 1970 Corning Glass overcame the problem. What was the problem and how was it solved?

UFO sightings UFO hoaxes have often been achieved by reflection–refraction phenomena. Research some of the more famous hoaxes, or try to videotape your own hoax. Late in the afternoon with the lights out in your house or garage, stand at a window and hold a torch in one hand. Direct the strong torch beam out of the window. You will be able to see the transmitted light from the backyard and sky as well as a superimposed reflection of the torch light in the window. You can make the reflected spot of light hover and shimmer as if it were out in the yard. A simple video recording of this type of reflection has been the basis of some famous UFO hoaxes in the past. Try it yourself and have some fun.

PHYSICS FACT

Have you noticed the green iridescent colours that sometimes appear on bacon and corned meat? This is not rotting meat but is caused by microscopic droplets of oil and water of differing refractive indices on the surface causing the interference of light. If it goes really green then that's the bacteria breaking down the oxygen transport protein (myoglobin) to produce green compounds. Heat will show the difference. Heat will make the oil droplets go away but not the green rot.

Practice questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

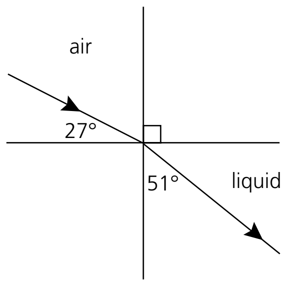
Review — applying principles and problem solving

***20** For each of the following situations where a light ray passes from one medium to another, state whether the light ray will bend away from or toward the normal:
- **(a)** Air to water.
- **(b)** Glass to air.
- **(c)** Water to glass.
- **(d)** Diamond to glass.
- **(e)** Flint glass to crown glass.
- **(f)** Perspex to a vacuum.

***21** A light ray strikes the surface of a block of fused quartz at an angle of 54° to the normal.
- **(a)** Calculate the angle of refraction.
- **(b)** Find the velocity of light in the quartz.

***22** Light from a light box is directed at an angle of 30° onto a block of glass whose refractive index is 1.5, and then onto the surface of salty water whose refractive index is 1.4. In which case will the light bend the most?

Figure 18.25
For question 23.



NOVEL CHALLENGE

Have you ever taken a photo of reflections in a still pool of water? Imagine you photographed some wallabies resting next to a still dam. How could you tell which way to hold the photo if the reflection was a perfect copy?

***23** A ray of light is directed onto the surface of a liquid as shown in Figure 18.25. Calculate the speed of the light in the liquid.

***24** Calculate the absolute refractive index for light going from air to a medium when the velocity of light in the medium is **(a)** 2.4×10^8 m s^{-1}; **(b)** 1.8×10^8 m s^{-1}; **(c)** 2.7×10^8 m s^{-1}; **(d)** 3.6×10^8 m s^{-1}.

***25** What is the relationship between the relative refractive index for light passing from glass to diamond ($n_{g \to d}$) and the absolute refractive indices of glass (n_g) and diamond (n_d)?

***26** The absolute refractive indices of certain media are **(i)** 1.78; **(ii)** 1.2; **(iii)** 2.1; **(iv)** 1.42.
(a) Calculate the speed of light in each of the media.
(b) Which substance is the most optically dense?

***27** The refractive indices of flint glass and turpentine are 1.65 and 1.5 respectively.
(a) Calculate the refractive index for light passing from turpentine to flint glass.
(b) If the angle of incidence in the turpentine is 49° calculate the angle of refraction in the flint glass.

***28** Red light from a laser of wavelength 633 nm is used in refraction experiments. What is the wavelength of this light in glass? ($n_g = 1.5$.)

****29** Biology students on a rocky shore excursion notice that a shell in a rock pool appears to be 50 cm from the surface of the water, but a physics student informs them this is not correct.
(a) What depth is the rock pool really? (The refractive index of water is 1.33.)
(b) How is the real depth influenced by the fact that it is salt water rather than fresh water?

****30** A mirage is formed when light from the sky passing through cool layers of air into hotter layers just above the road is totally internally reflected. Calculate the critical angle for light travelling from cool air to hot air. ($n_{\text{cool air}} = 1.0004$ and $n_{\text{hot air}} = 1.0002$.)

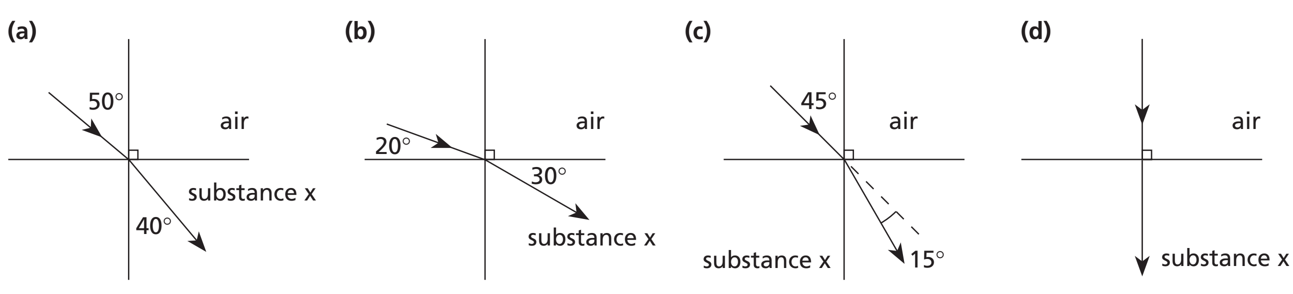
****31** Through what surface area can a fish see if it is 5.0 m deep in sea water? ($n_{sw} = 1.38$.)

****32** A pulse of light enters an optical fibre of refractive index 1.53. What is the refractive index of the cladding material if the critical angle required is 82°?

****33** The index of refraction for glass is different for different colours of light. The refractive index for blue light (λ = 430 nm) passing from air into flint glass is 1.650 and for red light (λ = 680 nm) is 1.615. If a beam containing blue and red light is shone onto a block of flint glass at an angle of 52°, find the angle between the blue and the red rays in the glass.

***34** In each of the four cases shown in Figure 18.26, a light ray travels from air to the substance. Use the diagrams to find the refractive index of the substances.

Figure 18.26
For question 34.



****35** Students experimenting with an unknown transparent substance used a light box to produce a ray of light. They shone the ray onto the unknown substance at various angles and measured the angles of refraction. Refer to Table 18.4.

Table 18.4

Angle of incidence, i (degrees)	20	30	40	50	60	70	80
Angle of refraction, r (degrees)	10	15	20	24	27	30	31

(a) Redraw the table including values of sin i and sin r.
(b) Plot a graph of sin i against sin r.
(c) What shape graph was obtained?
(d) What is the relationship that exists between sin i and sin r?
(e) From this graph find the refractive index of the substance.
(f) What is the substance?

***36** Complete the diagrams shown in Figure 18.27 where a ray of light passes from air to a block of glass.

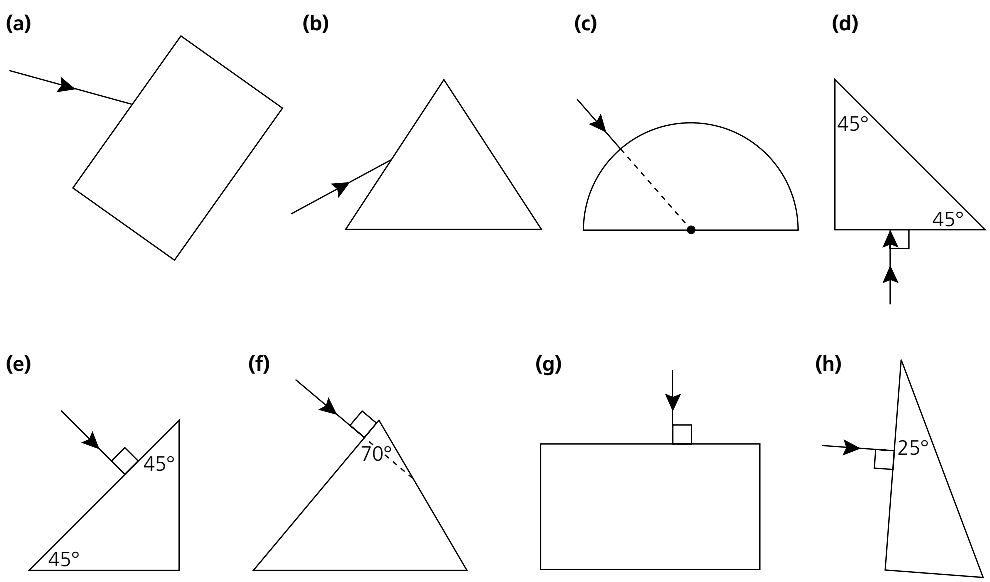


Figure 18.27
For question 36.

37 A ray of light strikes the surface of a beaker of water at the centre of the surface. If the ray hits the bottom of the beaker 4.0 cm from the centre (refer to Figure 18.28), calculate the angle of incidence. (n_w = 1.33.)

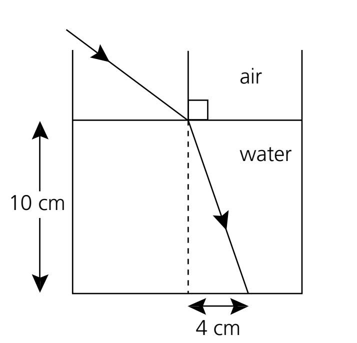


Figure 18.28
For question 37.

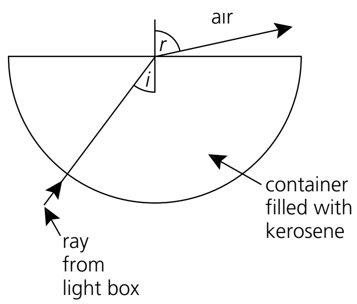


Figure 18.29
For question 38.

**38 Students were given the task of finding the critical angle for light passing from kerosene to air. They filled a semicircular container with kerosene and used a light box to produce a single ray. They intended to shine the ray through the curved side of the container onto the centre of the straight edge and gradually increase the angle of incidence until the refracted ray was along the straight edge. (Refer to Figure 18.29.) However, before they finished the experiment the power went out, but they did take some measurements before this happened. Refer to Table 18.5. Graphically find the critical angle.

Table 18.5

Angle of incidence, i (degrees)	10	15	20	25	30	35	40
Angle of refraction, r (degrees)	13	22	30	38	47	57	70

Extension — complex, challenging and novel

***39 A beam from a laser strikes the surface of a 5.0 cm thick block of Perspex at an angle of 41° to the normal. Find the perpendicular distance between the original direction of the beam and the direction of the beam as it leaves the Perspex. (See Figure 18.30.)

Figure 18.30
For question 39.

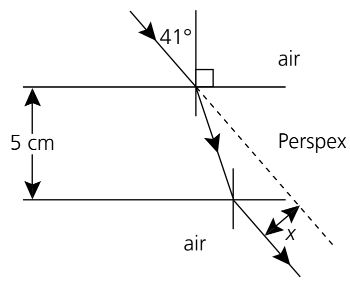
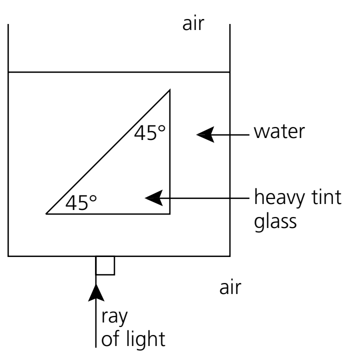


Figure 18.31
For question 40.



***40 A 45°/45° heavy flint glass prism is placed in a beaker of water. A ray of light from a light box is incident on one side of the prism. (Refer to Figure 18.31.) Analyse the passage of this ray through the water and the glass prism. (n_g = 1.62, n_w = 1.33.) Use a labelled diagram to show the passage of the light ray.

**41 A beam of white light is shone onto a glass prism such that the angle with the second surface is the critical angle for yellow light. (Refer to Figure 18.32.) Analyse what occurs to the beam of white light.

**42 In one of his first optics experiments, Newton laid two prisms and a sheet of paper on a bench; from overhead they appeared as in Figure 18.33.

He allowed a beam of white light to enter from the left (shown by the arrow), where it split into its colours and fell on to the second prism. What will you see on the paper screen on the right, lying flat on the bench?

Figure 18.32
For question 41.

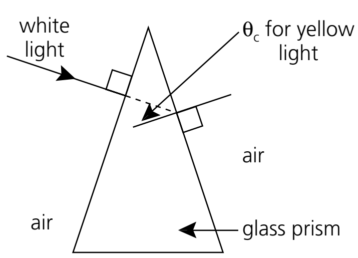
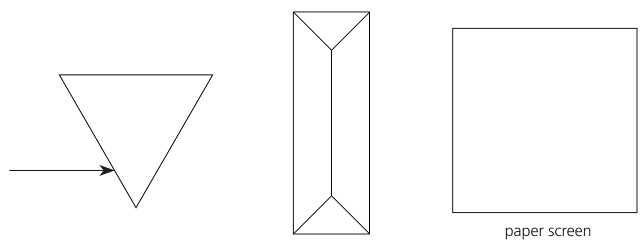


Figure 18.33
For question 42.



43 **(a) The plastic rings holding a six-pack of beer stubbies together is made from polythene. It has the same refractive index as sea water, as a result of which animals often eat them or get stuck in them. Propose as many ways as you can of solving this problem. We can think of at least four.

(b) The velocity of light is less in saltwater than in fresh. What would a rainbow look like in a saltwater spray?