Electromagnetic waves and geometrical optics

Unit 6

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Contents

Section	Learning competencies
	• Identify that the passage of a ray of light through a parallel-sided transparent medium results in the lateral displacement of a ray. • Define the critical angle θ_c. • Explain, with the aid of a diagram, what is meant by critical angle and total internal reflection. • Identify the conditions necessary for total internal reflection to occur. • Perform calculations involving critical angle and total internal reflection. • Describe how total internal reflection is used in optical fibres. • Distinguish between convex and concave lenses. • Identify the meaning of: principal focus, principal axis, focal point, radius of curvature, magnification in relation to converging and diverging lenses. • Apply the appropriate sign convention when using thin lens equations. • Find the position and nature of the image formed by a convex and concave lens using the thin lens formula and a ray tracing method. • Define the power of a lens. • Explain how the image is formed due to combination of thin lenses. • Draw a ray diagram to show how images are formed by lenses in a simple microscope and a simple telescope. • Compare and contrast the structure and functions of the human eye and the camera. • Describe how the human eye forms an image on the retina for different object distances. • Identify some defects of the eye and their correction with lenses. • Explain what is meant by the dispersion of white light to produce a spectrum. • Identify that the passage of a ray of light through a triangular transparent prism results in a deviation of a ray.

6.1 Electromagnetic waves

By the end of this section you should be able to:

- Explain how electromagnetic waves are produced.
- Describe the nature of electromagnetic waves.
- Compare mechanical and electromagnetic waves.
- Draw diagrams to represent transverse waves.
- Use straight lines to represent the direction of energy flow (rays).
- Identify that electromagnetic waves emitted by the Sun have a wide continuous range of frequencies (and wavelengths).
- Explain some uses of electromagnetic radiation.

KEY WORDS

transverse waves *waves that oscillate perpendicular to the axis along which they travel*

mechanical waves *travel through a material or substance, with time. They have frequency, period, wavelength and amplitude*

electromagnetic waves *transverse waves produced when a magnetic field and an electric field are at right angles to each other*

Types of wave

There are two types of wave: transverse and longitudinal. In this unit we shall be considering **transverse waves**.

All waves are produced by vibrations. In a transverse wave, the vibrations are at right angles to the direction of movement, as shown in Figure 6.1.

Figure 6.1 *Transverse waves.*

Mechanical waves travel through some medium (material), with time. They have a frequency, period, wavelength and amplitude. Mechanical waves transport energy and not material.

Electromagnetic waves

The vibrations in **electromagnetic waves** come from electric and magnetic fields. Electromagnetic waves are produced when a magnetic field and an electric field are at right angles to each other. Charges that are accelerated in an electric and magnetic field produce electromagnetic waves. They carry energy and momentum that may be transferred to matter with which they interact.

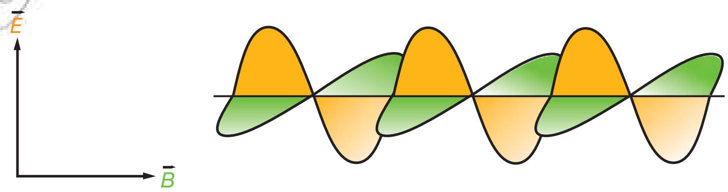


Figure 6.2 *Electromagnetic waves.*

Electromagnetic waves are transverse waves. Electromagnetic waves do not need a medium through which to travel – they can travel through a vacuum.

Activity 6.1: Modelling an electromagnetic wave

You will need to stand with a group of 20 of your fellow students in a line. Number yourselves from 1 to 20. Those of you who have an odd number are to represent the magnetic field. Those of you who have an even number are to represent the electric field.

Those of you who are representing the magnetic field should hold your hands out in front of you, while those of you who are representing the electric field should hold your hands in the air, as shown in Figure 6.3.

You learnt about Faraday's law in Unit 4. Remember that if you increase an electric field, you will induce a magnetic field and that decreasing the electric field will induce a magnetic field in the opposite direction.

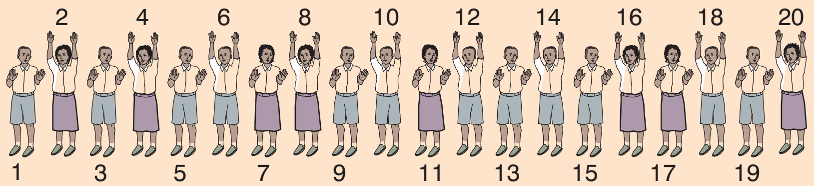


***Figure 6.3** Students representing an electromagnetic wave.*

Demonstrate Faraday's law using your hands: you can represent changes in the electric field by changing the height of your hands in the air and represent changes in the magnetic field by turning through 180°.

Representing transverse waves

You can draw diagrams to represent transverse waves such as the one in Figure 6.4.

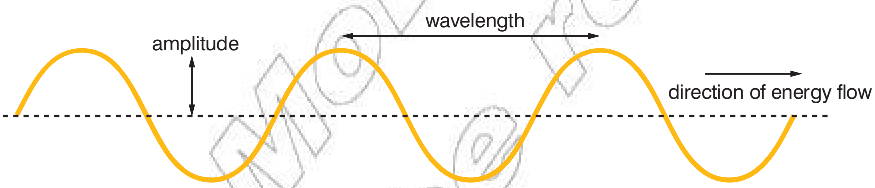


***Figure 6.4** Transverse wave diagram.*

The **amplitude** is the distance that the wave moves above or below the base line. The **frequency** of a wave is the number of complete waves passing a given point in a second. The **wavelength** is the distance between successive equivalent points (usually taken as peaks or troughs) on a wave. You can use straight lines (**rays**) to represent the direction of energy flow along the wave.

Relationship between frequency, wavelength and speed

The frequency, wavelength and **speed** of a wave are related by the formula:

speed = frequency × wavelength

In symbols this is written as:

$v = f\lambda$

The units need to be:

- speed: m/s
- frequency: Hertz
- wavelength: metres.

Activity 6.2: Compare mechanical and electromagnetic waves

In a small group, draw up a table to compare mechanical and electromagnetic waves. Make sure you understand what it is that is moving in each case.

KEY WORDS

amplitude *the maximum distance a wave moves above or below the base line*

frequency *the number of complete waves passing a given point in a second*

wavelength *the distance between successive peaks or troughs on a wave*

rays *straight lines extending from a point*

speed *distance travelled per unit time*

DID YOU KNOW?

Heinrich Hertz (1857–1894) was a German physicist who was the first to demonstrate satisfactorily the existence of electromagnetic waves by building an apparatus to produce and detect VHF or UHF radio waves.

The unit of frequency for waves is named after him.

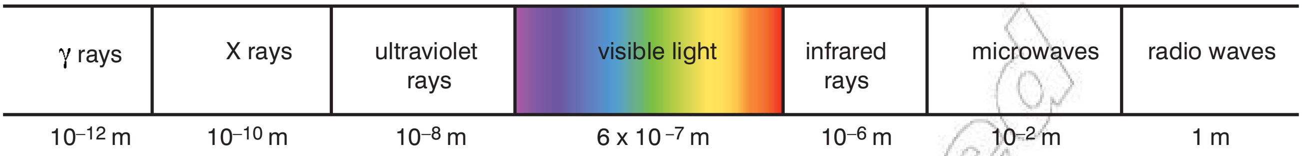


Figure 6.5 *Electromagnetic spectrum.*

Worked example 6.1

A water wave has a wavelength of 2 cm and a frequency of 15 Hz. Find its speed.

v (m/s)	λ (m)	f (Hz)
?	2 cm	15

First we need to make sure that the given values are in the correct units.

Wavelength = 2 cm = 0.02 m

Frequency = 15 Hz

Substitute these values into the equation:

speed = frequency × wavelength

gives

speed = 15 × 0.02
= 0.3 m/s

Activity 6.3: Uses of electromagnetic radiation

In a small group, design a poster showing uses of electromagnetic radiation. You may also like to include some hazards of electro-magnetic radiation – do some research to find out about gamma rays, for example.

KEY WORDS

electromagnetic spectrum *the entire frequency range of electromagnetic waves*

Electromagnetic waves emitted by the sun

The Sun emits electromagnetic waves with a wide range of frequencies and wavelengths. This is generally referred to as the **electromagnetic spectrum**, as shown in Figure 6.5.

In a vacuum, all electromagnetic waves travel at a speed of 3×10^8 m/s. They have different properties (and therefore uses) because, as shown in Figure 6.5, they have different wavelengths (and therefore frequencies).

Some uses of electromagnetic radiation

Visible light is the most important part of the electromagnetic spectrum to everyday life, even though its wavelengths are only a small part of the spectrum.

X-rays are used to take pictures of inside the body to show any bone fractures. They are absorbed more by bone (which is denser than the surrounding muscles).

Infrared radiation is used in infrared cameras, which are used in rescue operations to detect the presence of bodies.

Microwaves and radio waves are used for communications – for example, radio and telephone signals.

Figure 6.6 *Some uses of electromagnetic radiation.*

Summary

- Electromagnetic waves are produced when electric fields and magnetic fields are at right angles to each other.
- Electromagnetic waves are transverse waves that can travel in a vacuum.

- Mechanical waves transfer energy and need a medium through which to travel. Electromagnetic waves can travel through a vacuum. They have energy and momentum that may be transferred to bodies with which they interact.
- You can draw diagrams to represent transverse waves and use straight lines to represent the direction of energy flow (rays).
- Electromagnetic waves emitted by the Sun have a wide continuous range of frequencies (and wavelengths) – this is called the electromagnetic spectrum.
- X-rays are used to take pictures of inside the body to show any bone fractures. They are absorbed more by bone (which is denser than the surrounding muscles).
- Infrared radiation is used in infrared cameras which are used in rescue operations to detect the presence of bodies.
- Microwaves and radio waves are used for communications – for example, radio and telephone signals.

Review questions

1. Explain how electromagnetic waves are produced.
2. Describe the nature of electromagnetic waves.
3. Compare mechanical and electromagnetic waves.
4. Draw a diagram to represent a transverse wave. Show its amplitude, frequency and wavelength. Use straight lines to represent the direction of energy flow (ray).
5. What is the relationship between speed, frequency and wavelength for a transverse wave?
6. Give some types of electromagnetic waves on the electromagnetic spectrum.
7. What is the frequency of an X-ray with a wavelength of 1×10^{-10} m?

6.2 Reflection of light

By the end of this section you should be able to:

- Explain what is meant by the rectilinear propagation of light.
- State the laws of reflection.
- Perform experiments to test the laws of reflection using a plane mirror.
- Use the laws of reflection to explain how images are formed in a plane mirror.
- Find the position of a virtual image produced by a plane mirror using a ray tracing method.
- Use the laws of reflection to solve problems.
- Give examples of the uses of plane mirrors.
- Distinguish between concave and convex mirrors.
- Identify the meanings of: principal axis, principal focus, radius of curvature, magnification in relation to concave and convex mirrors.

- Distinguish between real and virtual images.
- Apply the appropriate sign convention when using mirror equations.
- Find the position and nature of the image formed by a concave and a convex mirror using the mirror equation and a ray tracing method.
- Use the relation magnification = $\frac{s_i}{s_o} = \frac{h_i}{h_o}$ to solve problems.
- Give examples of the uses of curved (concave and convex) mirrors.

Rectilinear propagation of light

In the previous section, you learnt that visible light is a form of electromagnetic radiation, or electromagnetic wave. **Rectilinear propagation** of light simply means that light waves travel in straight lines.

KEY WORDS

rectilinear propagation *a wave property by which waves travel in straight lines*

Activity 6.4: Investigating the reflection of light

Set up the apparatus as shown in Figure 6.7.

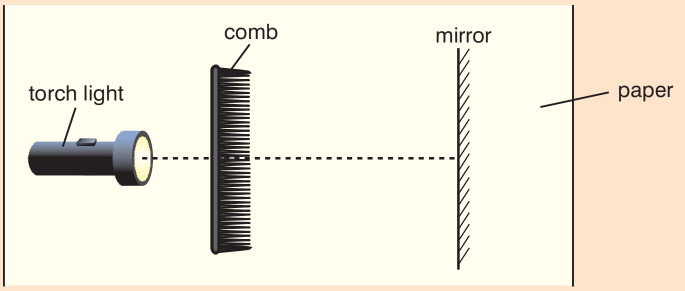


Figure 6.7 *Apparatus for investigating the reflection of light.*

Break every other tooth of the comb. Draw the rays that appear to be coming from the mirror on the paper.

Activity 6.5: Natural examples of reflection

In a small group, make a list of where you see reflection in nature.

The laws of reflection

Before we go on to state the laws of reflection, we need to sort out a few points.

The first is that angles are not measured from the mirror surface itself, but from a construction line called the normal. This line is at right angles to the mirror surface and should be drawn dotted. Thus a beam of light hitting the mirror at an angle of 30° would look as shown in Figure 6.8.

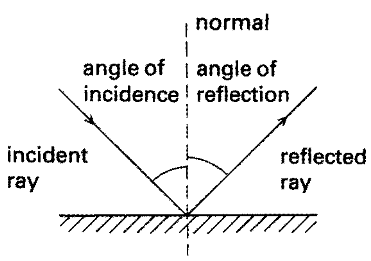


Figure 6.8 *Angles are measured from the normal.*

Remember that **angles are always measured from the normal**. It is easy to forget this and measure the wrong angle.

The beam of light on its way to the mirror is called the incident ray. It hits the mirror ('is incident upon the mirror') at a particular angle of incidence. After that the reflected ray leaves the mirror at the appropriate angle of reflection. Figure 6.9 illustrates this.

Now we can consider how light behaves when it is reflected. The results of Activity 6.4 can be summed up in two laws. The first law of reflection is straightforward:

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

In other words, if light hits a mirror at 30° to the normal, it will leave the mirror at 30° to the normal too.

At first sight this one law says everything. It takes a bit of thought to realise that this is not so. There is actually an endless number of possible rays of light at 30° to the normal, and they form a kind of cone round the normal, as in Figure 6.10.

The ray we mean is the one opposite to the incident ray. This is expressed more scientifically in the second law of reflection:

The reflected ray lies in the plane which contains the incident ray and the normal.

The word 'plane' means flat surface, like a sheet of paper. An ordinary flat mirror is more correctly known as a **plane mirror**.

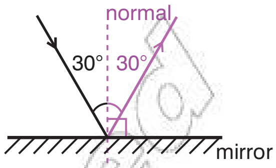


Figure 6.9 *Reflection at a mirror.*

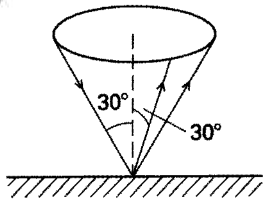


Figure 6.10 *The reflected ray is the one opposite to the incident ray.*

Why you cannot see your reflection in a sheet of paper

A sheet of white paper is a good reflector, yet it is useless if you wish to see to comb your hair. Why?

We say it is a good reflector because of all the light energy landing on it, perhaps 90% or more is reflected off again. It does not form a visible **image**, however, because that light gets scattered in all directions.

The key to this behaviour lies in the surface of the paper. At a microscopic level the paper is all humps and bumps whereas a mirror is smooth. The consequence of this is shown in Figure 6.12.

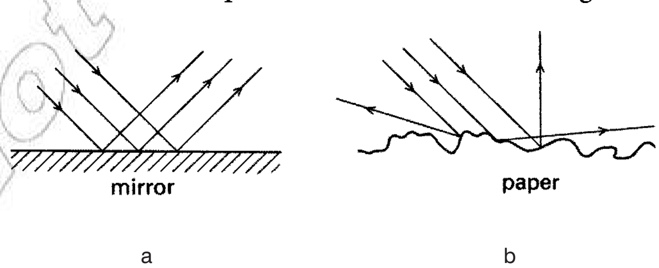


Figure 6.12 *a) Regular and b) diffuse reflection.*

Notice that with the paper the laws of reflection apply as much as with a mirror. The light still gets reflected off at the same angle that it hit the surface: it is just that the surface points in different directions.

A shiny black surface is just the opposite of the paper. It is smooth, but it absorbs much of the light that lands on it. The small amount of light that gets reflected leaves in a regular manner and so you may be able to see a faint reflected image in it.

Activity 6.6: Making a simple periscope

Figure 6.11 shows the principles of a simple periscope.

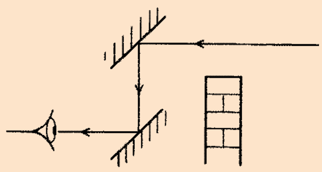


Figure 6.11 *Principles of a simple periscope.*

If you can acquire two small plane mirrors, you could make one for yourself. Each mirror needs to be inclined at an angle of 45°, so you will need to design a cardboard tube to support them.

KEY WORDS

plane mirror *a mirror whose surface lies in a plane*

image *an optically formed reproduction of an object*

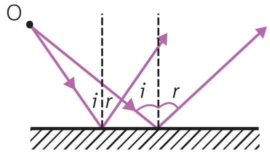


Figure 6.13

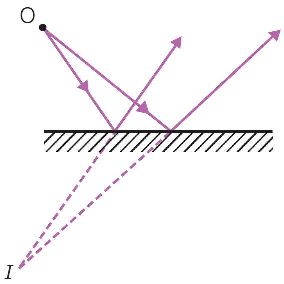


Figure 6.14

Using the laws of reflection to explain how images are formed in a plane mirror and using a ray tracing method to find the position of the image

Consider the mirror shown in Figure 6.13, with the object at point O.

The first law tells us that the angle of incidence is equal to the angle of reflection, so in the diagram $i = r$.

Now trace the reflected rays beyond the mirror using dotted lines, as shown in Figure 6.14.

The point where the dotted lines meet is the position of the image, I.

Worked example 6.2

The diagram shows a small source of light 'O'. Marked on the diagram are the edges of a cone of light which eventually enters the eye of a person placed roughly as shown in Figure 6.15.

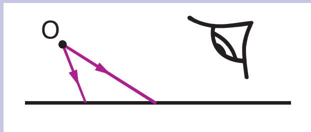


Figure 6.15

a) Using a sharp pencil and a ruler, draw a diagram which looks similar but larger. Leave some space below the mirror. Don't put the eye in the diagram at first.

b) With the aid of a protractor, accurately draw in the normals (dotted lines) where the edges of the cone of light meet the mirror. For each one, carefully measure the exact angle of incidence (from the normal!) and accurately draw the paths of the light after reflection.

c) The light entering the eye is diverging (i.e. spreading out). To locate the spot from which the light seems to be coming, extend each of your two reflected lines backwards to where they meet (again use dotted lines for this: no light actually takes that route).

a)

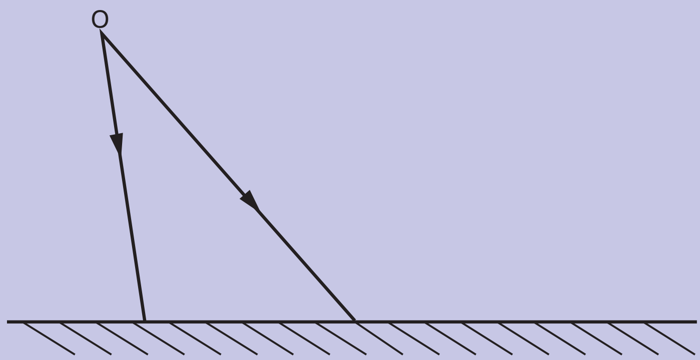


Figure 6.16

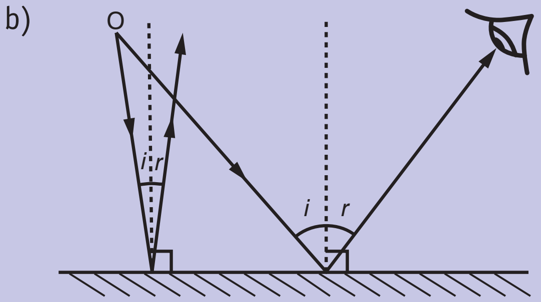


Figure 6.17

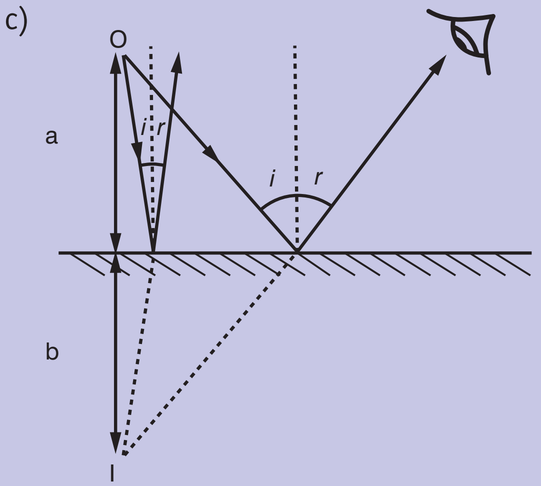


Figure 6.18

Activity 6.7: The uses of plane mirrors

Work in a small group to make a list of all the uses of plane mirrors that you can think of.

Concave mirrors

In the worked example above you found that, in a plane mirror, the image is erect, virtual, laterally inverted, and the same size as the object.

We will now consider curved mirrors. You have probably seen reflections in polished metal spheres. A shiny tablespoon forms reflections from its inside surface and from its outside surface. All these reflections are images, things we see even though the object is somewhere else. This section considers how these images are formed.

First, we must sort out a few names. All the mirrors in this section are spherical mirrors, which means that they are shaped like part of the surface of a sphere; their curvature in all directions is the same.

We will start with a **concave mirror**. Its shape and the way it behaves are shown in Figure 6.19, and you should soon be able to convince yourself that this is exactly in line with the basic laws of reflection.

KEY WORDS

concave mirror *a mirror with a reflecting surface that bulges inwards, away from the light source*

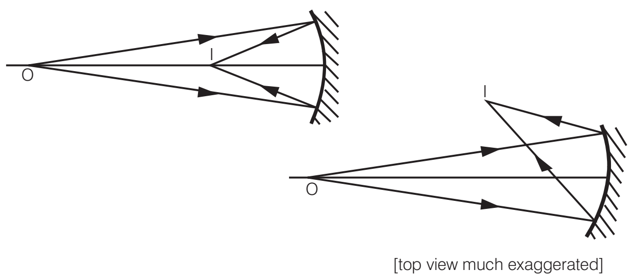


Figure 6.19 *Light reflecting off a concave mirror.*

Activity 6.8: Investigating the behaviour of a concave mirror

What happens as the object comes closer? The mirror may then still use the laws of reflection to bring the light to a focus, but if so it will no longer be at the focus (that is, the **principal focus**).

Experiment and find out. Figure 6.20 shows a possible experimental set-up.

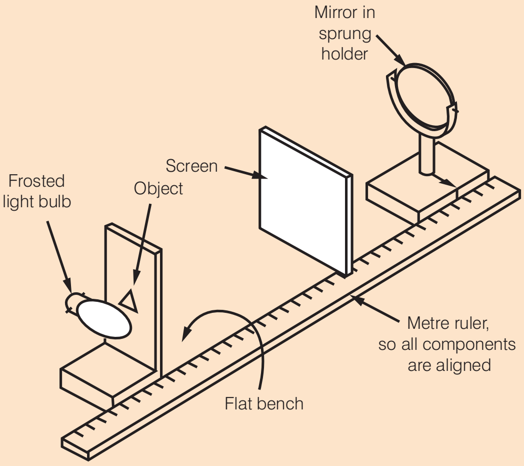


Figure 6.20 *Possible experimental set-up.*

The object is a triangular-shaped hole in a wooden board, and fine detail in the object is provided by a wire gauze across the hole. This fine detail helps in judging when the image is in sharp focus on the screen. (An alternative is a transparent plastic ruler with clear markings, held in a clamp.) To ensure that the image is bright enough to see, the object is illuminated from the back, just like the slide in a slide projector.

Start with the object as far away from the mirror as you can, around 1 m perhaps. The task now is to find where a screen must be to obtain a clear focused image on it. Immediately a difficulty crops up: the screen will have to be put right in the way of the light on its way to the mirror (as shown in Figure 6.19).

The easiest way round the difficulty is to have the mirror at a slight angle – as shown in the lower diagram of Figure 6.19, which is much exaggerated.

Once the apparatus is set up, test it fully. You should find you can get a sharp upside-down image on the screen. As the object gets closer to the mirror the screen has to be moved further and further back, while the image gets larger and larger.

KEY WORDS

focus *the point at which light rays converge*

convex mirror *a mirror with a reflecting surface that bulges outwards, towards the light source*

focal length *the distance from the centre of a curved mirror to the principal focus*

Concave mirrors and magnification of images

In Activity 6.8, you found that as the object approached the principal focus of the mirror, the screen had to be moved a great distance away. Once you are inside that focus there is nowhere for the screen to go to receive an image on it – the mirror no longer forms a real image anywhere.

Using your own face as the object, you will find that when you are close enough the mirror can still be used as a looking glass. It forms a virtual image, just as a plane mirror did. Conveniently, this image is the right way up and there is one big difference compared to the plane mirror: the image is larger than the object. It has been magnified. The field of view is less than that in a plane mirror. The magnification produced, however, means that a converging mirror is sometimes used as a men's shaving mirror.

Convex mirrors

Convex mirrors reflect the light so it spreads out. If the incoming light is a parallel beam, we take as the focal length the distance from the principal focus '*f*' to the centre of the mirror (see Figure 6.21).

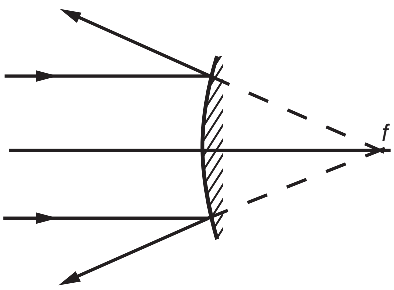


Figure 6.21 *Light reflecting off a convex mirror.*

A convex mirror cannot form a real image, so you will never need a screen with it. It can act as a looking glass, however, and you will be able to use it to see a virtual image, which seems to be a short way behind it.

This image has the following properties:

1. It is always the right way up.
2. It always has a **magnification** of less than 1. Although everything appears smaller, this means that the complete field of view is a wide one.
3. It has a striking clarity. This is because normally our eyes can only focus clearly on a limited range of distances – we can look at a fly crawling up a window pane or we can look at the view outside but not both at the same time. In the mirror all objects from nearby to the far distance are seen as images compressed into the short distance between the mirror and its focus. Now our eyes can view them all clearly at the same moment – a unique experience.

KEY WORDS

magnification *the ratio between the height of an image and the height of the object*

principal axis *the line passing through the optical vertex and centre of curvature of the face of a curved mirror*

principal focus *the point at which all light reflecting from a curved mirror converges*

radius of curvature *the radius of the sphere that forms the basic curve of a concave mirror*

real image *an image that can be captured on a screen*

Terms used in concave and convex mirrors

Figure 6.22 summarises the terms you have already met in relation to concave and convex mirrors. It shows the **principal axis**, **principal focus** and **radius of curvature** of a concave and a convex mirror. The magnification is given by $\frac{\text{height image}}{\text{height object}}$.

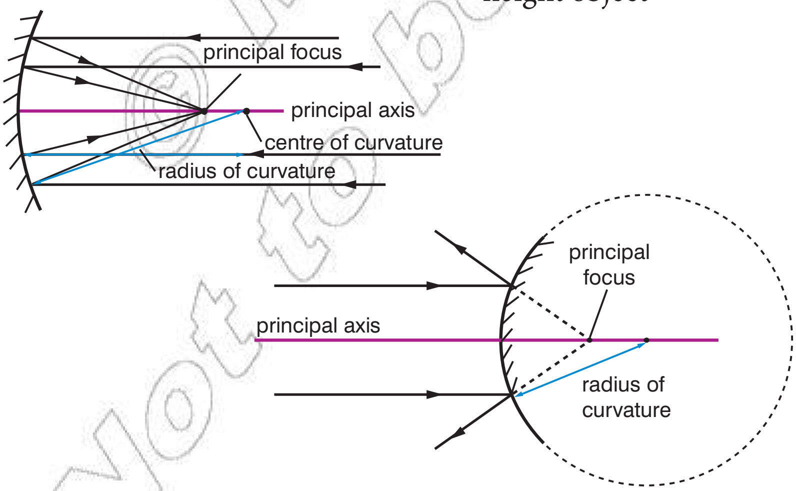


Figure 6.22 *Terms used in relation to concave and convex mirrors.*

Distinguish between real and virtual images

We have already met the terms real and virtual images. Now we shall explain what these terms mean.

When you can focus the light from an image on a screen, the image is called a **real image**. If no screen happens to be there, the light actually passes through that point, and an alternative way to view it is simply to stand back from it and look.

KEY WORDS

virtual image *an image that cannot be captured on a screen*

Notice that you must be sufficiently far back from the image to be able to see it. Placing your eye at the image position itself is like trying to read this book by resting your eyeball on the page.

The image produced by a plane mirror is different. We can stand back and view the image just the same, but this time it has been produced by what you could describe as a trick. If you put a screen behind the mirror, of course, no image will be formed on it because the light never actually started from that point. We call this a **virtual image**.

Activity 6.9: The uses of concave and convex mirrors

Some cars use diverging mirrors. Plane mirrors are also available and are sometimes fitted. It is not so easy to judge distances in them, but diverging mirrors provide a far better field of view (see Figure 6.23).

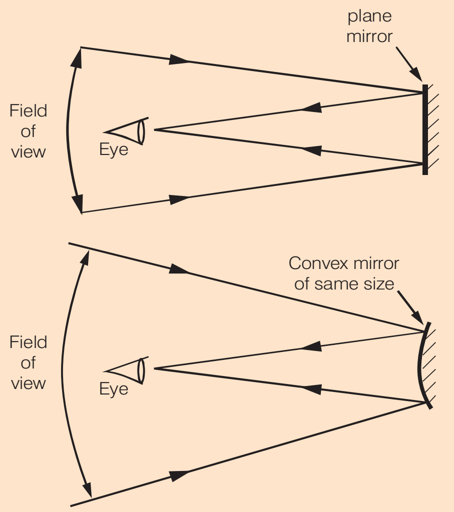


Figure 6.23 *Light reflecting off a car mirror compared to a plane mirror.*

Figure 6.24 *Light reflecting off a bus's mirror.*

In a small group, make a list of as many uses for concave and convex mirrors as you can. Think about their magnification and their field of view if it helps you to think about where they may be used.

Why we think of light from distant objects as parallel

It is not quite mathematically parallel, but as far as measurements are concerned it is parallel enough for the accuracy we are seeking.

The more distant the better, of course. Only a point object at infinity would give perfectly parallel light, but an object several metres away (let alone the Sun at about 1.5×10^{11} m distance) is adequate for our measurement.

Activity 6.10: Determining the focal length of a concave mirror

Imagine a test beam of parallel light being shone along the principal axis of a concave mirror. It will be brought to a focus (the *principal focus, F*) of the mirror. The distance from the principal focus to the vertex of the mirror is its *focal length, f*. The greater the curvature of the mirror, the closer will be its principal focus and the shorter its focal length will be (see Figure 6.25).

The easiest way to find the focal length is to shine parallel light onto the mirror and see where this light is brought to a focus. Hold the mirror in a stand and take a screen – a sheet of paper will do if need be. Light coming from distant objects is sufficiently parallel for this purpose, so move the paper towards the mirror until an image of a window at the far side of the room (or, even better, a tree in the distance) is formed clearly on the screen. It will be upside down, quite small and – to many people's surprise – in colour.

Measure the distance from the screen to the vertex of the mirror, and you have its focal length.

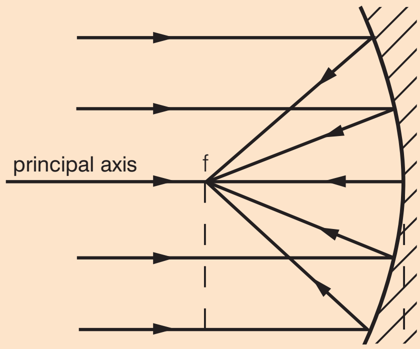


***Figure 6.25** Light coming to a focus after reflection from a concave mirror.*

The mirror equation

If you know the focal length of a converging mirror, it is possible to do a calculation to give answers to questions such as 'If I place an object at a given distance from the mirror, whereabouts will I have to put the screen, and how big will the image be?'

The notation used is:

f = the focal length of the mirror.

s_o = the distance from the object to the centre of the mirror.

s_i = the distance from the centre of the mirror to where the image is formed.

If the image is virtual, then we use a negative sign for the distances.

The connection between them is:

$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$$

Worked example 6.3

A mirror has a focal length of 200 mm (0.20 m). If an object is placed 0.60 m from the mirror, where will the image be formed?

Use $\frac{1}{f} = \frac{1}{s_o} + \frac{1}{s_i}$

f (m)	s_o (m)	s_i (m)
0.20	0.60	?

Putting in the values,

$$\frac{1}{0.60} + \frac{1}{s_i} = \frac{1}{0.20}$$

This gives $1.67 + \frac{1}{s_i} = 5.00$

Solving, $\frac{1}{s_i} = 5.00 - 1.67 = 3.33$

This is $\frac{1}{s_i}$, remember, so to find s_i we must 'turn the answer upside down'.

$s_i = \frac{1}{3.33} = 0.30$ m (30 cm, 300 mm).

Therefore a screen would have to be placed 300 mm back from the mirror.

Worked example 6.4

You stand 15 cm away from a converging mirror of focal length 20 cm.

a) Work out the distance to the image.

b) Calculate the magnification of the image. (For this purpose ignore the minus sign.)

s_o (cm)	s_i (cm)	f_i (cm)
15	?	10

a) Use $\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$

$\frac{1}{s_i} = \frac{1}{f} - \frac{1}{s_o} = \frac{1}{20} - \frac{1}{15}$

$= -\frac{1}{60}$

$s_i = -60$ cm

b) Use magnification $= \frac{s_o}{s_i} = \frac{60}{15} = 4$

Finding the position and nature of the image formed by a concave and a convex mirror using the mirror equation and a ray tracing method

Figure 6.26 shows how you can find the position and nature of the image formed by a concave mirror using a ray tracing method.

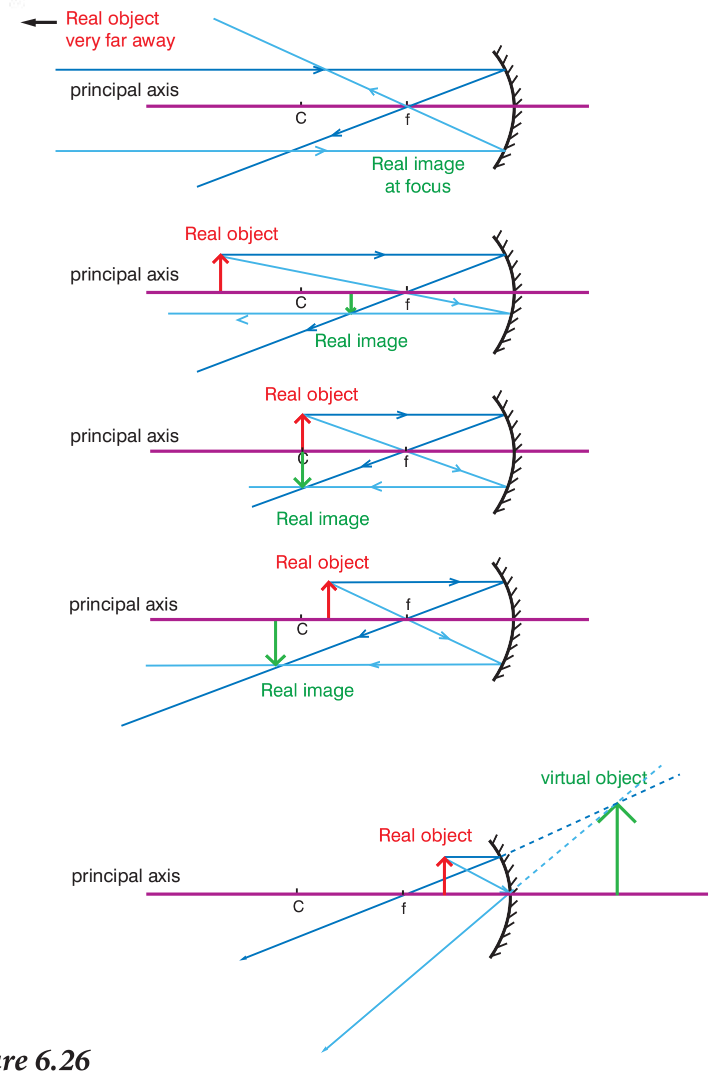


Figure 6.26

The magnification relationship for mirrors

Magnification is defined to be:

$$\frac{\textbf{the height of the image}}{\textbf{the height of the object}}$$

It is just a number, and will have no units. We can calculate what it will be like this:

$$\textbf{Magnification} = \frac{h_i}{h_o}$$

Thus if $h_o = 0.60$ m and $h_i = 0.30$ m, the magnification can be expected to be:

$$\frac{h_i}{h_o} = \frac{0.30}{0.60} = 0.50.$$

Notice that the magnification here turns out to be less than 1. The image will be only half as tall as the original object – if we used a ruler for the object, the millimetre divisions in the image would be only 0.5 mm apart. We still refer to this as magnification, however.

This table summarises what you have learnt about curved mirrors.

Quantity	Concave mirror	Convex mirror
Focal length f	+ve sign	–ve sign
Object distance s_o	In front of mirror +ve sign	Behind mirror –ve sign (virtual)
Image distance s_i	In front of mirror +ve sign (real)	Behind mirror (virtual)
Magnification m	Image upright +ve sign	Image inverted –ve sign

Summary

- Rectilinear propagation of light simply means that light travels in straight lines.
- The laws of reflection are:
  The angle of reflection is equal to the angle of incidence.
  The reflected ray lies in the plane which contains the incident ray and the normal.
- An example of a use of plane mirrors is seeing your reflection as you do your hair.
- Concave and convex mirrors curve as shown in Figure 6.27.

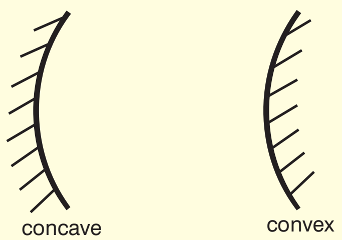


Figure 6.27

- Figure 6.28 shows the principal axis, principal focus, radius of curvature for concave and convex mirrors.

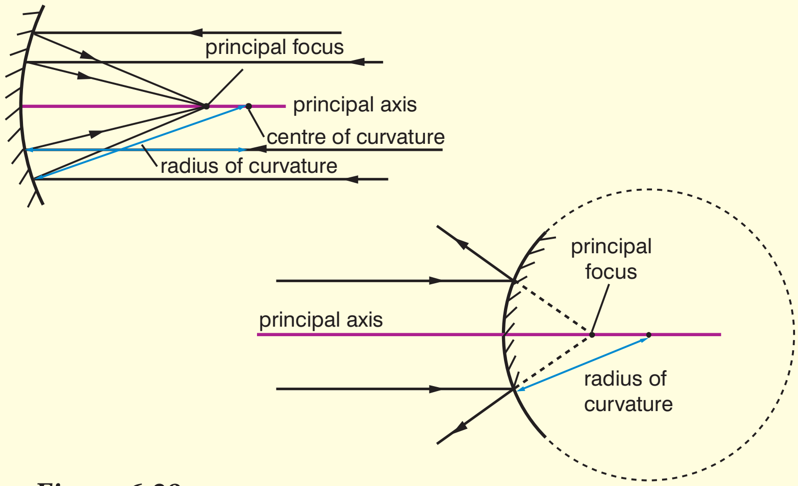


Figure 6.28

- Real images can be focused on a screen. Virtual images cannot be focused on a screen.
- When using the mirror equation, virtual images have a negative sign.
- You can find the position and nature of the image formed by a concave and a convex mirror using the mirror equation and a ray tracing method.
- Magnification = $\frac{s_i}{s_o} = \frac{h_i}{h_o}$
- Examples of the uses of curved (concave and convex) mirrors are shaving mirrors and wing mirrors on vehicles.

Review questions

1. Explain what is meant by the rectilinear propagation of light.
2. State the laws of reflection.
3. Use the laws of reflection to explain how images are formed in a plane mirror.
4. Find the position of the image produced by the plane mirror in Figure 6.29 using a ray tracing method.
5. An object is 10 cm from a plane mirror. The angle of incidence on a plane mirror is 35°. Draw a diagram to show the situation and work out:
   a) the angle of reflection
   b) the position of the virtual image.
6. Give examples of the uses of plane mirrors.
7. Distinguish between concave and convex mirrors.

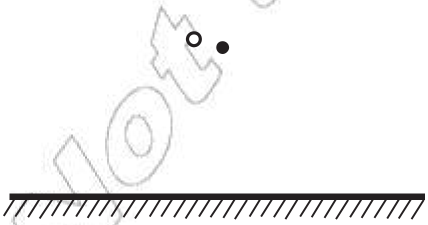


Figure 6.29

8. Draw a diagram to show the meanings of principal axis, principal focus and radius of curvature in relation to concave and convex mirrors.
9. Define magnification in relation to concave and convex mirrors.
10. Distinguish between real and virtual images.
11. State the mirror equation and the sign convention that you need to apply when using it.
12. Find the position and nature of the image formed by the concave and convex mirrors in Figure 6.30 using:
    a) the mirror equation
    b) a ray tracing method.

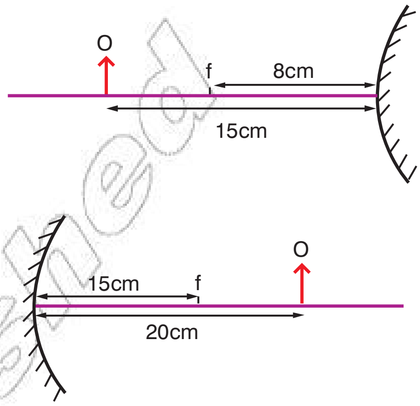


Figure 6.30

6.3 Refraction of light

By the end of this section you should be able to:

- Define the term refraction.
- State the conditions in which refraction occurs.
- Define the refractive index of a material.
- Use Snell's Law to solve simple problems.
- Use the formula refractive index = $\frac{\text{real depth}}{\text{apparent depth}}$ to find the refractive index of a liquid and a solid in the form of a rectangular glass block.
- Perform experiments to test the laws of refraction.
- Draw a diagram representing the passage of light rays through a rectangular glass block.
- Give examples of observations that indicate that light can be refracted.
- Identify that the passage of a ray of light through a parallel-sided transparent medium results in the lateral displacement of a ray.
- Define the critical angle θ_c.
- Explain, with the aid of a diagram, what is meant by critical angle and total internal reflection.
- Identify the conditions necessary for total internal reflection to occur.
- Perform calculations involving critical angle and total internal reflection.
- Describe how total internal reflection is used in optical fibres.

KEY WORDS

refraction *the change in direction of travel of a light beam as the light crosses the boundary between one transparent medium and another*

- Distinguish between convex and concave lenses.
- Identify the meaning of: principal focus, principal axis, focal point, radius of curvature, magnification in relation to converging and diverging lenses.
- Apply the appropriate sign convention when using thin lens equations.
- Find the position and nature of the image formed by a convex and concave lens using the thin lens formula and a ray tracing method.
- Define the power of a lens.
- Explain how the image is formed due to combination of thin lenses.
- Draw a ray diagram to show how images are formed by lenses in a simple microscope and a simple telescope.
- Compare and contrast the structure and functions of the human eye and the camera.
- Describe how the human eye forms an image on the retina for different object distances.
- Identify some defects of the eye and their correction with lenses.
- Explain what is meant by the dispersion of white light to produce a spectrum.
- Identify that the passage of a ray of light through a triangular transparent prism results in a deviation of a ray.

Figure 6.31

Figure 6.32

Refraction

Something odd is happening in Figure 6.31 and it is obviously being caused by the presence of the water. Reflection cannot account for it, so what is the explanation?

Now look at Figure 6.32. The light is coming from the left, and reaches a triangular glass prism. A little of that light is reflected from each surface of the glass – that is how you may be able to see your reflection in a glass window. Most of the light goes through the glass, however. You can see from the figure that at the boundaries between the air and glass, the light beam undergoes a sudden change in direction. This is what we call **refraction**.

Refraction is the change in the direction of travel of a light beam that occurs as the light crosses the boundary between one transparent medium and another.

This bending of a light beam as it crosses a surface is a very important effect in optics: it is the basic principle behind the working of cameras and telescopes, for example. We must therefore examine refraction in more detail.

Which way does the light get bent?

To work out which way the light gets refracted at a particular surface, it is helpful to draw the normal to the surface (as a dotted line). Having done that, remember that the word 'into' is enough to predict the path of the light. This tells you that as the light goes *in* to the water or the glass, it is bent towards the normal. What this means is shown in Figure 6.33. Notice that the light always crosses the normal.

Light going the other way (coming *out from* the water or the glass) would take the same route in the other direction: as it comes out it is refracted away from the normal.

The only time the light does not get refracted as it crosses the boundary is if it hits the surface 'square on', right along the normal (which will be an angle of incidence of 0°, remember, not 90°).

Activity 6.11: Observing refraction

Take a glass of water. Put a straw or stick into the glass and describe what you see.

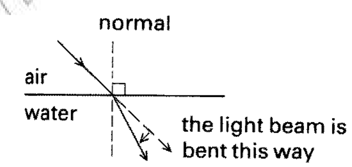


Figure 6.33 *The light always crosses the normal, but is bent towards it.*

A few consequences of refraction

We can now begin to understand why we get photographs like those at the start of this section. A careful study of Figure 6.34 provides the answer. The essential thing to realise is this: where something seems to be is determined solely by the direction in which the light is travelling as it *enters* the eye.

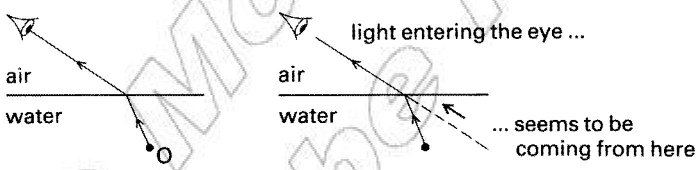


Figure 6.34 *The path of the light as it enters the eye is what determines where the object appears to be.*

If we look up at the night sky, a similar situation means that no star is really where it appears to be unless it happens to be directly overhead. This is due to refraction in the atmosphere. (The boundary does not have to be between two different substances; refraction will occur at a boundary between 'thin' air, as in the upper atmosphere, and the denser air lower down.) Figure 6.35 shows a simple model of the Earth's atmosphere which we can use. At each boundary the light goes *into* denser air and each time it gets refracted towards the normal.

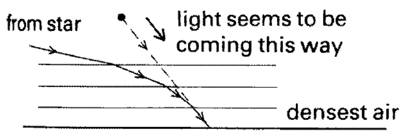


Figure 6.35 *The star seems to us to be higher than it really is.*

In practice the density of the air increases steadily as you go down, of course. We could improve our model by dividing it into a large number of very thin layers, which would turn the path of the light into a smooth curve. The end result is the same: the star looks higher in the sky than it really is.

Another example of refraction in the atmosphere is the shimmering effect that can be seen in the air above a Bunsen burner or a very hot surface. This is convection in action. As the hot air swirls upwards, its density keeps changing randomly. This causes light that crosses the hot air to be refracted first one way and then the other, so objects constantly appear to be shifting their position slightly.

KEY WORDS

refractive index *a measure of the extent to which a medium refracts light*

Snell's law *whenever light crosses a boundary between two media, the sines of the angles on each side of the boundary bear a constant ratio to each other*

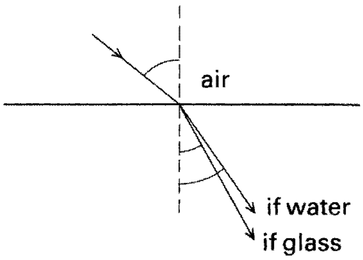


Figure 6.36 *The greater the refractive index, the more the light is bent.*

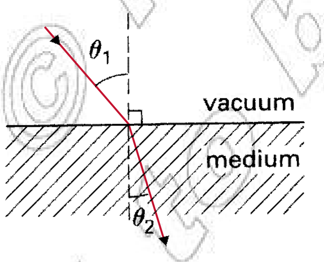


Figure 6.37 *Light crossing a boundary.*

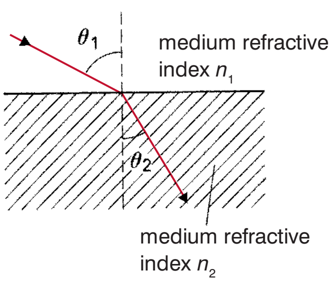


Figure 6.38 *The notation for Snell's law.*

The refractive index and Snell's law

Some materials refract light at their boundary more than others. The extent to which each one does this is measured by its **refractive index**, given the symbol '*n*'.

The refractive index is a number larger than 1 such that the greater the number the greater the refraction produced. Water, for example, has a refractive index of 1.33, while that of common glass is just a shade over 1.5. Figure 6.36 illustrates to scale the difference that this makes. The water has the smaller refractive index, so its surface bends the light less.

What does the number mean? It is a measure of the refraction that occurs at a boundary between the material or 'medium' in question (e.g. glass or water) and a vacuum. (In practice, we use a boundary with air, which behaves virtually the same way as a vacuum.)

Figure 6.37 shows the situation. No arrow has been drawn on the light beam because it follows the same path whichever way it is going. If angle θ_1 is increased to such an extent that its sine is doubled, then angle θ_2 will become larger so that its sine is doubled too.

This relationship was first spotted by a Dutch mathematician called Willebrord Snell back in 1621, and is now known as **Snell's law**:

Whenever light crosses a boundary between two transparent media, the sines of the angles on each side of the boundary bear a constant ratio to each other.

Mathematically, for a particular boundary:

$$\frac{\sin\theta_1}{\sin\theta_2}$$

always comes to the same number regardless of the size of the angles themselves. If that boundary is with a vacuum (or, near enough, with air), this number is the **refractive index** of the medium.

$$n = \frac{\sin\theta_1}{\sin\theta_2}$$

To calculate the path light will take as it crosses a boundary between *any* two media, the simplest way is to use Snell's law in the form:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

where the notation is as shown in Figure 6.38.

Since '*n*' is more than 1, irrespective of the direction the light is travelling in you always put the sine of the larger angle on top.

Activity 6.12: Discussion

In a small group, discuss these questions.

1. What do you think would happen if glass of refractive index 1.52 is immersed under a liquid whose refractive index is also 1.52?
2. How do you think the speed of light in the glass compares with that in the liquid?

Set up some apparatus to find out!

Why does refraction occur?

Refraction was first noticed with light. Early scientists soon found that the relationship on either side of a boundary was not between the angles themselves, but between their sines. They went on to use their observations to design lenses, and to make microscopes and telescopes.

It has since been discovered that refraction occurs with all types of waves, including ripples on the surface of water and sound waves. The bending is caused by a change in the speed of the wave when it crosses a boundary. If a medium has a high refractive index, that tells us that light entering the medium from a vacuum will undergo a large amount of refraction. It must also mean that the light will be slowed down a lot as it travels from the vacuum into the medium.

The real reason that the refractive index can be defined and measured by the ratio of the sines of the angles is that it is also the ratio of the speeds on either side of the boundary – the faster speed over the slower speed. It can be shown that these two alternative definitions are in fact equivalent, so one follows from the other.

Thus if the speed of light in a vacuum is denoted by c and its (slower) speed in the medium is v, then the refractive index n of the medium will be given by:

$$n = \frac{c}{v}$$

Lateral displacement

Because the two opposite faces of the block are parallel, by geometry the light must meet the second face at the same angle, θ_2, (see Figure 6.40b). This means that as the light leaves the glass it is refracted by the same amount the other way, and so must emerge on a path parallel to its original one as shown in Figure 6.40b. The sideways shift of the beam is called the **lateral displacement**.

The extent of the lateral displacement depends on the angle at which the light is incident on the outer surface of the glass block. At an angle of incidence of 0° (that is, when it hits the block at right angles to its surface) the lateral displacement is of course nil. As the angle of incidence increases, so does the displacement.

Worked example 6.5

Light travelling in air meets the surface of a block of Perspex at an angle of incidence of 50°. It enters the block at an angle of refraction of 31°. Calculate the refractive index of Perspex.

Start by drawing the diagram in Figure 6.39. Mark all the angles to the normal.

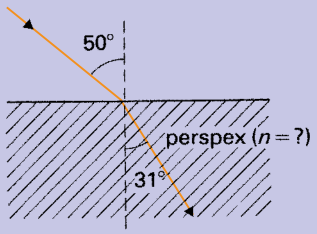


Figure 6.39

$$n = \frac{\sin\theta_1}{\sin\theta_2}$$

$$n = \frac{\sin 50°}{\sin 31°}$$

$$n = 1.49$$

KEY WORDS

lateral displacement *the perpendicular distance between the pathway of the incident light ray and the one that emerges after refraction from two surfaces of a medium*

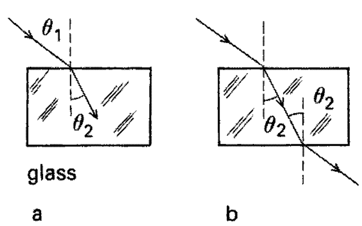


Figure 6.40 Light entering and leaving a rectangular glass block.

Activity 6.13: Testing the laws of refraction

Take a piece of plain paper. Set up the apparatus shown in Figure 6.40 so that a narrow beam of light is incident on one face of a rectangular glass block and is refracted as it crosses the boundary.

Trace round the outline of the block. Use a sharp pencil to trace the incident beam of light and the beam of light as it exits the block. Take the paper from under the block and join the two rays as shown in Figure 6.40b.

Draw on the normals for the incident beam and the exit beam. Now measure the angle of incidence and angle of refraction. Use Snell's law to find the refractive index of the block.

Apparent depth

Figure 6.41 shows a small object 'O' under water. If it is a light bulb, it is giving off its own light; if it is the tip of a fish's tail, the light is being reflected off it. Light within the cone drawn in the diagram ends up in your eye. Be sure you understand that the refraction as shown is correct: light coming out from the water will be bent away from the normal.

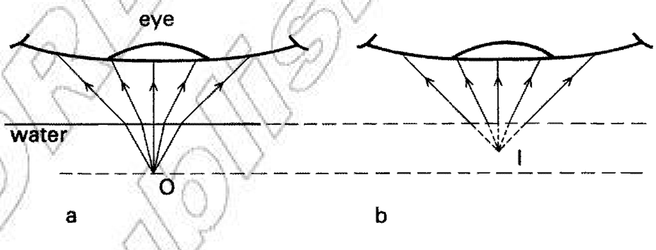


***Figure 6.41** The light, which starts from 'O', enters the eye as if it was spreading out from 'I'.*

What does the eye – or, more accurately, the brain – register? Look at Figure 6.41b. If no water was present but instead the object was placed at point 'I', the light reaching the eye would be exactly the same. To realise this, cover up the bottom part of diagrams (a) and (b) with a sheet of paper so all you can see is the eye and the light entering it, and you will find the two are identical.

Combining the two in a single diagram, and showing only the edges of the cone of light, we get Figure 6.42. What is really there is the object at 'O'. What we see is the image at 'I', and this appears to be nearer the surface. Notice that the lines from the surface to point 'I' are shown dotted. This is because no light takes that part of the path: they are just construction lines to pinpoint where the image appears to be.

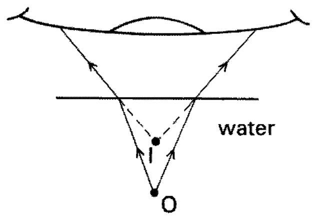


***Figure 6.42** The apparent depth of the image 'I' is less than the real depth of the object 'O'.*

It is possible to calculate just how marked this effect will be, and relate it to the refractive index n of the liquid. The relationship between apparent and real depths is given by:

$$\frac{\textbf{real depth}}{\textbf{apparent depth}} = n$$

This is not a definition of refractive index, merely a way of predicting what the apparent depth will be. Nevertheless, it offers a way to find the refractive index of the liquid.

Activity 6.14: Using refractive index = $\frac{\text{real depth}}{\text{apparent depth}}$ to find the refractive index of a liquid

Place the end of a ruler into some water in a tank, holding it at an angle to the surface. View it from above. Mark the real depth A and the apparent depth A′ on the side of the tank. Measure real and apparent depth. Use

$\frac{\text{real depth}}{\text{apparent depth}} = n$ to estimate the refractive index of the liquid. Repeat with other liquids.

Why does the ruler appear to be bent?

The effect is due to the refraction of light.

Indeed, it is another example of apparent depth. Looking at the ruler from above, the end A will seem to be at A′. Similarly B and C look as though they are at B′ and C′ respectively, and so the ruler seems to be bent.

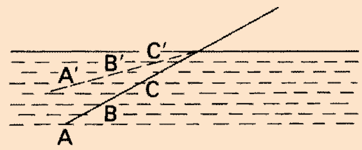


Figure 6.43

Total internal reflection

Suppose you find yourself under water with a torch that gives a narrow beam. Figure 6.44 illustrates the effect of shining the light on to the underside of the water surface at a progressively larger and larger angle (as measured to the normal, remember). Only the path of the main beam is shown – there will always be some reflection back as well.

At a particular angle of incidence (marked *c*) the light emerges along the surface.

What will happen if you shine the light at a greater angle of incidence than this?

Where will the beam come out? Activity 6.16 explores this.

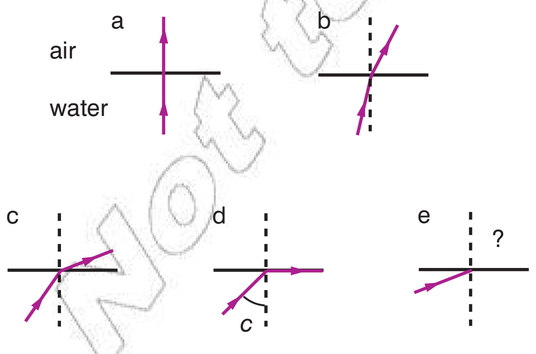


Figure 6.44 *What happens as the angle of incidence increases?*

Activity 6.15: Observations that indicate that light can be refracted

In a small group, make a list of observations that indicate that light can be refracted (you could start with the observations from the activities you have already carried out in this section).

Explaining the results

The light in the last section of Figure 6.44 does not emerge. Despite the fact that the air is a transparent medium, no light enters it.

What happens to the energy of the incident light beam? There has always been a second possibility, and that was the partial reflection back from the surface. Now there is only that one possibility. The reflection back is total: for light hitting it at such an angle, the inside of the water surface behaves as a perfect mirror.

Activity 6.16: Exploring increasing the angle of incidence

Figure 6.45 shows one possible arrangement.

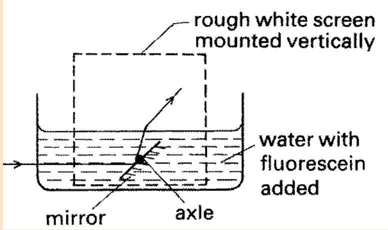


Figure 6.45 *Where does the light come out?*

The bright beam of light may be obtained from a slide projector with a horizontal slit in place of a slide. The mirror can be glued to an axle mounted in a rubber 'sucker' pressed against the side of the tank; to alter the angle at which the beam of light is incident on the underneath of the water surface, rotate the mirror.

Add fluorescein, a yellow-green dye which glows brightly along the path of the light to make it visible to the water. The route the light takes after emerging from the water can be traced on a rough white screen.

KEY WORDS

total internal reflection *occurs when light strikes a medium boundary at an angle of incidence greater than the critical angle, and all light is reflected*

critical angle *the angle of incidence on a boundary above which total internal reflection occurs*

This is called **total internal reflection**. It will occur only if two conditions are fulfilled: 1) that the light is inside the water or the glass, trying to 'escape'; 2) that the light hits the inside of the surface at a sufficiently large angle to the normal.

This may be stated more formally. Total internal reflection will occur if:

1. **Light travelling in a medium such as water or glass comes to a surface with a medium in which it travels faster (usually air).**
2. **It hits the inside of this surface at an angle of incidence greater than the critical angle.**

The **critical angle** is defined as:

the particular angle of incidence for which the light emerges along the surface (at an angle of refraction of 90°).

The critical angle is the angle marked as *c* back in Figure 6.44.

Worked example 6.6

Ordinary glass has a refractive index of about 1.5. Work out its critical angle at a boundary with air.

There are two points to bear in mind here: that at the critical angle refraction still takes place (just) as in Figure 6.46, and that sin 90° = 1.

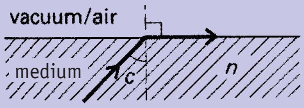


Figure 6.46 *At the critical angle, the angle of refraction is 90°.*

Using the relationship $n = \frac{\sin \theta_1}{\sin \theta_2}$ we get:

$n = \frac{\sin 90}{\sin c}$, but as sin 90 = 1, $\sin c = \frac{1}{n}$

The refractive index of ordinary glass is about 1.5 and its critical angle at a boundary with air can be worked out from:

$\sin c = \frac{1}{n} = \frac{1}{1.5} = 0.667$

so $c = 42°$

Total internal reflection and its use in optical fibres

If the glass block you considered in the last section becomes elongated into a rod, it will work in just the same way as it did before. Once introduced into one end, the light cannot escape so long as it always hits the side walls at an angle of incidence greater than the critical angle for the material of the rod. The light is trapped in what seems like a kind of pipe with silvered walls, as shown in Figure 6.47.

Recent advances in technology have led to a whole range of applications of this effect. Individual plastic fibres can be made which, optically insulated from one another, may be enclosed side by side in a non-transparent sheath. The result is a bundle no wider than the average electrical wiring to lamps, and so flexible that it can be tied in knots without affecting its performance.

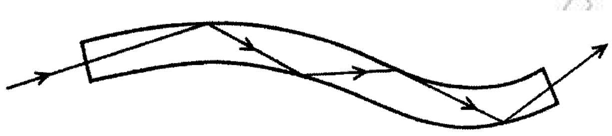


Figure 6.47 *The principle of fibre optics.*

Applications of fibre optics

An endoscope is a device used by doctors to see inside the body. It consists of two bundles of plastic fibres which can be passed down the throat, for example, to view the stomach. One bundle takes the light down to illuminate the area, while the other takes the reflected light back to construct the image.

Telecommunication companies can use light waves to convey messages and information in much the same way as they use radio waves. The possibility is very tempting because, for technical reasons, a single light beam can transmit far more telephone conversations at one time than a radio wave. Using a light beam raises severe problems, however. It does not travel well through the atmosphere, and on a foggy day communications would be cut completely. There is also a lot of synthetic interference which might swamp the signal, from street lights, bonfires and the like.

Fibre optics can provide the answer. Nowadays, in some places, a single cheap fibre optic cable has replaced several telephone wires. The material of the fibres has been made fantastically transparent, so the light can be detected at the far end of a cable as much as 20 km long.

A fibre can be used to monitor the temperature inside a jet engine. The optical cable carries the radiation from the hot surfaces inside to a pyrometer mounted outside the engine.

Convex and concave lenses

Before we proceed further, we must sort out a few points. The first of these is how to spell! Notice that in the singular 'lens' does not have an 'e' on the end. It is really a Latin word, and means 'bean'. Early lenses were just little blobs of glass and people were struck by their similarity in shape to beans, hence the name.

Figure 6.49 shows a **convex lens** acting on a beam of parallel light to bring it to a focus. Like a prism, it works by refraction at the two faces, but for convenience we think of the lens as bending the light once as shown.

The principal axis of the lens is the line passing through the centre of the lens, perpendicular to it.

Activity 6.17: Transmission of light through a fibre optic cable

Given a length of optical fibre cable, design a demonstration to show how it will transmit light.

As well as the cable you will have a white light source, a triangular glass prism and a suitable Perspex screen (either made of milky Perspex or with a roughened surface). If you feel you will need additional apparatus, consult your teacher.

Figure 6.48 *Fibre optics can also be used to produce decorative lighting such as this lamp.*

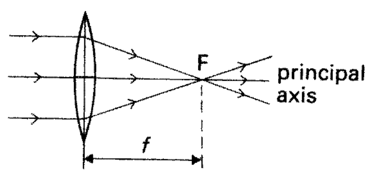


Figure 6.49 *A convex lens focusing a beam of parallel light.*

KEY WORDS

fibre optics *glass or plastic fibres that carry light along their length*

concave lens *a lens having at least one surface curved like the inner surface of a sphere*

dioptre *a unit of measurement of the optical power of a lens or curved mirror*

convex lens *a lens having at least one surface curved like the outer surface of a sphere*

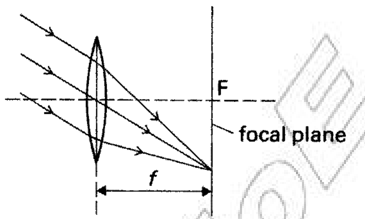


Figure 6.50 *Any parallel beam of light is brought to a focus somewhere in the focal plane.*

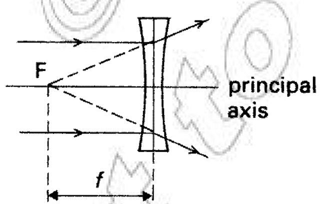


Figure 6.51 *A concave lens.*

Light which enters the lens parallel to its principal axis will be converged to the point marked 'F', the principal focus. The distance '*f*' from the centre of the lens to point F is called the focal length of the lens, and is a measure of the strength of the lens: a strong lens will have a short focal length. Since a lens is reversible there will be a point F on each side of the lens, equal distances from it.

An alternative way to measure the strength of a lens, used by opticians, is to specify its power *p*.

$$\text{The power of a lens} = \frac{1}{\text{(its focal length in metres)}},$$

so the larger numbers go with the stronger lenses. The unit of power in the optical sense will be m^{-1}, given the name **dioptres**. Thus a lens whose focal length is 20 cm would have a power of $\frac{1}{0.2}$ m = 5 dioptres.

The focal plane of the lens is where the surface of a screen would lie if it was placed the focal length away from the lens as shown in Figure 6.50. A parallel beam of light which does not enter along the principal axis will be brought to a focus somewhere in the focal plane as in the diagram.

A **concave lens** is similar, except that a beam of light parallel to its principal axis will emerge spreading out, as if coming from its principal focus as shown in Figure 6.51.

Activity 6.18: Comparing lenses and mirrors

Compare the terms used for lenses with those used for mirrors (see page 205). Draw a diagram of a concave lens and a convex lens and mark on the diagrams: principal focus, principal axis, focal point and radius of curvature.

Magnification

This is just a number: the number of times the image is larger than the object. A magnification of less than 1 means that the image is smaller.

Whenever we refer to magnification we mean linear magnification, defined as the height of the image divided by the height of the object. Two examples are shown in Figure 6.52.

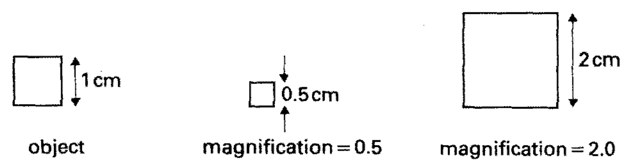


Figure 6.52

Notice that when the magnification is 2, the area of the square has increased fourfold. Some advertisements for binoculars give their area magnification: an area magnification of 49 sounds much better than a magnification of 7, but they are the same thing!

Activity 6.19: Using a convwx lens

Try getting a convex lens to cast an image on a screen. Where must the screen be placed? How big is the image? Is it the right way up or inverted?

Figure 6.53 shows one possible set-up. The object is a transparent plastic ruler with clear centimetre and millimetre markings held in a retort stand and clamp.

Start with the object as far back from the lens as you conveniently can, then adjust the screen until the image on it is in sharp focus. Measuring distances from the centre of the lens, record in a table the object distance (to the ruler) and the image distance (to the screen). Note also the magnification of the image, from the spacing of the centimetre markings on the screen and whether it is inverted or the right way up.

Keep moving the object closer to the lens in stages, and each time repeat the measurements.

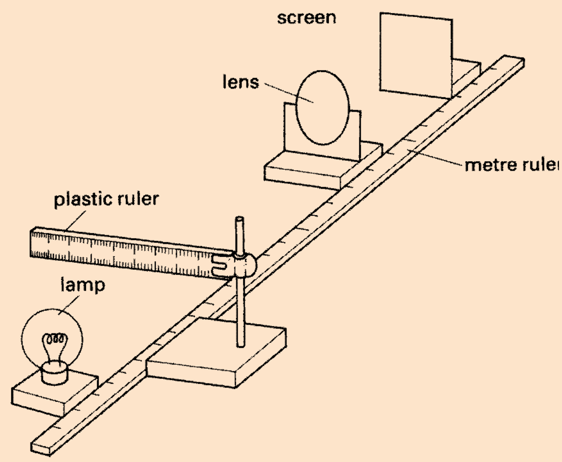


Figure 6.53 *Using a converging lens to cast an image on a screen.*

The thin lens formula

The formula that you met in the last section with curved mirrors also applies to lenses. To remind you, the notation used is this:

f = the focal length of the lens

s_o = the distance from the object to the centre of the lens

s_i = the distance from the centre of the lens to where the image is formed

The connection between them is:

$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$$

To represent a concave lens, we give the focal length a negative value. In a calculation, if the image distances works out to be negative, that tells us that the image is not a real one but a virtual one.

You can also predict the magnification from:

$$\textbf{magnification} = \frac{s_i}{s_o}$$

Finding the position and nature of an image formed by a convex and concave lens

To be able to say how big an image will be and which way up it is, we need to take an object which has a definite size and which has a top and bottom to it. The simplest object to choose is an arrow, as shown overleaf in Figure 6.54.

Worked example 6.7

An object is placed 40 cm from a converging lens of focal length 20 cm. Where will the image be formed, and what is its magnification?

s_o = 40 cm = 0.4 m and f = 20 cm = 0.2 m.

Putting these values into

$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$ gives us:

$$\frac{1}{0.4} + \frac{1}{s_i} = \frac{1}{0.2}$$

so $2.5 + \frac{1}{s_i} = 5.0$.

This means that:

$$\frac{1}{s_i} = 5.0 - 2.5 = 2.5$$

so $s_i = \frac{1}{2.5} = 0.4$ m (40 cm).

The magnification =

$$\frac{s_i}{s_o} = \frac{0.4}{0.4} = 1.0$$

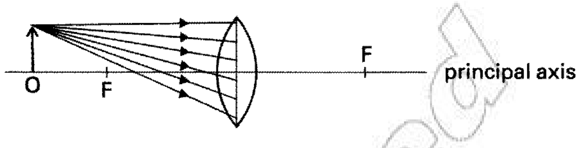


Figure 6.54 A cone of light will reach the lens from the tip of the arrow.

The foot of the arrow is placed on the principal axis, and we already know that light spreading out from a point on the principal axis will be brought together by the lens somewhere further along it.

We do not consider the image of the bottom of the arrow, therefore, but we concentrate instead on the light spreading out from its tip. A cone of light will reach the lens, and the focusing action of the lens will bring this cone of light together again to a point. Our problem is to say where this point will be.

Luckily within that cone there are two particular directions of travel for which we can predict the path of the light as it leaves the lens. The two special cases are these:

1. Light entering the lens parallel to its principal axis will be refracted through the focus 'F', as shown in Figure 6.55.
2. Light passing through the centre of the lens will carry on undeviated, as in Figure 6.56.

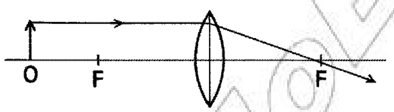


Figure 6.55 *Light parallel to the principal axis will be refracted through the focus.*

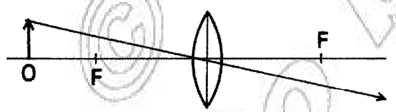


Figure 6.56 *Light passing through the centre of the lens will carry on undeviated.*

The second case needs a word of explanation. If a lens can be thought of as a series of prisms, then the middle section is a rectangular glass block. Light passing through such a block at an angle emerges still going in the same direction but shifted sideways, as shown in Figure 6.57.

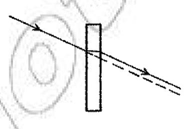


Figure 6.57 *The sideways displacement is negligible.*

A lens is very thin, perhaps 5 mm or thereabouts, and therefore the extent of the sideways displacement is so slight as to be negligible.

Figure 6.58 shows both these special 'predictable' rays combined on one drawing. Where these two lines meet at a point, so too will the rest of that cone of light from the tip of the object.

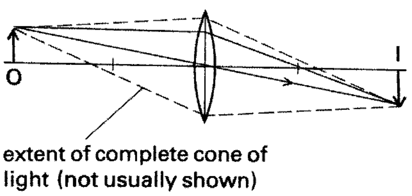


Figure 6.58 *Where the cone of rays shown in Figure 6.54 will meet.*

You can now draw the complete ray diagram for a converging lens being used as a projector. O is the slide, placed just outside the focus of the lens and strongly illuminated from behind; I is the enlarged real image formed on a suitably positioned distant screen (Figure 6.59).

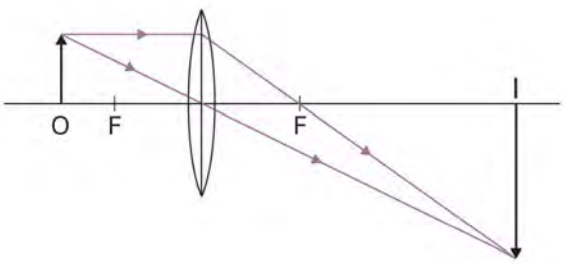


Figure 6.59 *Ray diagram for a converging lens being used as a projector.*

In the ray diagram for a camera, O is the distant object being photographed, and I is a small real image just beyond the focus of the lens, which is cast on light-sensitive film at the back of the camera (Figure 6.60).

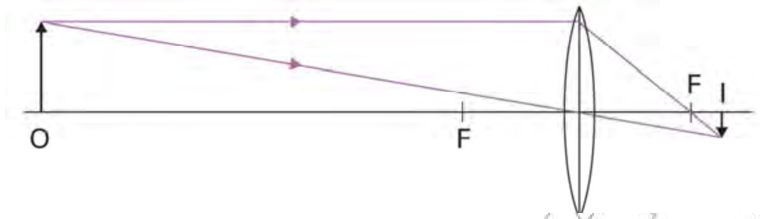


Figure 6.60 *The ray diagram for a camera.*

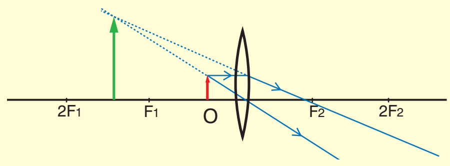
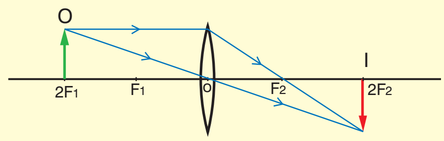
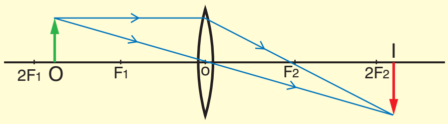
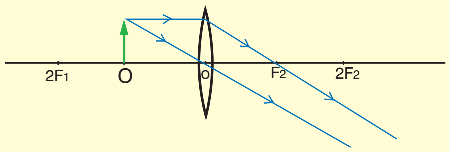
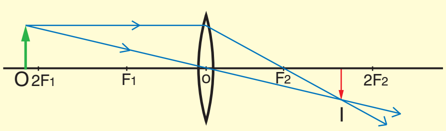
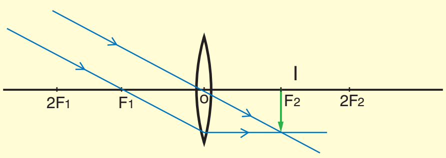
Position of object	Key diagram	Image is
Between F_1 and lens		virtual erect magnified
At $2F_1$		real inverted same size as object
Between F_1 and $2F_1$		real inverted magnified
At F_1		formed at infinity real inverted magnified
Beyond $2F_1$		formed between F_1 and $2F_1$ real inverted diminished
At infinity		formed at F_1 inverted real highly diminished

Figure 6.61 *How to find the position and nature of the image formed by a convex lens using a ray tracing method.*

How an image is formed due to combination of thin lenses

To view an image and make best use of the available light, you need an arrangement such as that shown in Figure 6.62.

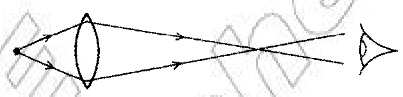


Figure 6.62 One method of viewing an image.

It is no good putting your eye at the point 'I' itself – that would be like trying to read this print by resting your eyeball on the page! You must stand back so you can focus on it clearly.

The first stage in forming an image with a combination of thin lenses can therefore be drawn as in Figure 6.63 (though the angles are much exaggerated for clarity).

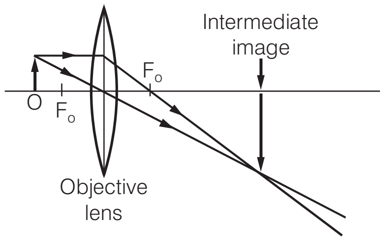


Figure 6.63 The first stage in forming an image.

The image, labelled 'intermediate image' in Figure 6.63, is typically 10–15 cm back from the objective.

In principle, you could cast this image onto a screen put there, but in practice it would be far too faint. It would be better to try to view it by placing your eye back to the right of the drawing – it does not matter how far back, so long as the image is outside your near point so you can focus on it.

In a combination of thin lenses you achieve a second stage of magnification by looking at the image not directly but through a second lens.

The intermediate image must therefore lie inside the focus F_e of the second lens. Unfortunately the two rays whose progress we have followed so far are not 'special' ones for the second lens – they will be refracted through it and help to form the virtual final image which we see, but their path is not predictable. Therefore we have had to add some construction lines (shown in blue) to see where the image would be produced, and then draw the rays emerging from the second lens spreading out from there (Figure 6.64).

KEY WORDS

objective lens *first lens encountered by incoming light rays from the object*

eyepiece lens *lens nearest to the eye*

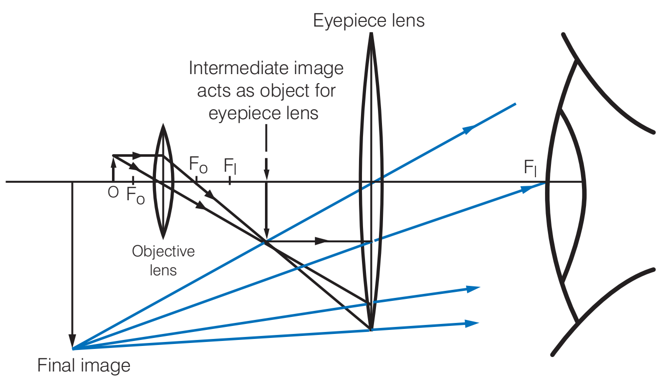


Figure 6.64

The simple microscope

A simple microscope is a magnifying glass. If the object lies between the focus of the lens and the lens itself, the light comes out diverging, as shown in Figure 6.65.

No real image will be formed: wherever you put a screen, you cannot recreate on it an image of the original point of light. As you move the screen back from the lens, all you can get is an ever-widening circle of light.

If you place your eye as shown, however, you should see something: a virtual image. Light enters the eye as if it was coming from the point I, located somewhere behind the lens and further away than the object really is.

The image you see is the right way up and enlarged, as shown in Figure 6.66.

If we trace the progress of the two 'predictable' rays, this time they emerge from the lens still spreading out. No real image will be produced, but if you put your eye as shown in Figure 6.67, you will be able to see a virtual image located back behind the lens at I.

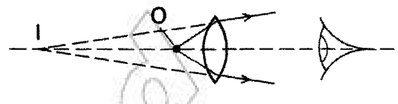


Figure 6.65 *You will see a virtual image at 'I'.*

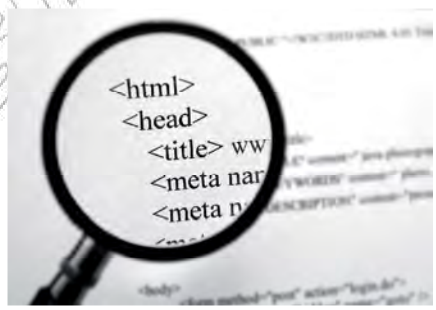


Figure 6.66 *Virtual image the right way up and enlarged.*

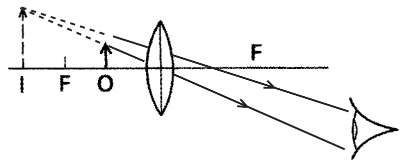


Figure 6.67 *The image you see is upright, enlarged and further back than the object.*

The telescope

A telescope is designed for seeing more detail in an object that is a long distance away.

If we are using a lens, the only magnified images that are possible are formed with a converging lens having the object within 2 f (as in the projector) or within f (as in the simple microscope). Neither is possible if we are looking at the surface of the moon, so how do we do it?

The solution is to use the objective lens to form a real image in its focal plane. You then examine that image through a magnifying glass (the eye lens) or a whole set of converging lenses (the eyepiece).

Let us consider each stage in turn. The crucial factor in a quality telescope is the objective. What we examine is the image it produces, not the real object, and if the fine detail is not present in that image, we will never be able to see it. It would be like looking at a photograph in a newspaper through a microscope: all we would see is a big blur because no further detail is present in it. Therefore a telescope is often described just in terms of its objective – what sort is being used, and what its diameter is.

The image produced by the objective is, of course, smaller than the original object – not desirable, but unavoidable. If you look at the images of the window frames through a series of different lenses, you will find that the stronger lenses form smaller images.

Here therefore we need a weak lens, so the image is still as large as possible – the main limit is the length of the instrument.

The eye lens that we use to look at that image needs to be a strong one, as with the microscope. If we set it so the final image is offered to us back at infinity, that means having the intermediate image at its focus. Therefore the total length of the telescope will be the focal length of the objective, f_o (which will be large), added to the focal length of the eye lens, f_e (which is tiny) (Figure 6.68).

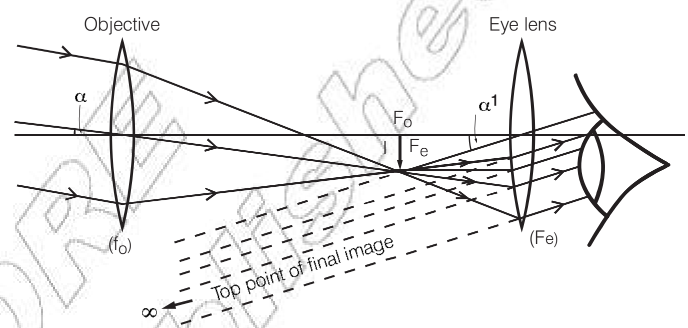


Figure 6.68 *Telescope.*

The light rays traced through the telescope started from one off-axis point back at infinity. The two angles marked with α indicate the angles subtended with and without the telescope. Their ratio is the angular magnification.

It is possible to work out the angular magnification of the telescope used like this by the ratio $\frac{f_o}{f_e}$.

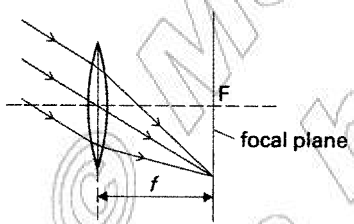


Figure 6.69

The camera

If the lens and screen in Figure 6.69 are enclosed in a light-tight box, you have a camera.

For distant objects a small upside-down picture of the outside world will be cast on the film, which really just consists of light-sensitive chemicals mounted in the focal plane of the lens. In a digital camera, the film is replaced by an image capture surface that converts the image into a computer file.

If the object being photographed comes in much closer, then the distance from the lens to the film must increase slightly. With most modern cameras this is done by rotating the lens: a screw thread then winds it a small distance backwards or forwards. The other possibility is to slide the lens along, in which case the camera is kept light-tight by a concertina-like cloth 'bellows'.

The human eye

The human eye (see Figure 6.70), works rather like that of the camera, where a converging lens forms a tiny upside-down image of the distant world on a screen. The lens in the eye is not a glass one, of course, but is made of living tissue. The screen on which the image is cast is not a white board; instead, it is the back surface of the eyeball (called the **retina**), packed with light-sensitive cells all connected straight to the brain via many separate nerves, which leave the eye in a bundle called the **optic nerve**.

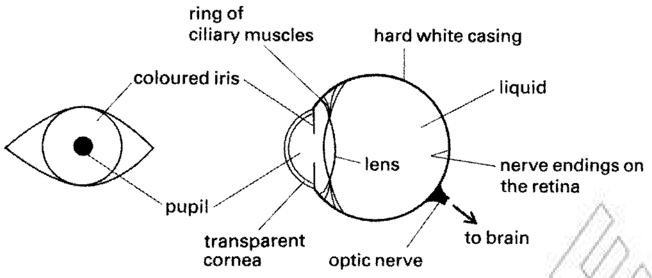


Figure 6.70 *The structure of the eye.*

Each eye is enclosed in a tough white casing whose front part is visible as the white of your eye. The bulge at the front of the eyeball is the transparent window (the cornea) by which the light enters. The amount of light reaching the retina is controlled by a ring called the iris – usually brown or blue. It is the iris that determines the colour of your eyes.

The size of the hole in the middle of the iris (the **pupil**) adjusts itself as the brightness of the light changes. In bright light the pupil is just a dot, while at night the iris opens right up to leave a large pupil. The pupil looks black because the inside of the eye is covered in a black pigment. The effect of this is to absorb stray light, and so prevent it from being reflected onto the retina (otherwise the contrast in the image would be reduced, rather like using a slide projector in a poorly darkened room).

The lens in the eye is surrounded by a circular sheet of muscle, which divides the eyeball into two quite separate regions. The eye is filled with liquid, which gives rigidity to the whole structure. The liquid in the front compartment is salty, rather like tears, while the space between the lens and the retina contains a thicker, less runny liquid. Tear drops themselves are produced by glands in the sockets into which the eyeballs fit, and act as a lubricant for the outside surface of your eyes.

How the eye focuses

You can look at close-up objects or distant ones. Unless you require spectacles, the image in both cases is clearly focused on the retina.

A camera would achieve this by altering the position of the screen (the film) relative to the lens, by moving the lens slightly. With the eye the story is quite different, however. Most of the refraction of the light, to make it converge to a focus on the eye's retina, takes place as the light first enters the eyeball at the boundary between air and the cornea. This is where the greatest change in the speed of light occurs, and it is that speed change which causes the refraction.

The fine control of the focusing is done by the lens, but it must be realised that only a little of the total refraction takes place there. As the light goes between the liquid in the eye and the lens, there is only a small change in speed and therefore only a small difference in refractive index.

KEY WORDS

retina *light-sensitive cells lining the inner surface of the eye*

optic nerve *a nerve transmitting visual information from the retina to the brain*

pupil *an opening in the centre of the iris of the eye*

KEY WORDS

accommodation *the eye's ability to focus on objects at various distances*

Activity 6.20: Exploring 'near points'

Your 'near point' is the closest distance at which you can focus clearly. Bring this book up towards your eye and eventually the print becomes blurred. The lens in your eye has then reached the limit of its adjustment; it will bulge up no more.

Locate your near point in this way, and get a friend to measure how far it is from your eye.

Carry out a survey of other people's near point distance. Include people much older than you. If someone wears spectacles, take the measurement both with and without them: do the spectacles make any difference?

It is said that as people age the lens in their eye becomes less supple and so their near point gets further away. Can you find any evidence to support this in your survey?

Activity 6.21: Compare and contrast the structure and functions of the human eye and the camera

In a small group, use the information you have learnt so far to draw up a comparison between the camera and the human eye.

The eye's ability to focus on objects at varying distances is called **accommodation**. It is the ring of muscles around the lens that enables the eye to accommodate. With a distant point object the light is almost parallel, and the eye's lens focuses it back to a point on the retina. When you view a near object, the light spreading out from it and reaching your eye will be diverging strongly and yet the same lens has to focus it on the same retina. A stronger lens is needed to accomplish this second feat, and the muscles achieve this by causing the lens to bulge up into a fatter more rounded shape.

Figure 6.71 illustrates this process in a well-adjusted eye which does not need spectacles. For simplicity, all the bending of the light is shown occurring at the lens.

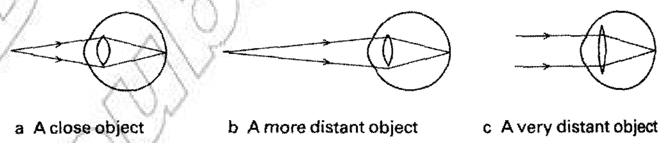


Figure 6.71 *The lens changing shape to focus light from objects at differing distances.*

In Figure 6.71a the eye is focusing on a close object. The lens has to be made into a very rounded shape to refract the light enough for it to meet on the retina. In Figure 6.71b the object is more distant. The light is not diverging so much, so less bending is needed to make the rays meet on the retina, and the lens is not so 'bulged up'. Finally, in Figure 6.71c the object is very distant. The apparently parallel rays are actually diverging from a point a long way off. Less refraction is needed and the lens is its natural shape and the muscles are relaxed.

Defects of the eye and their correction with lenses

The lens in the eye needs to be at its weakest when you are viewing objects a long way away, at infinity. With a correctly adjusted eye, at this point your lens is completely relaxed.

As an object approaches, the power of your eyeball has to increase, to refract the light a greater amount so it still focuses on the retina. To accomplish this the lens bulges into a fatter shape, thus giving it a shorter focal length. There is a limit to how much your lens can bulge, and when this limit is reached the object is at your near point. With a correctly adjusted eye the near point is taken to be 250 mm, though many young people can manage shorter distances than that.

The first three defects in vision described below all involve the lens in the eye. The fourth one is due to the shape of the cornea.

1. *Short sight* (*myopia*). This happens if the lens is too strong for the eye or, looked at another way, the eyeball is too long for the lens. With an object at the far point (that is, the greatest distance which can be focused clearly), the lens is fully relaxed – and for this eye the far point is not all that far away!

For objects at greater distances the lens can go no weaker, so light from them is made to meet in front of the retina and so the image is blurred.

The one compensation is that the near point will be exceptionally close.

To correct this fault, a diverging lens must be placed in front of the eye so parallel light is made to enter the eye as if it was spreading out from the eye's far point (see Figure 6.72).

2 *Long sight* (*hypermetropia*). This time the lens is too weak. The parallel light from distant objects would not be focused by the relaxed lens until past the retina, but they can still be seen clearly by causing the lens to bulge – thus using up some of the available accommodation already. This means that as an object approaches, the lens soon bulges to its maximum extent. Thus the near point will be an inconveniently large distance away.

This fault may be corrected with spectacles containing converging lenses, to strengthen the eyeball's optical system (see Figure 6.72).

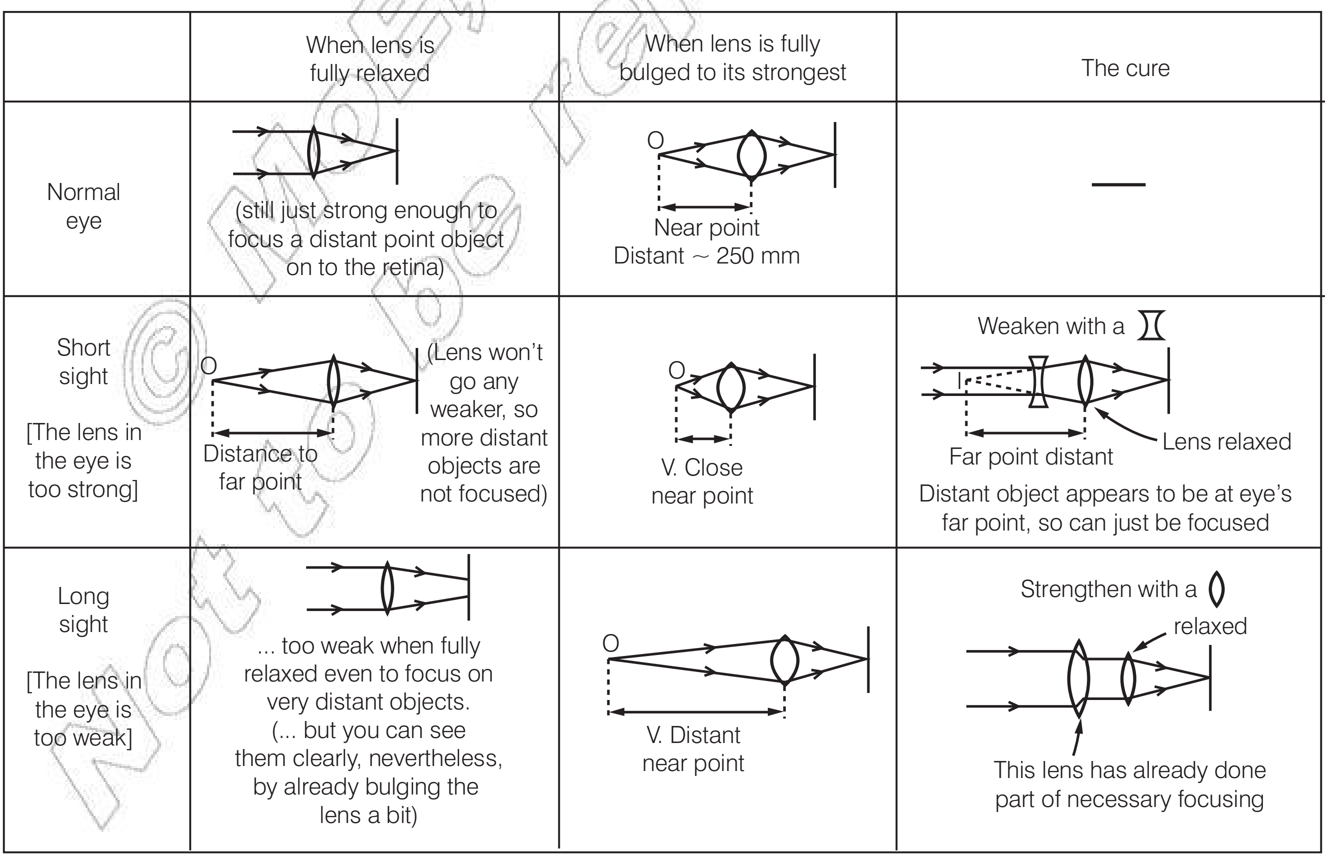


Figure 6.72 *Sight defects.*

3 *Old sight* (*presbyopia*). As people age, the lens in their eye may become less supple. In that case the power of accommodation may become affected at both ends of the range – their near point is too far away, so a book has to be held at arm's length, and their far point is too close so they cannot see distant things clearly.

In that case a pair of reading spectacles with diverging lenses and a pair of general viewing spectacles with converging lenses may be needed, or else a single pair of bifocals.

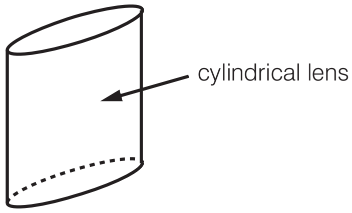


Figure 6.73 *Cylindrical lenses.*

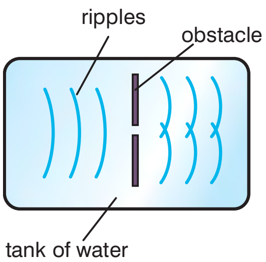


Figure 6.74 *Diffraction.*

KEY WORDS

diffraction *the change of direction of a wave at the edge of an obstacle in its path*

4 *Astigmatism.* This problem arises if a person's cornea has a different curvature in the horizontal plane from that in the vertical plane. This results in two slightly different powers. Vertical lines in the field of view may be sharply focused, for instance, while horizontal lines are a bit blurred.

The remedy is a pair of spectacles fitted with cylindrical lenses, whose surfaces are each part of a cylinder rather than a sphere (see Figure 6.73). These increase the power of the eye in one plane, to bring it up to the power in the other plane.

Diffraction of light

Diffraction of light (or any type of wave) is a change in direction that happens as the waves move through or round obstacles. You can see this effect with water waves if you place an obstacle in a tank of water and cause waves of different wavelengths to go through the obstacle (see Figure 6.74).

Diffraction is greatest when the wavelength of the waves is long compared to the size of the gap or obstacle.

Activity 6.22: Diffraction of light

Use two pencils or other straight edges. Place tape around the shaft of one pencil to create a space between them, as shown in Figure 6.75.

Darken the room and then look through the slit between the pencils and observe a candle flame at a distance of about 2 m (take care with the candle!). What do you see? Rotate the pencils and describe how your observations change. Change the width of the gap between the pencils slightly. What do you see now?

Figure 6.75 *Diffraction of light.*

Activity 6.23: Two-slit diffraction

Set up the apparatus as shown in Figure 6.76. What do you see?

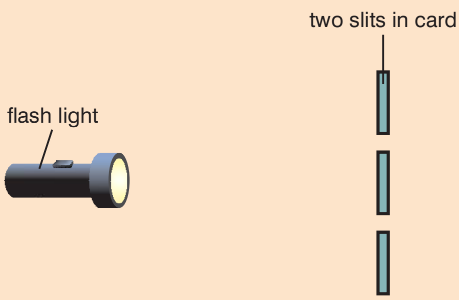


Figure 6.76 *Apparatus for two-slit diffraction.*

Activity 6.24: Using a diffraction grating

Set up the apparatus as shown in Figure 6.77. What do you see?

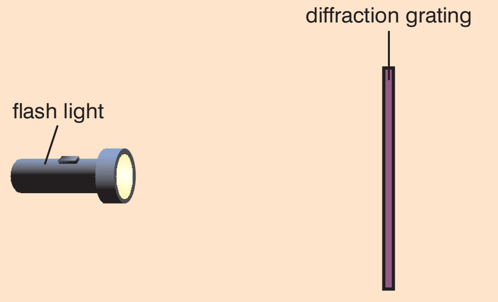


Figure 6.77 *Apparatus for a diffraction grating.*

KEY WORDS

diffraction grating *a material with a large number of narrow, regularly spaced slits, designed to produce a diffraction pattern*

In a small group, look back to the section on the electromagnetic spectrum on page 198 and see if it helps you to explain your observations before you read on.

Explaining the dispersion of white light to produce a spectrum

White light has a range of wavelengths, from blue to red. Since wavelength and speed are related by the equation $v = f\lambda$ (see page 197), then a range of wavelengths will produce a range of speeds. You know from page 215 that the amount of refraction is related to speed and so the different wavelengths in white light are refracted by different amounts to produce a spectrum, as shown in Figure 6.79. The rays are deviated by the prism.

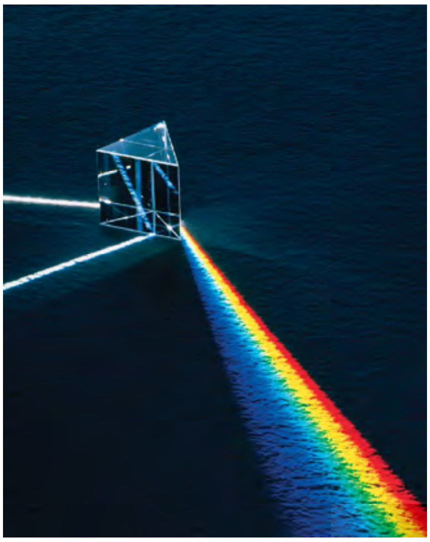


Figure 6.79 *Producing a spectrum by refracting white light through prism.*

Activity 6.25: Exploring dispersion of white light

Set up the apparatus as shown in Figure 6.78. What do you see?

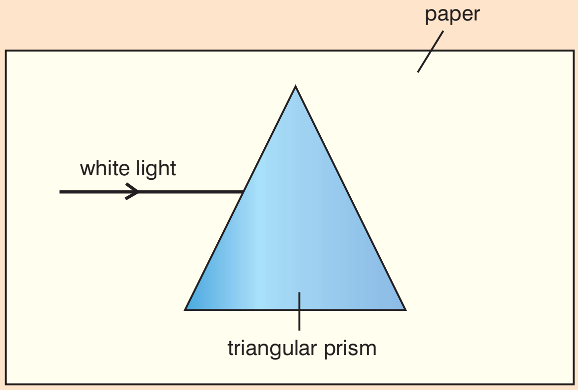


Figure 6.78 *Apparatus for exploring dispersion of white light.*

Activity 6.26: The CD spectroscope

Use a cracked CD to build a spectroscope. Observe the spectra of a flashlight, a regular bulb, an infrared bulb, a flashlight with a coloured filter, sunlight and a fluorescent bulb. Experiment with other light sources. Observe sunsets. Record your observations in a suitable manner.

Discuss in a small group why this works.

Warning: never look directly at the Sun.

The Fresnel lens

Fresnel lenses are thinner and lighter than conventional spherical lenses. They are made with separate sections known as Fresnel zones mounted in a frame. Fresnel lenses are used to concentrate solar light for use in solar cookers, solar forges, and solar collectors to heat water for domestic use.

KEY WORDS

solar constant *the average solar power striking the Earth's atmosphere in regions directly facing the Sun is about 1370 W/m². This is the solar constant.*

Activity 6.27: Measuring the solar constant using a Fresnel lens

Use a Fresnel lens like the one shown in Figure 6.80 to measure the heat input from the Sun.

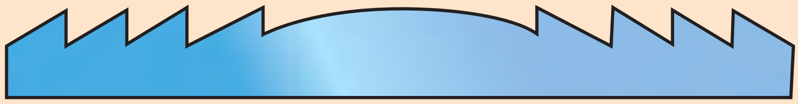


Figure 6.80 *Fresnel lens.*

Activity 6.28: Design a collector for the heat of the Sun

Design a collector that will concentrate and capture the heat of the Sun. You need to be able to heat up 5 cc of water to the highest possible temperature in 10 minutes. You may use a Fresnel lens or some other reflective surface such as mirrors or aluminium. The area of the collector must be less than 1 m^2.

Summary

- Refraction is the change in the direction of travel of a light beam that occurs as the light crosses the boundary between one transparent medium and another.
- The refractive index of a material is:

  $n = \dfrac{\sin\theta_1}{\sin\theta_2}.$
- Snell's law can be used to solve simple problems.
- The formula

  $\text{refractive index} = \dfrac{\text{real depth}}{\text{apparent depth}}$

  can be used to find the refractive index of a liquid and a solid in the form of a rectangular glass block.
- A diagram representing the passage of light rays through a rectangular glass block is as shown in Figure 6.81.

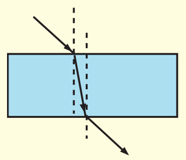


Figure 6.81

- Examples of observations that indicate that light can be refracted are the dispersion of white light to produce a spectrum and the passage of light through lenses.
- The passage of a ray of light through a parallel-sided transparent medium results in the lateral displacement of a ray.
- Total internal reflection is as shown in Figure 6.82.

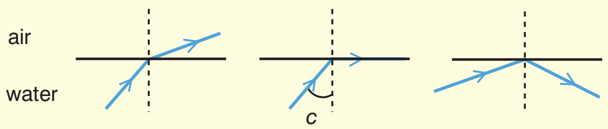


Figure 6.82

- The critical angle θ_c is the angle of incidence in a dense medium when the angle of refraction in a less dense medium is 90°.
- Total internal reflection occurs when the angle of incidence is more than the critical angle.
- You can use the formula $n = \sin 90/\sin c$ in calculations involving critical angle and total internal reflection.
- Total internal reflection is used in optical fibres because the light is trapped within the cable as shown in Figure 6.83.

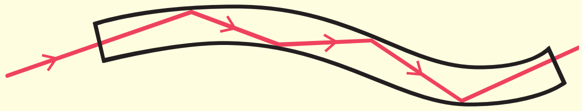


Figure 6.83

- Figure 6.84 shows the difference between convex and concave lenses and the terms used when talking about lenses.

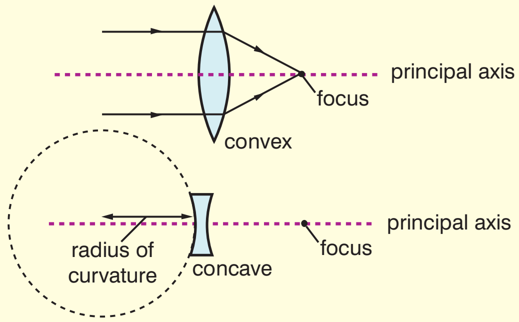


Figure 6.84

- Magnification in relation to converging and diverging lenses is $\dfrac{\text{image distance}}{\text{object distance}}$.
- When using the thin lens the equation, convex lenses have negative signs for image, object and focal length.
- The position and nature of the image formed by a convex and concave lens can be found using the thin lens formula and a ray tracing method.
- The power of a lens is defined by

  $\text{power of a lens} = \dfrac{1}{\text{its focal length in metres}}$

Review questions

1. Define the term refraction.
2. Define the refractive index of a material.
3. Find the refractive index of a material where the angle of incidence is 56° and the angle of refraction is 34°.
4. Use the formula refractive index = $\frac{\text{real depth}}{\text{apparent depth}}$ to find the refractive index of a liquid in which the real depth was 5 cm and the apparent depth was 3 cm.
5. State the conditions in which refraction occurs.
6. Describe an experiment to test the laws of refraction.
7. Give examples of observations that indicate that light can be refracted.
8. Why does the passage of a ray of light through a parallel-sided transparent medium result in the lateral displacement of a ray?
9. Define the critical angle θ_c.
10. Identify the conditions necessary for total internal reflection to occur.
11. What is the critical angle for total internal reflection to occur when the refractive index of the material is 1.52 and the angle of incidence is 32°?
12. Describe how total internal reflection is used in optical fibres.
13. Distinguish between convex and concave lenses.
14. Draw a diagram to identify the meaning of: principal focus, principal axis, focal point, radius of curvature and magnification in relation to converging and diverging lenses.
15. Find the position and nature of the image formed by a convex lens using a ray tracing method.
16. Define the power of a lens.
17. Explain how the image is formed due to combination of thin lenses.
18. Draw a ray diagram to show how images are formed by lenses in a simple microscope and a simple telescope.
19. Compare and contrast the structure and functions of the human eye and the camera.
20. Describe how the human eye forms an image on the retina for different object distances.
21. Identify some defects of the eye and their correction with lenses.
22. Explain what is meant by the dispersion of white light to produce a spectrum.
23. Why does the passage of a ray of light through a triangular transparent prism result in a deviation of a ray?

End of unit questions

1. What speed do all electromagnetic waves have in a vacuum?
2. Explain some uses of electromagnetic radiation.
3. Describe an experiment to test the laws of reflection using a plane mirror.
4. The height of an object is 5 cm and the height of its image in a concave mirror is 25 cm high. What is the magnification of the image?
5. Give examples of the uses of curved (concave and convex) mirrors.
6. State Snell's law.
7. Draw a diagram representing the passage of light rays through a rectangular glass block.
8. Explain, with the aid of a diagram, what is meant by critical angle and total internal reflection.
9. Use the thin lens equation to find the focal length of a convex lens where the object is 4 cm from the lens and the image is 6 cm from the lens.
10. In December 1901 Marconi succeeded in sending the first radio signals through the atmosphere 3200 km across the Atlantic Ocean. Many scientists at the time predicted that this experiment was impossible. Their prediction would have been true for television signals. Why did Marconi's experiment work? Why was it not possible to send a television signal the same distance until the 1960s? (Hint: compare how radio and television signals are transmitted.)
11. a) State what is meant by the diffraction of waves.

    b) Draw a diagram to show how water waves are diffracted when they pass through a gap.
12. Diffraction is a property of all waves, but is only a significant effect when the wavelength of the diffracted waves is about the same size as the aperture. Explain why the diffraction of sound is easily observed in everyday life but the diffraction of light is not.
13. Calculate the critical angle for

    a) water ($n = 1.33$)

    b) diamond ($n = 2.42$)
14. A certain transparent material, A, has a higher refractive index than another material, B.

    a) Through which one does light travel more slowly?

    b) How do both speeds compare with the speed of light in air?

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