UNIT 06

Optics

CHAPTER 17

Reflection of Light

17.1 INTRODUCTION

Light has played an important part in the evolution of humans since the beginning of time. Light from the Sun has supplied the energy for plants to photosynthesise, thus producing plant growth and food for animals and humans. A by-product of this, if it can be called such, is the production of oxygen — a necessary ingredient for sustaining life on Earth.

Over the past two decades energy from sunlight has played an important part in the conservation of other forms of energy. The development of non-polluting forms of energy will add to our quality of life. Use of solar energy will play a major part in our energy needs in the future. Light energy from the Sun is used to provide energy to heat water in solar hot water systems, reducing the dependence on coal-burning electricity production. Light is used in the production of solar electricity — electricity used to provide energy for remote telephone boxes, to fuel cars that race experimentally, and for energy-conscious households of the future.

But light has a more important use — it allows us to see. It allows us to identify objects, see colours and in most cases to choose our partners.

Scientists have developed many devices that enhance our perception of the world around us, with the development of mirrors and lenses that allow us to see better — glasses; to see further — telescopes and binoculars; and to see finer detail — microscopes. This is the content of this chapter and the next three chapters: Optics — the study of light and devices that use light.

A study of mirrors and lenses will enable you to answer questions such as:

- Where is light energy being used today?
- How can we concentrate light energy to be able to use it?

17.2 THE PRODUCTION OF LIGHT

Light energy can be converted to other forms of energy and vice versa. Light energy from the Sun is converted into chemical energy stored in plants, as well as into heat energy, and electrical energy. Other forms of energy such as heat energy and electrical energy are converted into light energy, such as when a light is turned on. Objects that emit their own light energy such as light bulbs, light from a star, or even a hot flame are called **luminous** objects. But these are few, because we see most objects by the reflection of light. When a light source illuminates objects they reflect light to our eyes; these objects could not be seen in a dark room. These are **non-luminous** bodies.

Light travels at a speed of 3×10^8 m s^{-1} in a vacuum and, contrary to Newton's original proposal, at a slower speed in water, glass, or any other medium.

17.3 LIGHT RAYS

Contrary to the belief of small children and our early ancestors, we see objects because light from these objects travels to our eyes, and not the other way around. It is no use covering your eyes, the 'bogey man' will still be there and able to see you.

To determine the position of an object requires narrow beams of light, **light rays**, to reach your eye, preferably your two eyes. Your brain traces these rays back to where they appear to meet. This, your brain tells you, is where the light originates. The wider the base for triangulation the better the positioning of the object. We call this 'stereoscopic vision'.

EI Activity 17.1 DEPTH PERCEPTION

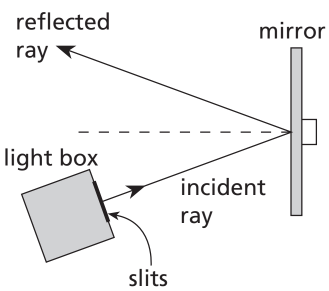
1. Ask a partner to hold up a finger within your reach.
2. Close one eye and try to touch your finger on the top of theirs.
3. How close did you get?
4. Try this again with both eyes open.
5. How close did you get this time?
6. Is one eye better than the other?

When only one eye is open, rays enter this eye at either side of the pupil, creating a narrow base and producing poor depth perception. With both eyes open, the base for triangulation is greater and so is the depth perception. Animals and fish that are hunters have eyes placed wide apart on the front of their heads so as to improve depth perception.

We use rays of light to determine where objects or images are. Rays of light travel in straight lines from objects. Importantly, rays from distant objects are close enough to be considered parallel.

Light boxes are common devices used to produce thin beams or rays of light for the investigation of optics in the laboratory (Figure 17.1).

Figure 17.1
Light boxes that produce thin beams of light (rays) are used in laboratory optical investigations.



A **laser** is another device used to produce thin beams of light. These also have the added convenience of emitting light of one wavelength. Laser stands for 'light amplification by stimulated emission of radiation'. Briefly, light is produced when the atoms of the laser medium are excited by electrical discharges or intense light flashes. When these atoms return to their unexcited state they give off energy in the form of light of a particular frequency and phase. Notice that you cannot see the light of a laser or even the light from a light box unless it strikes a wall or an object, as your eye and brain only respond to light when it strikes your eye. However, the following activity will allow you to see the laser beam without looking directly into it **as this is very dangerous and can damage your eye.**

EI Activity 17.2 LASER LIGHT

1. Place a laser at one end of the laboratory and turn it on so the beam strikes the wall at the other end of the room.
2. Hit a chalk-filled duster with a ruler around the area where the beam passes.
3. What do you notice?
4. Try to explain why this occurs.

PLANE MIRRORS 17.4

Plane mirrors normally consist of flat pieces of glass that have their backs coated with a thin layer of aluminium, and with lacquer to stop the aluminium from flaking. However, up until 1857 mirrors mainly consisted of highly polished pieces of steel. In that year Jean Foucault developed a method of silvering glass to make mirrors, thus producing a lighter and better-quality mirror than the common polished metals ones that tarnished. This brought about large advances in the development of astronomical telescopes.

Laws of reflection

What happens to a ray of light when it strikes a mirror? Everyone would say it is reflected. But in what way is it reflected?

Activity 17.3 LAWS OF REFLECTION

EI

1 Stand a mirror on a piece of white paper.
2 Using a light box with one slit, shine a ray onto the mirror at various angles.
3 In each case draw in the incident ray, the reflected ray and the position of the mirror.
4 Measure the angles between the normal to the mirror and the rays.
5 What do you notice?

We call:
- the ray that strikes the mirror the **incident ray**
- the ray that leaves the mirror the **reflected ray**
- the perpendicular to the mirror **the normal**
- the angle between the incident ray and the normal **the angle of incidence**
- the angle between the reflected ray and the normal **the angle of reflection**.

These are shown in Figure 17.2.

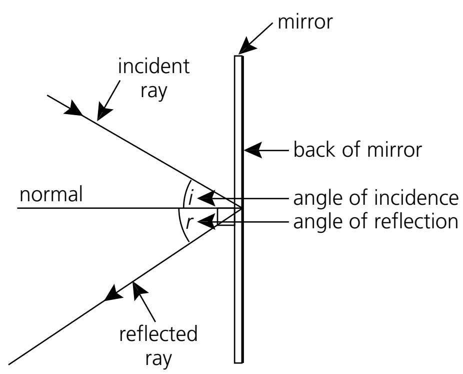


Figure 17.2
The common terms associated with rays of light and plane mirrors ($\angle i = \angle r$).

The above activity should have demonstrated the first law of reflection:

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

There is something else you may have noticed from the activity even though it may have been regarded as trivial. To obtain the angles in the activity, **the incident ray, the normal and the reflected ray all lie in the same plane**, that is, the plane of the paper.

If many parallel rays strike the mirror they leave the mirror parallel to each other, as shown in Figure 17.3.

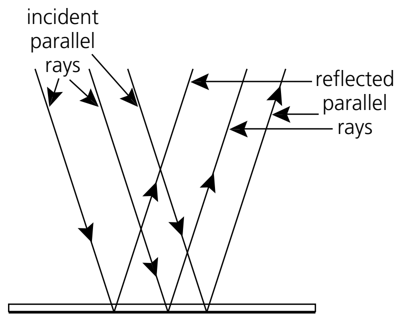


Figure 17.3
Specular reflection from a plane mirror. Parallel incident rays produce parallel reflected rays.

NOVEL CHALLENGE

You walk towards a plane mirror at 1 m s^{-1}. *How fast does your image approach you?* The mirror now approaches you at 1 m s^{-1}. *How fast does your image approach you now?*

Activity 17.4 REGULAR REFLECTION

1. Shine the light from a light box with a number of slits producing parallel light onto a plane mirror.
2. What do you notice about the rays that are reflected from the mirror?

This property is called **regular** or **specular reflection**. However, if these parallel rays are incident on an uneven surface such as a sheet of paper or a table top the reflected rays are not parallel.

Activity 17.5 DIFFUSE REFLECTION

1. Shine light from a light box with a number of slits onto a sheet of paper instead of a mirror.
2. What do you notice this time?

This is called **diffuse reflection**. It is not that the laws of reflection are being broken; it is just that the surface is uneven and the incident rays are not striking the surface, or parts of the surface, at the same angle (Figure 17.4). The angle of incidence still equals the angle of reflection for each ray at the particular point of contact.

NOVEL CHALLENGE

In the April 1984 edition of *New Scientist* magazine, a report appeared on the work of British inventor Charles deSelby. DeSelby reasoned that when you look at yourself in a mirror you are not seeing yourself at that instant in time but when you were a fraction of a second younger (the time it takes light to travel from your face to the mirror to your eyes). He set up two parallel plane mirrors facing each other and produced an enormous number of images as the light reflected back and forth. If you place your head between the mirrors you can verify this (even at home). Each successive image was further away in time than the one before. He used a telescope to peer at the receding images and he said he noticed that his image appeared successively younger until he finally noticed he looked like a young boy of particularly beautiful countenance. *Was deSelby a big liar or what? What is wrong with his theory?*

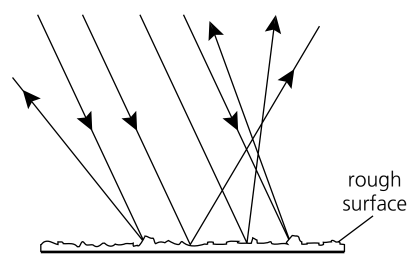


Figure 17.4
Diffuse reflection occurs from a rough surface. Parallel incident rays do not produce parallel reflected rays.

Because of this, images cannot be produced by surfaces that produce diffuse reflection.

Images

If you look into a mirror you can see the image of yourself but where is this image? The position of this can be found with a little investigation.

Activity 17.6 IMAGES

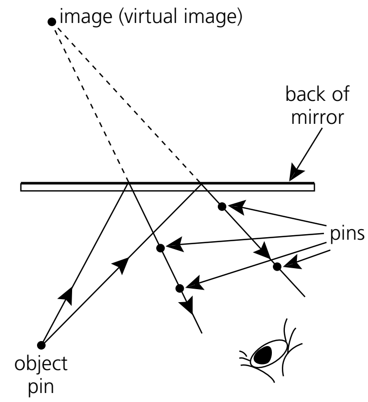
1. Place a sheet of paper on a styrofoam board.
2. Stand a mirror on this paper.
3. Place a pin in the paper a distance of about 10 cm from the mirror — this is the object.
4. Move your head to a position at an angle to the mirror and observe the image of the pin. Place two pins in line with this image. These represent a reflected ray.
5. Move your head to another position and place two more pins in line with the image — another reflected ray.
6. Mark the position of each pin and the mirror.
7. Draw up the reflected rays and extend them to where they meet. This will give you the position of the image (Figure 17.5).
8. What did you find?

You would have found that when this ray diagram is drawn and extended back (this is what your brain does), the rays appear to meet behind the mirror. Notice that they only appear to do so. This is called a **virtual image** as the rays do not pass through it and therefore the image could not be focused on a screen.

You may have also noticed that:

> *the image is the same distance behind the mirror as the object is in front*
>
> and
>
> *the line joining the object to the image is perpendicular to the mirror*

Figure 17.5
Two rays are needed to determine the position of the image.

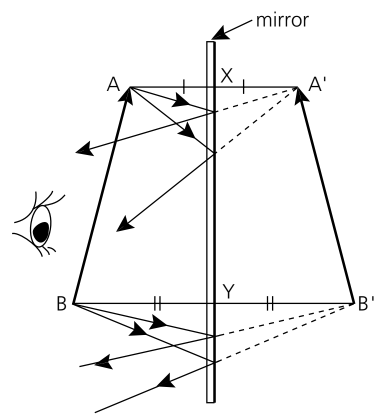


EI Activity 17.7 TRIANGULATION

This is just a short activity to demonstrate the importance of using a wide base of observation to locate images in mirrors.

1. Ask a student at the back of the classroom to speak and ask a student at the front, with eyes closed, to indicate where the speaker is.
2. Repeat the procedure but ask two students sitting close together at the front to indicate where the speaker is. (This gives a better indication of the source of the sound.)
3. Repeat the procedure but this time ask two students sitting a large distance apart at the front to indicate the source of the sound.
4. What did you find?

Figure 17.6
The image of an object can be determined using ray diagrams.



You get the idea — you need two rays, and the wider the base of observation the better and more accurate the placement of the source of the sound.

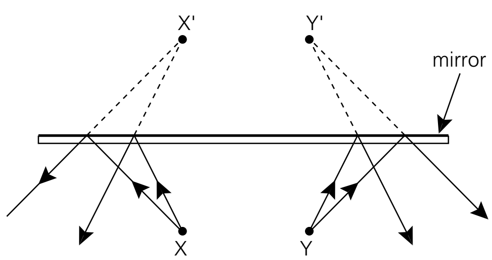
Ray diagrams, the principles of reflection, and triangulation can be used to diagrammatically show the relationship between objects and their mirror images.

Figure 17.6 shows the image of an arrow AB in a mirror. Using two rays from point A reflecting from the mirror to your eyes the image of A can be established. The same applies to B. Remember — to position an object two rays are needed and your brain, using the learnt fact that light travels in straight lines, traces the rays back to where they appear to come from.

Notice the arrow slopes the opposite way. This should have been predicted as it has already been established that the image of an object lies the same distance behind a mirror as the object does in front and is on the perpendicular to the mirror. Therefore $AX = XA'$, and $BY = YB'$. The same applies for all points between A and B. Notice also that the image $A'B'$ is the same size as AB.

Another curious fact about images in plane mirrors is that the image is **laterally reversed**. This is seen when you observe yourself in a mirror. If you wink your right eye it is the image's left eye that does the winking — left and right are reversed. Again, this can be established by drawing ray diagrams (Figure 17.7). The object X is on your left and Y on your right. In the image, X′ is on the image's right.

Figure 17.7
A ray diagram shows lateral inversion in a plane mirror.



Plane mirrors have been used for many years in various ways; for example, as beauty aids, and in cameras. They were used by First World War soldiers in the trenches, and are used in submarine periscopes and at football matches.

Figure 17.8
For question 2.

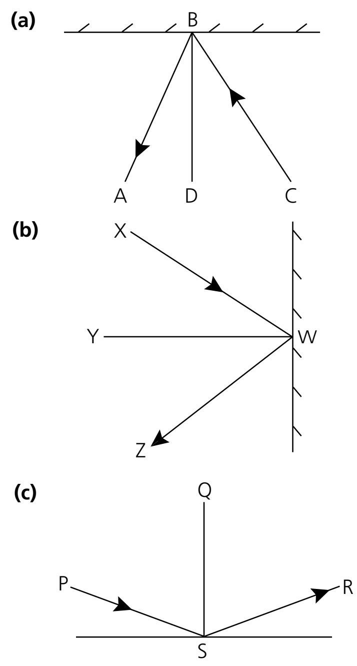
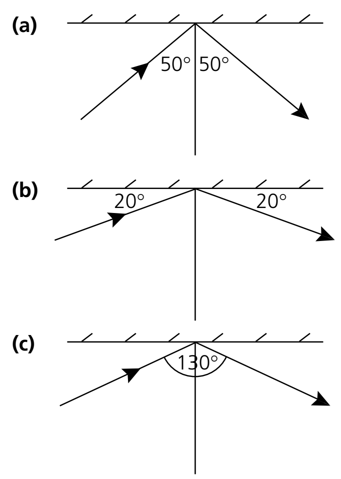


Figure 17.9
For question 3



People often think that a photograph of themselves is not very complimentary. This can be explained because they are used to seeing themselves in a mirror. The image they see of themselves has been laterally inverted, unlike the photograph.

Questions

1. Give examples of luminous and non-luminous bodies.
2. For the three cases shown in Figure 17.8, state the angle of incidence, the angle of reflection, the incident ray, the reflected ray, and the normal.
3. For each of the cases shown in Figure 17.9, state the size of the angle of incidence.
4. A student walks toward the front door of the school building at night. If she approaches the doors at a speed of 2 m s^{-1}, at what speed will her image in the doors approach her?
5. If a plane mirror produces images that are laterally reversed, then explain with the aid of a diagram why periscopes do not produce images that are reversed.

Corner reflectors

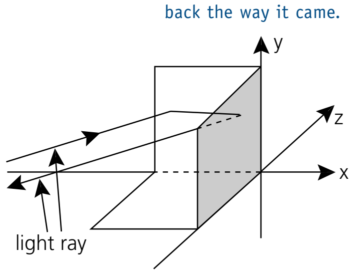
Interesting reflections occur from plane mirrors when three plane mirrors are placed along the three axes (x, y, and z) like the internal corners of a cube (Figure 17.10). This is called a **corner reflector**. Corner reflectors reflect light directly back towards the source no matter what angle the light strikes the reflector from. 'Cats'-eyes' on many roadways are made of corner reflectors. They also have many applications in science; for example, a laser geo-dynamic satellite 'LAGEOS' has over 400 corner reflectors and is used to measure continental drift by bouncing laser beams from the satellite. Scientists have placed corner reflectors on the Moon to reflect laser pulses from the Earth and thus accurately measure the changes in the Earth–Moon distance.

One-way mirrors

Everyone has seen police movies where a witness stands behind a 'one-way mirror'. The witness can see the criminal but the criminal cannot see the witness. How do these work? One-way mirrors rely on the lighting in the rooms. Just as you can very easily see your reflection when you try to look through a window on a dark night, the same occurs when a criminal tries to see through the one-way mirror. The room containing the 'line up' is very well lit while the observation room is dark. The criminal looking into the window sees his or her reflection and the glass appears to be a mirror. However, the witness in the dark room can observe the criminal, as light from the well-lit room passes through the glass. The 'one-way mirror' can be improved if a thin layer of metal is coated on the mirror's back surface. This improves the reflection properties but still allows enough light to be transmitted for observations to be made.

CURVED MIRRORS 17.5

Figure 17.10
A corner reflector, which consists of three perpendicular mirrors, reflects light back the way it came.



Curved mirrors are just as common today as plane mirrors but in many cases not as obvious. Can you identify some places where they are used?

A curved mirror can be one of two types, either **convex** or **concave**, depending on where the reflecting surface is. Curved mirrors are normally spherical mirrors, that is, they come from a part of a sphere. Imagine you had a hollow glass sphere. If you could take a section out of the sphere and silver either the outside or the inside you would have a spherical mirror. If the outside is coated this becomes the back of the mirror, producing a concave mirror. If the inside is silvered it becomes a convex mirror. Curved mirrors can make light rays converge (come together) or diverge (spread out), as shown in Figures 17.11 and 17.12.

Features of spherical mirrors

The centre of the sphere of which the mirror forms a part is called the **centre of curvature (C)**. The line through the centre of the mirror to the centre of curvature is the **principal axis**.

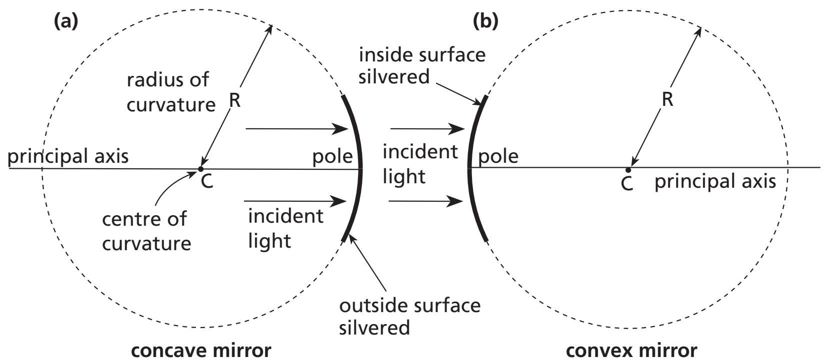


Figure 17.11
The spherical section becomes a concave **(a)** or convex **(b)** mirror, depending on which surface is silvered.

The point at which light rays parallel to the principal axis converge, in the case of a concave mirror (**converging** mirror), or appear to converge when extended back, in the case of a convex mirror (**diverging** mirror), is the **principal focus** (F). (See Figure 17.12.) This point could be found experimentally using a light box with multiple slits. In the case of the convex mirror these rays would have to be traced back to establish the focus — a virtual focus. In each case the focus could be found geometrically using the laws of reflection. (See Figure 17.13.)

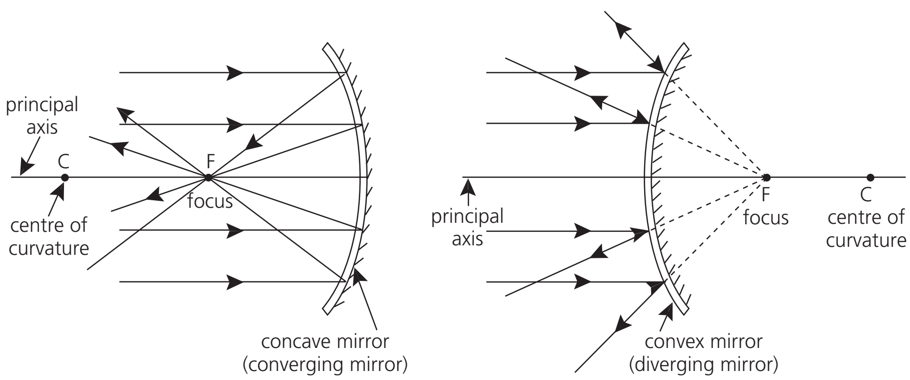
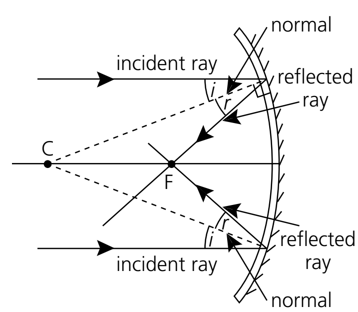


Figure 17.12
Common terms associated with spherical mirrors.

In either case the focal point is found to be half the distance from the mirror to the centre of curvature ($c = 2f$). The distance from the mirror to the focus is the **focal length** (f) of the mirror.

Figure 17.13
Using the law of reflection, $\angle i = \angle r$, with a number of rays, the focal point can be determined.



Measuring the focal length of a concave mirror

There are a few methods for determining the focal length of a concave mirror including finding the position of the image and then using the mirror formula. However, the simplest methods use the principle of 'parallel rays converge at the focal point'.

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Activity 17.8 FOCAL LENGTH

1. Shine the light from a light box with a slide that contains three or four slits on to the concave mirror. The focal point is where these rays intersect after reflection.
2. Use the light from a distant object outside the window of the laboratory. Focus the light from this object onto a screen placed in front of the mirror and measure the distance from the mirror to the screen when a clear, distinct image falls on the screen.
3. How do the two methods compare?

But how do you measure the focal distance of a convex mirror?

Images

The position of images seen in curved mirrors can be determined by drawing ray diagrams. To establish the position of the image requires drawing at least two rays. Any number of rays can be drawn using the laws of reflection, but these require the use of protractors to ensure the angle of incidence equals the angle of reflection. For this reason three easily drawn rays are normally used:

A A ray parallel to the principal axis reflects through the principal focus, or appears to come from this point in the case of a diverging mirror.

B The reverse of **A**. A ray through the focus reflects parallel to the principal axis.

C A ray through the centre of curvature reflects back through the centre of curvature.

(Remember — the centre of curvature is the centre of the sphere of which the mirror forms a part, therefore all rays from this point are perpendicular to the curved surface.)

Images — concave mirrors

The following examples are ray diagrams drawn to find the image of objects placed at various distances from a concave mirror.

Example 1 — object outside the centre of curvature Look at Figure 17.14. Notice that we only need to find the image of the head of the object as the foot is on the principal axis directly below the head; therefore the image of the foot will be directly below the head of the image.

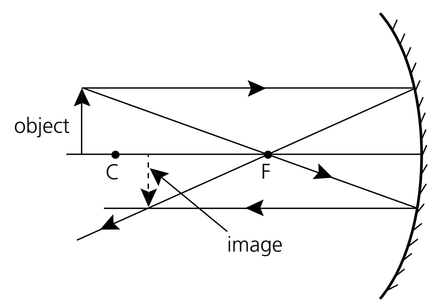


Figure 17.14
An object placed outside the centre of the curvature of a concave mirror produces an image that is smaller, real, inverted, and between F and C.

Example 2 — object at C See Figure 17.15.

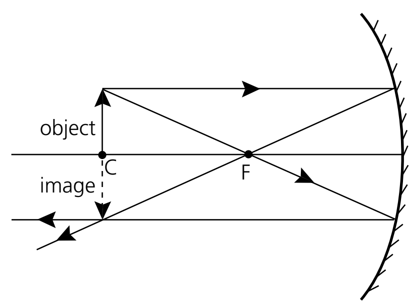


Figure 17.15
An object placed at the centre of the curvature of a concave mirror produces an image that is the same size, real, inverted and at C.

Example 3 — object between C and F See Figure 17.16.

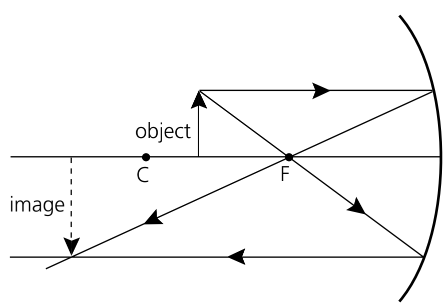


Figure 17.16
An object placed between the centre of curvature and the focal point of a concave mirror produces an image that is larger, real, inverted and outside C.

Example 4 — object between F and the mirror See Figure 17.17.

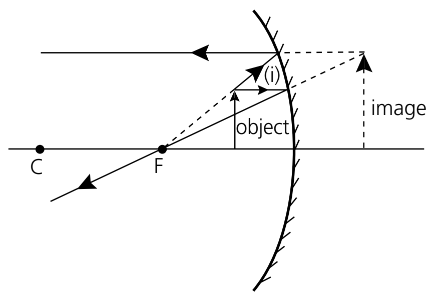


Figure 17.17
An object placed between the focal point and a concave mirror produces an image that is larger, virtual, upright and behind the mirror.

Notice that in Example 4, ray (i) does not actually pass through the focus but lines up with the focus. Also, to find the image the reflected rays have to be constructed back to where they appear to meet.

The characteristics of images are usually described using a set of common descriptors:

- size
- real or virtual
- upright or inverted
- position.

In the above examples for concave mirrors the characteristics of the images are as follows:
Example 1 — diminished (smaller); real (as the rays actually pass through the image, and because of this it can be focused on a screen); inverted; on the same side as the object between the focal point and the centre of curvature.
Example 2 — same size; real; inverted; at C on the same side.
Example 3 — magnified; real; inverted; outside C on the same side.
Example 4 — magnified; virtual; upright; behind the mirror.

Images — convex mirrors

Rays similar to those drawn for concave mirrors can be drawn to find the images in convex mirrors.

Example 1 — object a long distance from the mirror See Figure 17.18.

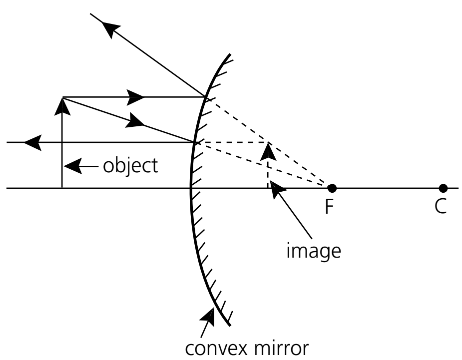


Figure 17.18
An object placed a long distance from a convex mirror produces an image that is smaller, virtual, upright, and behind the mirror.

Note 1: C and F are behind the mirror. (As C is the centre of the sphere, it has to be behind the mirror and F is half-way between C and the mirror.)
Note 2: The rays have to be traced back to where they appear to come from.
Description — diminished; virtual; upright; and behind the mirror between F and the mirror.

Example 2 — object close to the mirror See Figure 17.19.
Description — diminished; virtual; upright; and behind the mirror between F and the mirror.

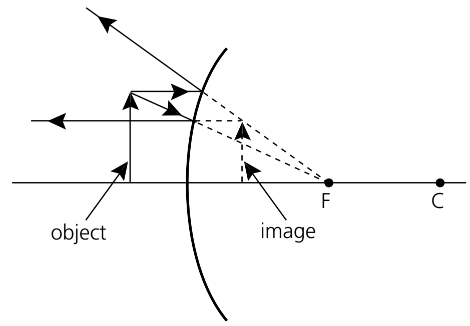


Figure 17.19
An object placed close to a convex mirror produces an image that is smaller, virtual, upright, and behind the mirror.

Notes on images

- In each of the above cases when virtual images are formed they are always upright.
- Where real images are formed they are always inverted.
- Convex mirrors always form virtual images.

Magnification

Magnification (*M*) is the size of the image compared with the size of the object.

$$M = \frac{H_i}{H_o}$$

where H_i is the height of the image; H_o is the height of the object.

Example 1

An object of height 1.0 cm is placed 6.0 cm in front of a concave mirror of 4.0 cm focal length.

(a) Draw an accurate ray diagram to locate the image.
(b) Describe the image.
(c) Find the magnification.

Solution

(a) See Figure 17.20.
(b) Magnified, real, inverted, outside C on the same side as the object.

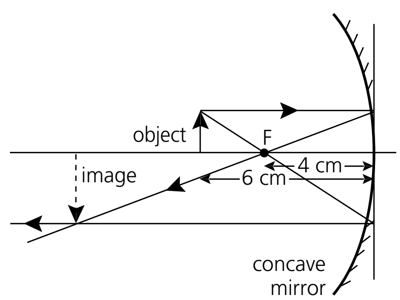


Figure 17.20
For sample problem.

(c)

$$M = \frac{H_i}{H_o} = \frac{1.8\text{ cm}}{1.0\text{ cm}} = 1.8$$

Note: to make drawing of ray diagrams easier, that is, without the use of compasses to draw the mirror, we can use a vertical line through the back of the mirror to represent the reflecting surface. This is a reasonable approximation as long as we stay within the middle part of the mirror.

Example 2

A convex mirror has a focal length of 6.0 cm. An object of height 1.5 cm is placed 2.0 cm in front of the mirror.

(a) Draw an accurate ray diagram to find the position of the image.
(b) Describe the image.
(c) Find the magnification.

Solution

(a) See Figure 17.21.
(b) Diminished, virtual, upright, behind the mirror between the mirror and F.

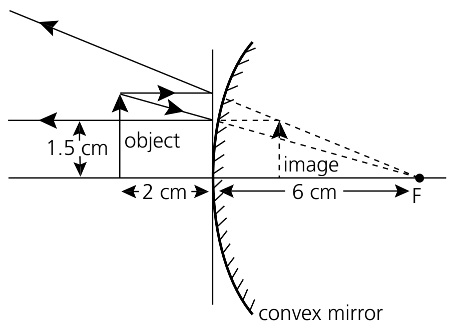


Figure 17.21
For sample problem.

(c)

$$M = \frac{H_i}{H_o}$$

$$= \frac{1.0\text{ cm}}{1.5\text{ cm}}$$

$$= 0.67$$

Questions

6 State as many differences as you can between concave and convex mirrors.
7 Which of the two mirrors, concave or convex, **(a)** spreads parallel light out, or diverges the light; **(b)** focuses parallel light to a point, or converges the light?
8 Use a ray diagram and an appropriate scale to find the position of the image of a 10 cm high object placed 1.5 m in front of a concave mirror of focal length 20 cm.
9 An object of 2.0 cm height is placed 5.0 cm in front of a diverging mirror of 10 cm focal length.
(a) Draw a ray diagram to find the position of the image.
(b) Describe the characteristics of the image.
(c) Use the magnification formula to find the height of the image.

17.6 THE MIRROR FORMULA

We need a more accurate method of finding the position of an image without drawing ray diagrams, which are not very accurate. We can do this by using a formula.

Consider the following derivation and refer to Figure 17.22.

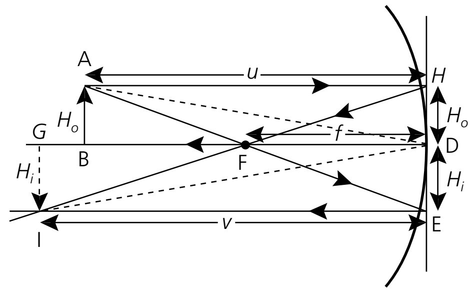


Figure 17.22
Used for the derivation of the mirror formula.

$$\triangle ABD \simeq \triangle IGD$$

$$\therefore \frac{H_o}{H_i} = \frac{u}{v}$$

$$\triangle ABF \simeq \triangle EDF$$

$$\begin{aligned} \therefore \frac{H_o}{H_i} &= \frac{BF}{DF} \\ &= \frac{u - f}{f} \end{aligned}$$

$$\triangle HDF \equiv \triangle FGI$$

$$\begin{aligned} \therefore \frac{H_o}{H_i} &= \frac{DF}{GF} \\ &= \frac{f}{v - f} \end{aligned}$$

$$\begin{aligned} \therefore \frac{u - f}{f} &= \frac{f}{v - f} \\ (u - f) \times (v - f) &= f^2 \\ vu - uf - vf + f^2 &= f^2 \\ vu &= vf + uf \\ vu &= (v + u)f \\ \frac{1}{f} &= \frac{(v + u)}{vu} \\ &= \frac{v}{vu} + \frac{u}{vu} \\ &= \frac{1}{u} + \frac{1}{v} \end{aligned}$$

This formula, $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$, relates the focal length f to the object distance u and the image distance v and is called the **mirror formula**.

The equation $M = \frac{H_i}{H_0} = \frac{v}{u}$ is used to find the magnification.

Note: since we have measurements on either side of the mirror, in front and behind, an order convention is required. We will make all measurements on the object side of the mirror positive and those behind the mirror (taken as the origin) negative. Hence concave mirrors have a positive focal length, and convex mirrors have a negative focal length.

To remember that u represents the object distance and v the image distance, recall that u comes before v in the alphabet and that light goes to the object before the image.

When using the magnification formula ($M = \frac{v}{u}$), the absolute valves of v and u should be used. That is, ignore + and – values.

Now let's see how accurate we were in drawing ray diagrams.

Example 1

An object of height 1.0 cm is placed 6.0 cm in front of a concave mirror of focal length 4.0 cm.

(a) Find the position of the image.
(b) Find the magnification and the height of the image.

Solution

(a) Using the formula, the mirror is concave, therefore $f = +4.0$ cm.

$$\frac{1}{f} = \frac{1}{v} + \frac{1}{u}$$
$$\frac{1}{4} = \frac{1}{v} + \frac{1}{6}$$
$$\frac{1}{4} - \frac{1}{6} = \frac{1}{v}$$
$$\frac{6}{24} - \frac{4}{24} = \frac{1}{v}$$
$$v = 12 \text{ cm}$$

The image is 12 cm in front of the mirror.

(b)

$$M = \frac{H_i}{H_o} = \frac{v}{u}$$
$$= \frac{12}{6}$$
$$= 2$$
$$\therefore H_i = 2H_o$$
$$= 2 \times 1$$
$$= 2 \text{ cm}$$

Example 2

A convex mirror has a focal length of 6.0 cm. An object of height 1.5 cm is placed 2.0 cm in front of the mirror.

(a) Find the position of the image.
(b) Find the magnification and the height of the image.

Solution

(a) The focal length is negative for convex mirrors as it is on the opposite side of the mirror as the object, hence $f = -6$ cm.

$$\frac{1}{f} = \frac{1}{v} + \frac{1}{u}$$
$$\frac{1}{-6} = \frac{1}{v} + \frac{1}{2}$$
$$\frac{1}{-6} - \frac{1}{2} = \frac{1}{v}$$
$$\frac{-1}{6} - \frac{3}{6} = \frac{1}{v}$$
$$\frac{-4}{6} = \frac{1}{v}$$
$$v = -1.5 \text{ cm}$$

The image is 1.5 cm behind the mirror.

(b)

$$M = \frac{H_i}{H_o} = \frac{v}{u}$$
$$= \frac{1.5}{2}$$
$$= 0.75$$
$$\therefore H_i = 0.75H_o$$
$$= 0.75 \times 1.5$$
$$= 1.125 \text{ cm}$$

Note: the image distance for real images is positive whereas the image distance for virtual images is negative.

Questions

10 A small light bulb is placed 20 cm in front of a concave mirror of focal length 15 cm.
(a) Calculate the image distance.
(b) Calculate the ratio of the width of the image of the bulb to the width of the actual bulb.
(c) If the bulb was 1 cm across how wide would the image be?
(d) What type of image is produced?

11 Students performing experiments with diverging mirrors try to locate the image of a small candle of height 2 cm in the mirror. When the candle is placed 25 cm from the mirror they see the image in the mirror to be smaller. (The focal length of the mirror is 20 cm.)
(a) Draw a ray diagram to locate the image.
(b) Use the mirror formula to calculate the position of the image.
(c) What is the height of the image?

12 An object of height 2 cm is placed 4 cm in front of a diverging mirror of focal length 6 cm.
(a) Draw a ray diagram to find the position and height of the image.
(b) Use the mirror and magnification formulae to verify your answer to part **(a)**.

13 A concave mirror of focal length 10 cm is used to produce an image on a screen that is half the size of the object.
(a) Find the position of the object and the image.
(b) If you wanted to produce a real image of twice the size where would be the position of the object and the image?

SPHERICAL ABERRATION 17.7

Spherical aberration is the inability of a concave mirror to focus parallel light to a point. Parallel rays after reflecting from the mirror do not meet at a point but over a small region,

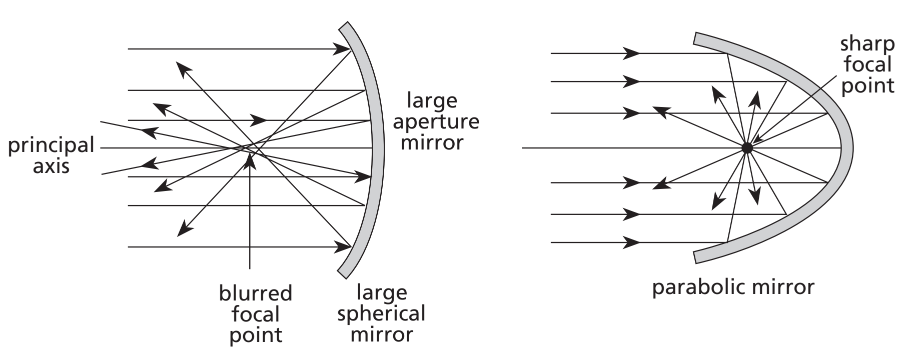


Figure 17.23
Parabolic mirrors help to eliminate spherical aberration where a blurred focal point is produced.

producing a blurred focal point rather than a sharp point. This defect of curved mirrors is called spherical aberration. It occurs more often when the mirror is large. It can be overcome by using smaller aperture mirrors or by only using the central region of larger mirrors. Special larger parabolic mirrors whose geometry results in the sharp focusing of parallel light are also manufactured to overcome this defect (Figure 17.23).

17.8 USES OF CURVED MIRRORS

Concave mirrors

- Concave mirrors are also used to produce magnified images so as to observe more detail in objects. Recall that if an object is inside the focal length then it produces an upright magnified image. Larger focal length concave mirrors are therefore used as shaving and make-up mirrors. Small concave mirrors are used by dentists.
- Concave mirrors are used as the reflectors in a number of applications where parallel or almost parallel light is required. If the light source is placed at the focal point of the mirror almost parallel light will be produced; for example, reflectors in headlights of cars, torches, and searchlights.
- Concave mirrors, because they bring together (or focus) light rays, are used to collect light energy as well as other forms of energy. Solar furnaces or ovens use large concave mirrors to concentrate light energy from the Sun onto pots and kettles placed at the focus. The biggest solar furnace in the world is located in the Pyrenees mountains in southern France. An array of computer-controlled plane mirrors (heliostats) on a nearby hill track the Sun and reflect the light onto an eight-storey-high converging mirror. The converging mirror focuses the sunlight onto a small building housing the solar furnace. Temperatures in excess of 3000°C have been reached in this experimental furnace.

  Concave mirrors are also used to concentrate other electromagnetic radiations such as radio and TV waves. Satellite dishes concentrate TV waves to be used by TV sets. Radio waves from stars can be focused onto the antennae placed at the focus of the receiving dish, which conducts the signal to an amplifier. (See Photo 17.2.)
- The same principle applies to astronomical telescopes. Larger optical reflecting telescopes concentrate visible light energy to the focus, where the eye piece or photographic equipment is placed. (Refer to Chapter 20, Optical Instruments.)
- Interestingly enough, because sound is so important to bats, bats' ears are concave in shape to collect and concentrate sound energy.

Photo 17.1
Torches use concave mirrors to produce a nearly parallel beam of light.

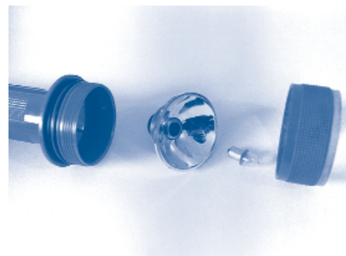


Photo 17.2
Satellite dishes enable TV sets to pick up TV waves that are reflected from satellites by concentrating TV waves on to an aerial.

Convex mirrors

Convex mirrors, because they have a wider field of view than plane mirrors and produce upright images, are used as rear-vision mirrors in cars; however, they have a disadvantage in that distances can be misjudged. They are also used on intersections of streets where vision is obscured. This allows drivers to see around 'blind' corners.

Because of their wide field of view they are also used in shops for security purposes.

Photo 17.3
Bats' ears are concave to collect reflected ultrasound waves.

Practice questions

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

Review — applying principles and problem solving

***14** White paper or the desk top does not produce an image of an object. Does this mean the laws of reflection are not true for these surfaces? Explain!

***15** If you observe yourself in a plane mirror what are three significant optical facts about the image?

***16** One method of taking your own photo is to photograph your image in a large mirror. If you are standing 2.0 m in front of the mirror what distance setting should you use to obtain a photo in focus? Would an autofocus camera focus correctly?

***17** If you wish to view your whole body in a mirror what is the minimum length of such a mirror and where on the wall should it be placed?

***18** Explain the difference between a real and a virtual image.

***19** In each of the following cases state whether the light is parallel, converging, or diverging:
- **(a)** Light from a light bulb.
- **(b)** Light from a light bulb reflected from a mirror.
- **(c)** Light from a star.
- **(d)** Light from a star reflected from a concave mirror.
- **(e)** Light from a star reflected from a plane mirror.
- **(f)** Light from a star reflected from a convex mirror.
- **(g)** Light from a bulb placed at the focal point of a concave mirror.
- **(h)** Light from a bulb placed at the focal point of a convex mirror.

****20** A 1.0 cm high object is placed 10 cm in front of a concave mirror of 7.0 cm focal length.
- **(a)** Draw a ray diagram to find the position of the image.
- **(b)** Describe the nature of the image.
- **(c)** Use the mirror formula to find the exact position of the image.
- **(d)** Use the magnification formula to find the height of the image.

****21** A dentist wishes to use a concave mirror to view a patient's teeth. If he wants the image to be twice as large as the object and upright when the mirror is placed 2.0 cm from the teeth, what focal length mirror is needed?

****22** Students doing experiments with convex mirrors place a small candle 15 cm in front of the mirror. They are able to see a smaller image of the candle in the mirror but are unable to produce an image on a screen.
- **(a)** Explain why an image could not be formed on the screen. (Use a ray diagram.)
- **(b)** What sort of image is it?
- **(c)** If the focal length of the mirror was 20 cm, calculate the position of the image.

***23** Large diverging mirrors are used for security purposes in small shops. They are placed in the corners. What are the advantages of these mirrors for this purpose?

****24** A student places a 5.0 cm high candle 20 cm in front of a concave mirror. The image is formed on a screen placed 40 cm from the mirror.
- **(a)** What is the focal length of the mirror?
- **(b)** What is the size of the image?
- **(c)** Is the image virtual or real?
- **(d)** Is the image upright or inverted?

***25** You are unable to see your reflection in a dull, unpolished car; however, if the car is polished you can see your image. You have not changed the material structure of the car so why does this occur?

***26** When you go for your driver's licence you are required to read an eye chart. Issuing centres use plane mirrors to make sure the correct distance between the chart and the observer is maintained. If a distance of 6.0 m is required describe characteristics of the physical set-up of the chart and mirror as well as the chart itself to obtain this situation.

***27** Why do some police cars and ambulances have the words on their fronts as shown in Figure 17.24?

****28** Draw a reasonably accurate ray diagram to find the image of objects in the three cases shown in Figure 17.25.

Figure 17.24
For question 27.

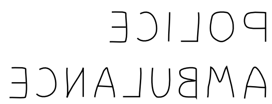
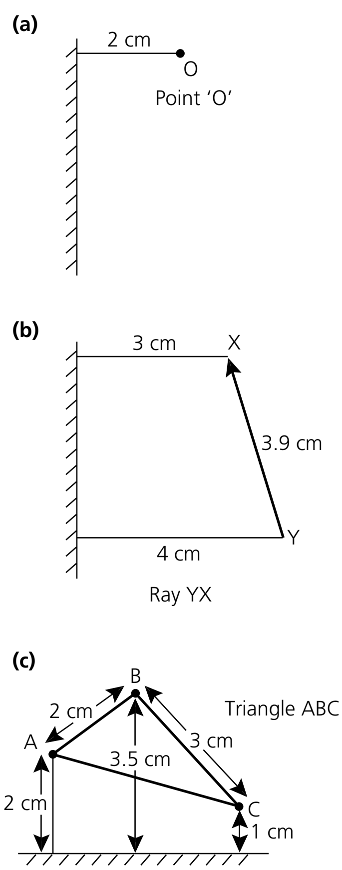


Figure 17.25
For question 28.



****29** Figure 17.26 shows the position of two mirrors at 45° to each other. A ball is placed at point X. Draw ray diagrams to find the image of the ball in the mirrors.

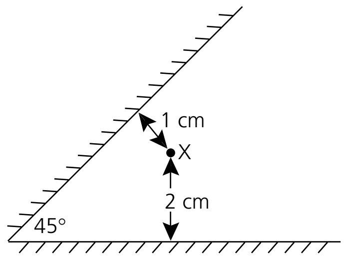


Figure 17.26
For question 29.

****30** Figure 17.27 indicates a light ray making an angle of 40° with the mirror. If the mirror is rotated so the ray now makes an angle of 10° with the mirror, through what angle does the reflected ray move?

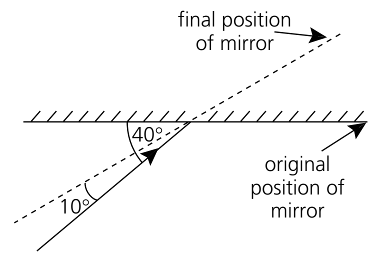


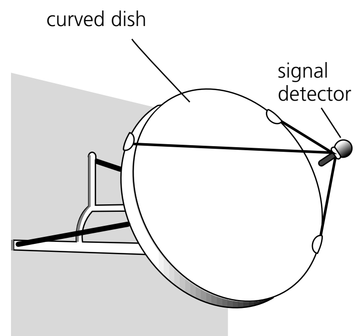
Figure 17.27
For question 30.

***31** Figure 17.28 shows a satellite dish used for receiving TV signals.
(a) What shape should the dish be?
(b) Where should the signal detector (aerial) be situated? Why?
(c) What features of the dish should be changed to improve its performance?

***32** Construct a table for concave mirrors showing the position of the object from outside the centre of curvature to inside the focus, the size of the image, the position of the image, the nature of the image, and whether it is upright or inverted.

***33** If you were sitting at the breakfast table and a piece of dust flew into your eye, explain how you could use a spoon to observe a larger image of your eye to help remove the dust particle.

Figure 17.28
For question 31.



***34** Some solar hot water systems use curved enclosures/supports to hold black PVC pipe in which water flows. (See Figure 17.29.) Discuss the purpose of these shiny curved enclosures and the positioning of the black PVC pipe.

***35** Figure 17.30 (opposite) shows an object with several rays reflecting from a convex mirror. Which of the rays are correctly drawn?

***36** Students going on a hike from an outdoor education centre decide to heat their food by making a solar cooker out of sheets of aluminium foil.
(a) What shape should they press the foil into?
(b) Where should the food be placed?

****37** In a laboratory experiment, students measured the position of the image of a small 4.0 cm high candle with respect to a concave mirror, and the magnification of the candle by measuring the size of the real image produced on a screen. Table 17.1 shows the results obtained.

Figure 17.29
For question 34.

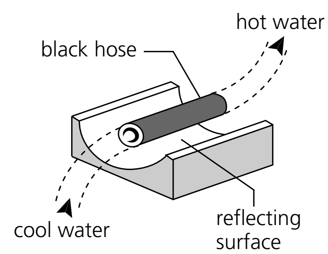


Table 17.1

Image distance (cm)	60	37.5	26.3	24	21.4	20	18.5
Image height (cm)	12	6	3	2.4	1.7	1.3	1.0
Magnification							

(a) Complete the table.
(b) Plot the graph of magnification verses image distance.
(c) Find the magnification when the image distance is 45 cm.
(d) Find the image distance when the magnification is 0.50.
(e) *From the graph*, find the focal length of the mirror.

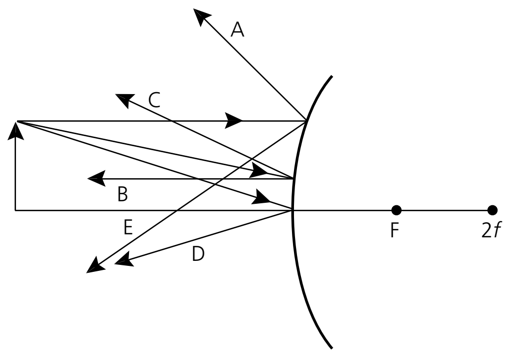


Figure 17.30
For question 35.

Extension — complex, challenging and novel

*****38** A plane mirror and a convex mirror are placed facing each other and 50 cm apart. A candle is placed on the principal axis 20 cm from the plane mirror, as shown in Figure 17.31. If the distance between the two images in the plane mirror is 40 cm, calculate the focal length of the convex mirror.

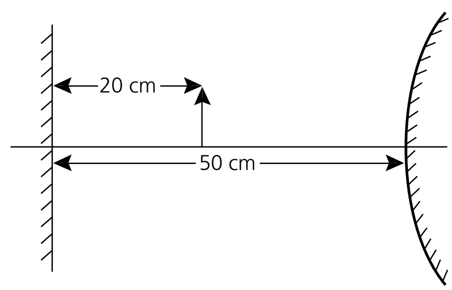


Figure 17.31
For question 38.

*****39** An object is placed 20 cm in front of a convex mirror of focal length 30 cm. A plane mirror is placed between the object and the mirror so that the image of the top half of the object in the convex mirror and the bottom half of the object in the plane mirror coincide. What distance is the plane mirror from the convex mirror?

*****40** A candle is placed in front of a concave mirror whose focal length is 20 cm. Find the position of the object and the image if **(a)** a virtual image of twice the size of the object is produced; **(b)** a real image of twice the size of the object is produced.

*****41** Students determining the focal length of a concave mirror obtained the measurements listed in Table 17.2 for the distances of the object and the image formed on the screen. Plot the graph of image distance against object distance to determine the focal length of the mirror.

Table 17.2

Object distance (cm)	60	50	40	30	25	20	15	10
Image distance (cm)	9.2	9.5	10	10.9	11.8	13.3	17.1	40