Geometrical Optics

Physics 05

5.1 Reflection of light

We cannot see anything in the dark. The reason for this is that light is required to give rise to visual sensation. We would be able to see an object only if light from the object reaches our eyes.

Objects that emit light such as a candle flame or a light bulb are known as **luminous objects**. We can see them because our eyes receive light from them. Objects that do not emit light are known as **non - luminous** objects. When light from the Sun or some artificial light source falls on such objects they reflect part of the light and when the reflected light reaches our eyes we see the objects.

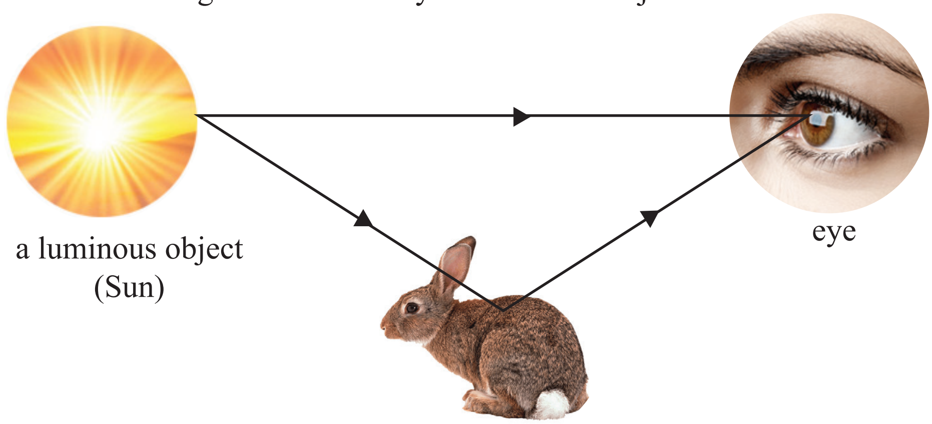


Figure 5.1 – Seeing luminous and non-luminous objects

Light passes through some objects. They are known as transparent objects (eg: glass, polythene). Objects through which light does not pass at all are known as opaque objects (eg: stones, bricks). Light passes through some materials with irregular changes of direction, making it impossible to see the objects on the other side clearly. Such materials are known as translucent materials (eg: tissue paper, oil paper).

A light ray is represented by a straight line with an arrow head marked on it. The arrow head is essential to indicate the direction of the light ray.

A light ray →

A bundle of rays is known as a beam. A bundle of parallel rays form a parallel beam. A bundle of rays that meet at a certain point is known as a convergent beam. A bundle of rays that travel away from a given point is known as a divergent beam.

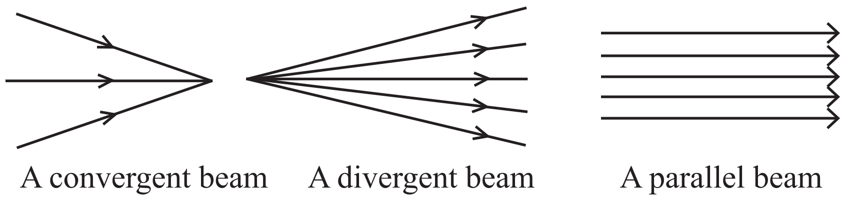


Figure 5.2 – beams of light

Let us review what we have learned about the reflection of light before.

The dressing table mirrors familiar to you are plane mirrors. The change in the propagation direction of light rays incident on a plane mirror is known as reflection. Figure 5.3 shows how a light ray (*AB*) incident perpendicularly on a plane mirror is reflected. *BA* is the reflected ray.

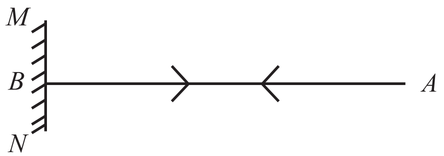


Figure 5.3 – The way a light ray incident on a plain mirror is reflected

- In figure 5.4, *MN* is a plane mirror. *AB* is a ray that is incident on point *B* of the reflecting surface of the mirror and it is known as the **incident ray**. This ray is reflected along *BC*.
- *BX* is an imaginary line drawn perpendicular to the mirror at the point of incidence. It is known as the **normal** to the reflecting surface at the point of incidence.
- The angle between the incident ray and the normal is known as the **angle of incidence** (*i*). The angle between the reflected ray and the normal is known as the **angle of reflection** (*r*).

MN - plane mirror
AB - incident ray
BC - reflected ray
BX - normal at the point incidence
$A\hat{B}X$ - angle of incidence (*i*)
$C\hat{B}X$ - angle of reflection (*r*)

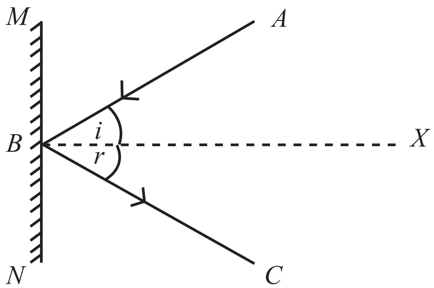


Figure 5.4 – Reflection of a light ray from a plane mirror

You have learnt two laws of reflection of light before.

First Law

The incident ray, the reflected ray and the normal at the point of incidence lie on the same plane.

Second Law

The angle of incidence is equal to the angle of reflection.
That is $i = r$

Now let us see how an image is formed when a point object is in front of a plane mirror.

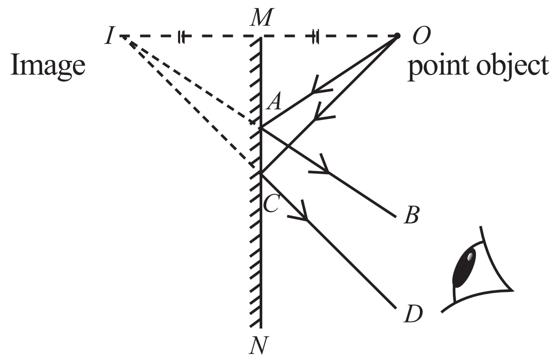


Figure 5.5 – The formation of an image of a point object by a plane mirror

In figure 5.5, a point object *O* is placed in front of a plane mirror *MN*. *OA* and *OB* are two rays propagating from the object towards the mirror. These two rays are reflected respectively along *AB* and *CD* and reach the eye of the observer.

Not just these two rays, but many such rays from *O* are reflected by the mirror and reach the observer's eye.

The observer sees these rays as coming from the point *I*. Therefore the observer sees as if the object is placed at *I*.

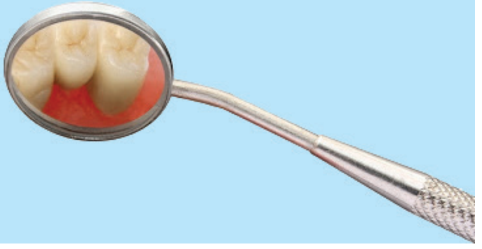
- No rays actually pass through this image. Because there are no light rays at the location of the image, this image cannot be projected on a screen.
- An image like this is known as a virtual image.
- All images formed by plane mirrors are virtual.
- Distance from the object to the mirror (object distance) is equal to the distance from the image to the mirror (image distance).
- Images formed by plane mirrors are identical to the objects, but they are lateral inverted. That means the right side of the object appears as its left side, and vice versa.

The term AMBULANCE written in the front face of ambulances is inverted (ƎƆNA⅃UBMA). However, when the ambulance is going behind another vehicle, the driver of the vehicle in front sees it through his rear view mirror as AMBULANCE.

5.2 Curved (Spherical) Mirrors

We know that the type of mirrors called convex mirrors are used in vehicles so that the driver can see the road behind him from both sides of the vehicle.

With these the driver can see a large area behind the vehicle, as a small image. In some shops, convex mirrors are used to observe a large part of the shop for security purposes.



Dentists use another type of curved mirrors called concave mirrors to view inside the mouth of patients. These mirrors show enlarged images of teeth.

Concave mirrors are used for shaving too. In both of these cases, the ability of concave mirrors to produce enlarged images is used.

Figure 5.6 shows an enlarged image from concave mirror and a diminished image from a convex mirror.

Figure 5.6 – images formed by concave and convex mirrors

Now let us discuss more about curved mirrors.

Mirrors with curved reflecting surfaces are known as **curved mirrors**. If the curved surface is a part of a sphere, the mirror is known as a **spherical mirror**.

There are two main types of curved mirrors.

1. Concave mirrors
2. Convex mirrors

The reflecting surface of a concave mirror is curved inward. The reflecting surface of a convex mirror is curved outward.

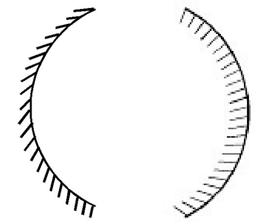


Figure 5.7 shows that spherical mirrors are parts of hypothetical spheres.

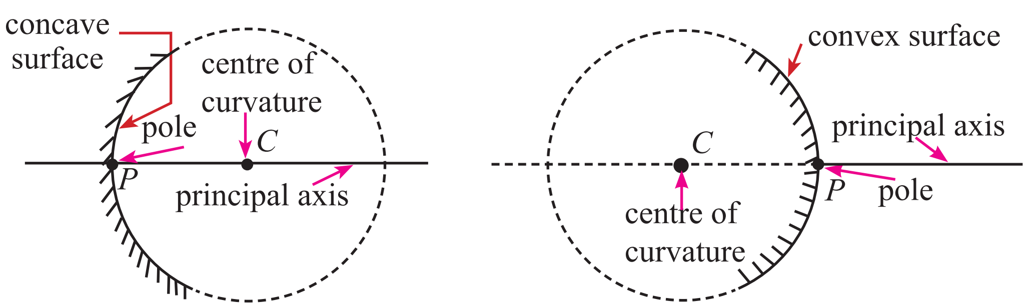


Figure 5.7 - Center of curvature, pole and principal axis of a spherical mirror

- The centre of each sphere (*C*) to which the mirror surface belongs is called the **centre of curvature** of the mirror.
- The centre point of the curved mirror (*P*) is called the **pole** of the mirror.
- The line joining the pole *P* and the centre of curvature *C* is called the **principal axis**.
- The principal axis is perpendicular to the mirror surface at *P*.

5.2.1 Focal point of a curved mirror

For light rays coming along the principal axis, the incident angle is zero and therefore the angle of reflection is also zero. Therefore light rays coming along the principal axis reflect back along the same path.

Rays coming parallel to the principle axis towards a concave mirror pass through a point on the principal axis after reflecting from the mirror. If a screen is placed on that point so as to allow the reflected rays to fall on it, a small bright spot would be visible. This point marked as *F* in Figure 5.8 is known as the **focus or the focal point** of the mirror.

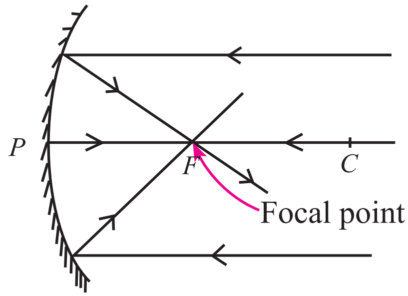


Figure 5.8 – Converging a parallel beam of light after reflection

Now let us see what happens in the case of convex mirrors. As shown in figure 5.9, rays coming parallel to the principal axis and incident on a convex mirror are reflected as a divergent beam. These divergent reflected rays appear to be coming from the focal point *F*.

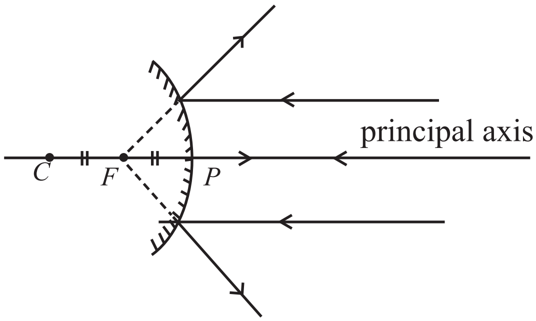


Figure 5.9 - Diverging a parallel beam of light upon reflection from a convex mirror

The focal point of a spherical mirror is situated at the mid-point on the line connecting the pole and the centre of curvature. The distance between the pole and the focal point is known as the focal length of the spherical mirror. The distance between the pole and the centre of curvature is known as the radius of curvature of the spherical mirror. The radius of curvature (r) is exactly twice the focal length (f).

5.2.2 Reflection from a concave mirror

(i) Rays coming along the principal axis of a concave mirror return along the principal axis after reflection.

In ray diagrams light rays are drawn as if they are reflected by the perpendicular line drawn to the principal axis at the pole *P*.

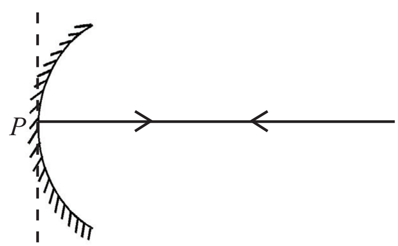


Figure 5.10 – Reflection of light coming along the principal axis of a concave mirror

(ii) Rays coming parallel to the principal axis pass through the focal point after being reflected by the concave mirror.

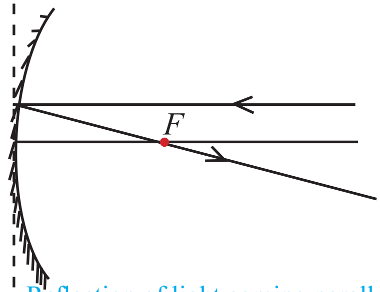


Figure 5.11 – Reflection of light coming parallel to the principal axis of a concave mirror

(iii) Rays coming towards a concave mirror through the focal point are reflected parallel to the principal axis.

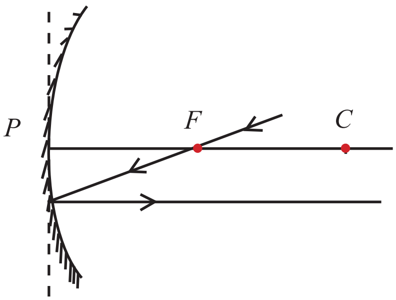


Figure 5.12 – Reflection of light coming through the focal point of a concave mirror

(iv) Rays coming towards a concave mirror through the center of curvature are reflected back through the center of curvature. The reason for this is that any line drawn to the surface of the mirror from the center of curvature is perpendicular to the surface of the mirror.

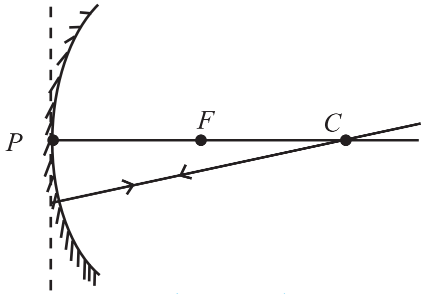


Figure 5.13 - Rays coming towards a concave mirror through the center of curvature

(v) Rays making a certain angle of incidence with the principal axis are reflected back with an equal angle of reflection. This means, in figure 5.14, $i = r$.

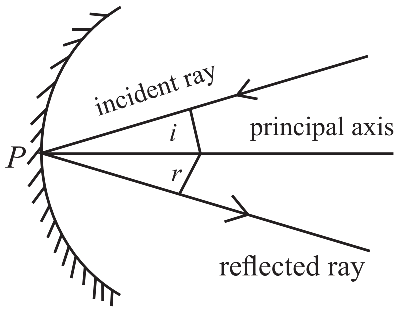


Figure 5.14 – Reflection of a ray coming to the mirror making some angle with the principal axis

Note

(1) Rays coming along the principal axis, return along the principal axis after reflection.
(2) A ray travelling parallel to the principal axis passes through the focal point after reflection.
(3) A ray that passes through the centre of curvature of the mirror is reflected back along its own path.

Images formed by concave mirrors

Observe your face through a plane mirror. The image seen in the mirror will be the same size as your face.

Observe your face through a concave mirror placed closer to the face than the focal length. You will observe a very large image of your face. In addition it will be an upright and virtual image.

Figure 5.15 – A concave mirror shows an enlarged image of your face

Let us do the activity 5.1 to find the focal length of the concave mirror.

Activity 5.1

Apparatus : concave mirror, white screen.

- Open the window of a room.
- Hold a concave mirror, turned towards the window. as shown in figure 5.16.
- Hold a screen (or a white paper) in front of the concave mirror and adjust the distance between the concave mirror and the screen until a clear image of the scene outside the window is formed on the screen.
- Because this image is formed on the screen, it is a real image.
- Measure the distance between the mirror and the screen when you get a very clear, up side down image on the screen.

Because the light rays coming from a far away object can be considered as parallel, the distance from the mirror to the image can be considered to be approximately equal to the focal length of the mirror.

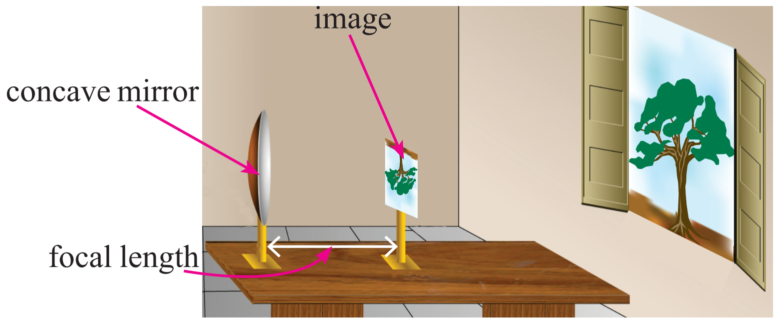


Figure 5.16 – Measuring the focal length of a concave mirror

Let us do the activity 5.2 to study the nature of the image formed by a concave mirror using a candle and screen.

Activity 5.2

Apparatus : concave mirror, white screen, candle.

- Fix a concave mirror on a stand and place it on a table.
- As in the activity 5.2 find the approximate focal length of the concave mirror.
- Keep a lighted candle on the table near the principal axis at a distance about five times the focal length from the mirror.
- Hold a screen in front of the concave mirror and move the screen till a sharp image of the flame is obtained.
- Now try to obtain the image on the screen while moving the candle towards the mirror and placing it at different distances from it.
- Is it possible to obtain an image on the screen when the candle is very close to the mirror?

The position of the image, the nature of the image and the size of the image formed by a concave mirror depend on the position of the object with respect to the mirror.

• Drawing ray diagrams for images formed by concave mirrors

The image of a point object placed in front of a mirror is formed at the point where two or more light rays coming from that point meet (or at the point where the extended light rays meet).

- To find the position of the image, it is necessary to consider rays coming from the top and bottom of the object separately.
- If the bottom of the object is situated on the principal axis, all the rays coming from the bottom travel along the principal axis. Therefore the image of the bottom of the object is formed on the principal axis.

- Therefore the image of a vertical object which is located on the principal axis is formed on the principal axis.

Therefore, to draw the image of an object which is placed vertically on the principal axis it is sufficient to draw the rays which are coming from the top of the object. For this any two light rays mentioned under the note in page 111 can be used.

The image of the top of the object is the point of intersection of these two rays.

A ray diagram can be used to find the nature of the image formed when an object is placed at different distances from the mirror.

1. Object between the mirror and the focal point

When the object is positioned between the mirror and the focal point, the image cannot be formed on a screen. This means that the image is not real. This image can be seen by viewing through the mirror. Such images are known as virtual images.

In order to find the location of the image in this instance, consider two rays coming from the top of the object. It would be convenient to choose one of these rays to be parallel to the principal axis and the other to pass through the center of curvature as shown in Figure 5.17. Drawing the ray parallel to the principal axis to return through the focal point after reflection and the ray coming through the center of curvature to return through the same path after reflection, the point of intersection of these two rays can be found by extending the two rays an shown by dotted line. This point is the position where the image of the top of the object is formed.

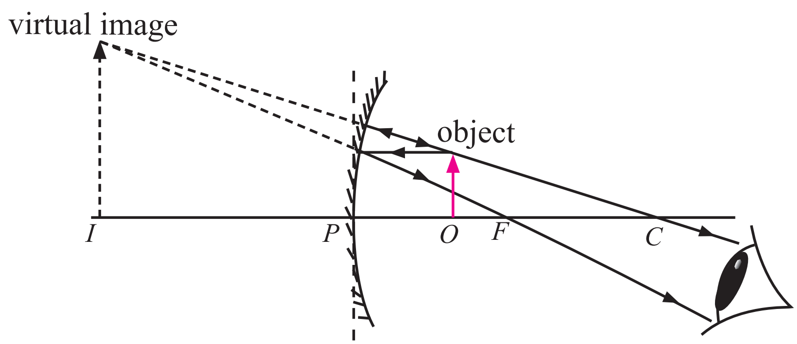


Figure 5.17-Formation of the image of an object placed between the mirror and the focal point

As shown in figure 5.17, for objects positioned between the focal point and the mirror (pole of the mirror), the images are upright, virtual and larger than the object.

2. Object on the focal point

The image of an object on the focal point must be formed at infinity. This can be shown by considering the paths of two rays, as shown in figure 5.18. If we assume that the two parallel rays meet at infinity, the image will be very large and inverted.

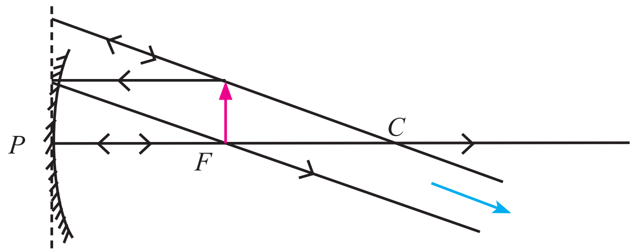


Figure 5.18 - Image of an object placed on the focal point

3. Object between the center of curvature and the focal point

For an object placed between the center of curvature and the focal point, it can be shown that the image is real, inverted, larger than the object and is formed beyond the centre of curvature, by considering a ray coming from the top of the object parallel to the principal axis and another ray passing through the center of curvature. The ray diagram for this case is shown in Figure 5.19.

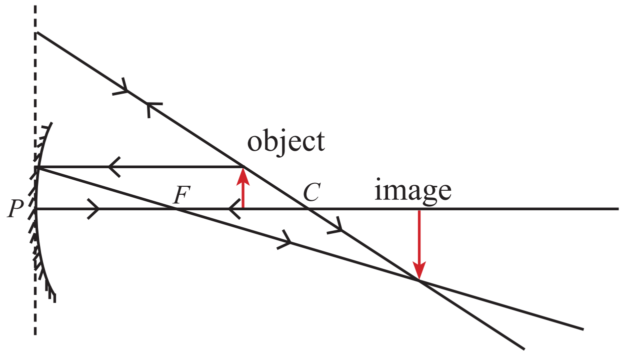


Figure 5.19 - Image of an object placed between the center of curvature and the focal point

4. Object on the center of curvature

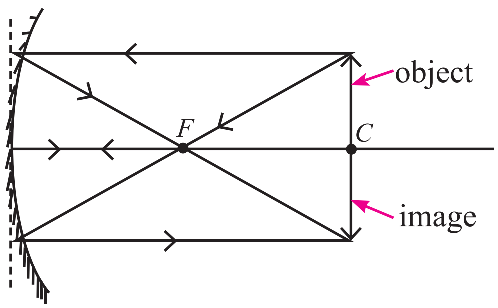


Figure 5.20 - Formation of the image of an object placed on the center of curvature

In order to find the position of the image for an object positioned at the center of curvature, we can consider a ray coming from the top of the object through the focal point and a ray coming parallel to the principal axis. As shown in Figure 5.20, the ray that passed through the focal point returns parallel to the principal axis while the ray that was parallel to the principal axis passes through the focal point after reflection. It can be shown that these two rays intersect at a point directly below the center of curvature and that the height of the image is equal to the height of the object. This too is an inverted real image.

5. Object at a point beyond the center of curvature

In order to find the location of the image in this instance, consider two rays coming from the top of the object. It would be convenient to choose one of these rays to be parallel to the principal axis and the other to pass through the center of curvature as shown in Figure 5.21. Drawing the ray parallel to the principal axis to return through the focal point after reflection and the ray coming through the center of curvature to return through the same path after reflection, the point of intersection of these two rays can be found. This point is the position where the image of the top of the object is formed. Here, the image is formed between *C* and *F*. This image is smaller than the object, inverted and real.

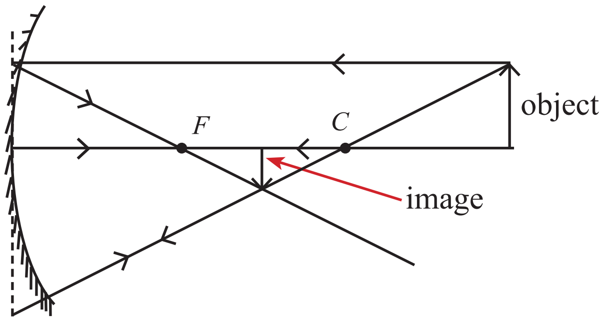


Figure 5.21 - Formation of the image of an object placed at a point beyond the center of curvature

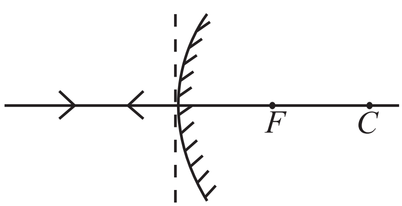
6. Object very far from the mirror

The image of an object placed very far from a concave mirror is formed on the focal point of the mirror, on the same side of the mirror as the object, smaller than the object and is inverted. Since this image can be seen on a screen, it is a real image.

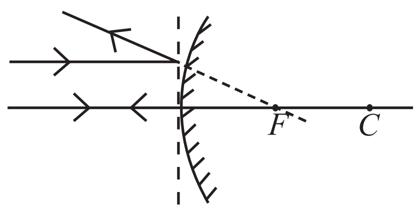
table 5.1 - images formed by concave mirror

Object distance	Position of the image	Real/ virtual	Upright/ inverted	Image size
less than focal length	greater than object distance	virtual	upright	larger than the object
focal length	infinity			
greater than focal length and less than twice the focal length	greater than twice the focal length	real	inverted	larger than the object
twice the focal length	twice the focal length	real	inverted	same size as the object
greater than twice the focal length	greater than focal length and less than twice the focal length	real	inverted	smaller than the object
very far	at focal point	real	inverted	much smaller than the object

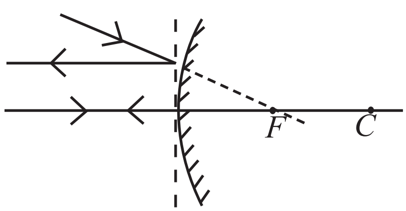
5.2.3 Reflection from a convex mirror



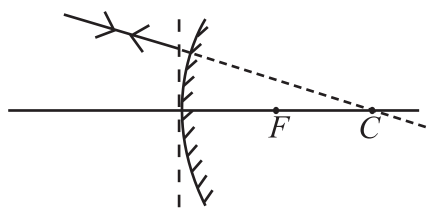
(a) Light rays coming along the principal axis.



(b) Light rays coming parallel to the principal axis.



(c) Rays coming toward the focus.



(d) Rays which are coming toward the centre of curvature.

Figure 5.23 - Reflection of light from a convex mirror

Figure 5.23 shows how reflection of light occur from a convex mirror.

- In a convex mirror too, rays coming towards the mirror along the principal axis are reflected back along the same path after falling on the mirror (figure (a)).
- Rays coming parallel to the principal axis are reflected as a divergent beam after falling on the mirror (figure (b)).
- These divergent rays appear to be coming from a single point on the principal axis inside the mirror. This point is known as its **focal point**.
- A ray that comes toward the focal point is reflected back along a path parallel to the principal axis (figure (c)).
- A ray that comes toward the centre of curvature of the mirror is reflected back along its own path (figure (d)). This is because any straight line drawn from the centre of curvature to the mirror surface is a normal to the surface.

Images formed by convex mirrors

Bring a convex mirror close to your face and observe the image formed in it. Image is upright and smaller image of your face.

Let us do the activity 5.3 to study the nature of image formed by convex mirror.

Activity 5.3

Apparatus : a concave mirror, a screen, a candle.

Try to repeat activity 5.2 using a convex mirror instead of a concave mirror.

You will find that convex mirrors do not form real images.

To obtain an image from a convex mirror, you have to look at the object through the convex mirror.

Regardless of the distance between an object and the mirror, you will always see an upright, virtual image from a convex mirror.

Figure 5.24 shows how the image of an object placed in front of a convex mirror is formed. Here too, the position of the image and its nature can be determined by tracing the paths of two rays coming from the top of the object after reflection just as was done with concave mirrors.

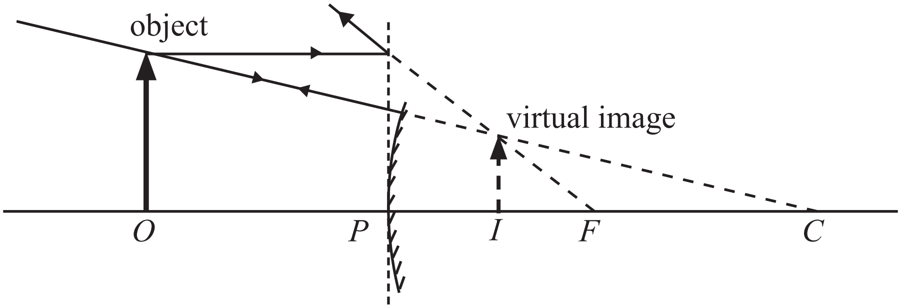


Figure 5.24 - Formation of an image from a convex mirror

5.3 Refraction of Light

Place a pencil inside a glass of water as shown in Figure 5.25 and view it from a side. You will see the pencil as if it is bent.

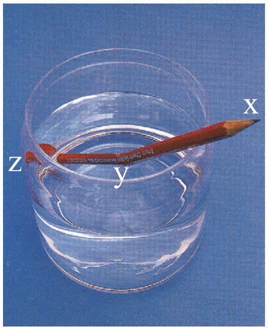


Figure 5.25 - A pencil inside a glass of water

The reason for this appearance is the bending of light rays when they enter from medium to another medium with different optical properties. Light rays coming to the eye from the part of the pencil inside the water travel through water before reaching the eye through air. When light rays enter air from water, the direction of the light rays changes. However, the rays coming to the eye from the part of the pencil above the water level do not change their direction as they travel only through air before reaching the eye.

The bending of light rays upon entering one medium from another medium is known as **refraction of light**.

Look at a coin at the bottom of a container with water. The coin will appear to be slightly raised above the bottom level of the container. If the coin is in air, the rays from the coin will reach the eye straight. But when the coin is in water, the rays from the coin do not come to the eye straight. When they enter air from water, the rays bend away from the normal to the surface as shown in figure 5.26. Therefore, the rays from the coin appear to come to the eye from a point slightly above the actual position.

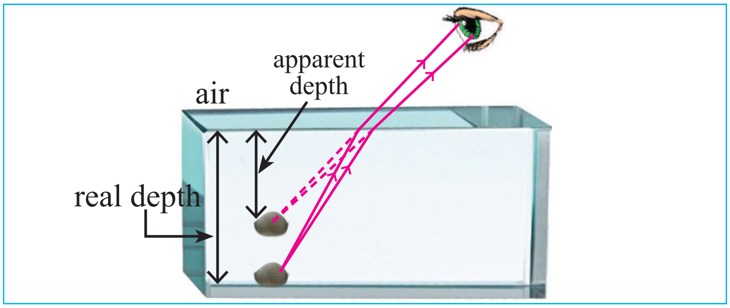


Figure 5.27- Slightly raised appearance of an object at the bottom of a vessel of water

When a page of a book is viewed through a block of glass placed on it, the script on the page seems to be raised up a little, also due to refraction.

A ray of light travelling in one medium bends upon entering a second medium as described above only if the rays arrive from a direction other than at a 90^{o} angle on the surface separating the two media. The reason for refraction is the difference in the speeds of light from one medium to another. Light travels at the speed of 3×10^{8} ms^{-1}. When light enters another medium from a vacuum, the speed reduces to a lower value. A medium with a lower speed of light compared to another medium is called a denser medium. The medium with the higher spped of light is called a rare medium.

Extra knowledge

The speed of light in several different media are given below.

Medium	Speed (km s^{-1})
Air	3, 00, 000
Water	2, 25, 000
Glass	1, 97, 000
Perspex	2, 01, 000
Diamond	1, 24, 000

In order to investigate how light is refracted in entering a block of glass from air and when entering from glass back to air let us engage in the following activity.

Activity 5.4

- Place a piece of white paper on a drawing board and place a block of glass on it. Next, mark the edges of the block of glass with a pencil. In Figure 5.28, the position of the block of glass is marked as *PQRS*.
- Now place one pin (*A*) vertically at a short distance away from the surface *PQ* and another pin (*B*) in contact with the surface.

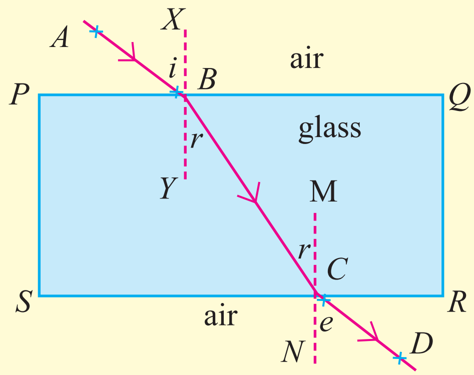


Figure 5.27 - Light refraction through a block of glass

- Next, view the pins through the surface *SR* and place pin *C* in contact with the surface *SR* so as to be collinear with *A* and *B* and thereafter place pin *D* at some distance away from the surface so that all four pins appear to lie on the same line.
- Now remove the block of glass and the pins and draw lines *AB*, *BC* and *CD* connecting the points where the pins were placed. Draw also the normal lines to the surface *PQ* at point *B* and to the surface *SR* at point *C*. You will obtain a diagram like the one shown in Figure 5.27.

In this diagram, *ABCD* is the path of a ray travelling across the block of glass which entered the glass medium from air along the line *AB*. Since *AB* is the ray that was incident on the block of glass, it is known as the **incident ray**.
XY is the normal drawn to the glass surface at the point of incidence. The angle between the incident ray and the normal is known as the angle of incidence (*i*).

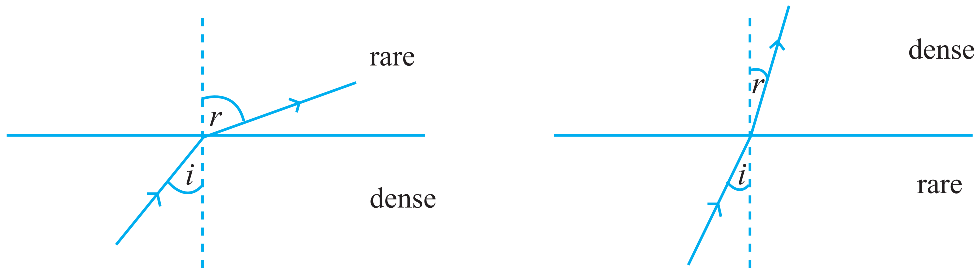
After entering the block of glass, the incident ray travels along *BC*. The refracted ray (*BC*) is bent towards the normal at point *B*.

The angle between the ray of refraction and the normal is known as the **angle of refraction** (*r*). This refracted ray travels back into air from glass at point *C*. This means that the ray has emerged back into air. Therefore the ray *CD* is known as the **emergent ray.** The angle between the transmitted ray and the normal drawn to the glass surface at the point of emergence *C* is known as the **angle of emergence** (*e*).

When light enters from air which is a rare medium to glass which is a dense medium, you will notice that the light rays are refracted towards the normal.

When light enters from glass which is a dense medium to air again, which is a rare medium, the light rays are refracted away from the normal. From this activity you will observe that a light ray entering a dense medium from a rare medium refracts towards the normal while a light ray entering a rare medium from a dense medium refracts away from the normal.

Refraction of light from rare medium to dense medium.	Refraction of light from dense medium to rare medium.



When a light ray travels from one medium to another medium if it bend towards the normal, the second medium is denser compared to the first medium. If the ray bends away from the normal, the second medium is a rare medium. compared to the first medium.

5.3.1 Laws of refraction

There are two laws of refraction.

First law

The incident ray, the refracted ray and the normal to the surface drawn at the point of incidence lie on the same plane.

Second law

When light refracts from one medium to another medium, the ratio of the sine of the incident angle to the sine of the refracted angle is a constant that depends only on the two media. This constant is called the refractive index of the second medium with respect to the first medium.

The second law above is also called Snell's law.

$$\text{Index of refraction } (n) = \frac{\text{sine of the incident angle}}{\text{sine of the refracted angle}} = \frac{\sin i}{\sin r}$$

For a light ray that travels from air to glass, the refractive index is written as ${}_an_g$.

For rays that enter from glass to air, the refractive index is written as ${}_{g}n_{a}$.

$$\text{refractive index of water relative to air } {}_{a}n_{w} = 1.33$$
$$\text{refractive index of glass relative to air } {}_{a}n_{g} = 1.5$$

The refractive index defined above is the refractive index of one medium relative to another medium. Therefore, it depends on both media. If we use a vacuum instead of the first medium (if we consider a light ray entering from a vacuum to some medium), then the refractive index depends only on one medium. This is normally referred to as the refractive index of that medium.

For example, refractive index of water is the ratio of the sine of the incident angle to the sine of the refracted angle when a light ray travels from a vacuum to water. Because the velocity of light in air is only slightly different from that in a vacuum, and because it is practically difficult to make measurements of refractive index relative to a vacuum, often the refractive index of a medium relative to air is used as the refractive index of that medium. There are no units for the index of refraction.

5.3.2 Total Internal Reflection and Critical Angle

When a light ray travels from a dense medium to a rare medium, it bends away from the normal, as shown in figure 5.28.

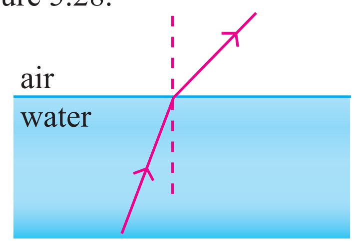


Figure 5.28 – A light ray traveling from water to air

When the incident angle inside the dense medium is gradually increased, the refracted ray bends further away from the normal. At a certain value of the incident angle, the refracted ray travels along the interface between the two media, as shown in figure 5.29. In this case, the angle of refraction is 90^{o}. The incident angle inside the denser medium when this happens is called the critical angle.

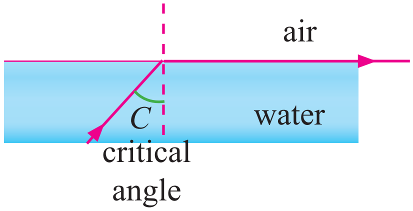


Figure 5.29 – Critical angle

If the incident angle is further increased, the incident light ray will be reflected back into the dense medium as shown in figure 5.30. This reflecting back into the same medium is called **total internal reflection**.

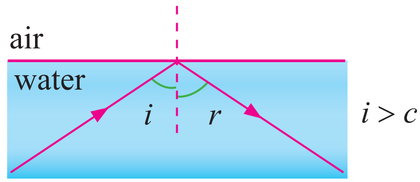


Fig. 5.30 – Total internal reflection

Extra knowledge

The table below shows the critical angle for a few different materials.

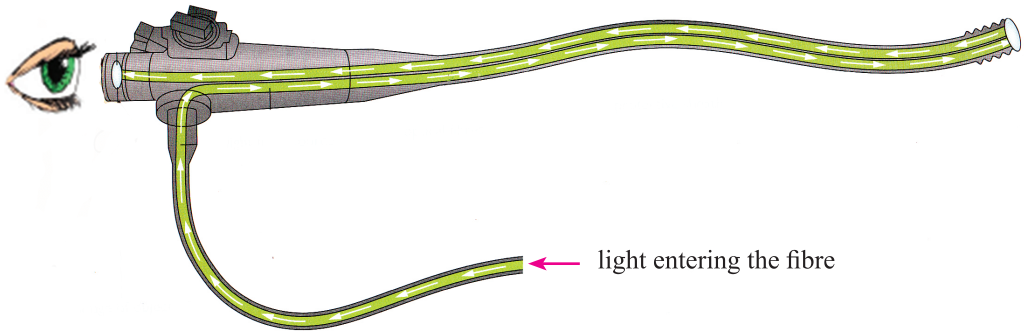
Material	water	glass	diamond
critical angle	49°	42°	24°

• Several applications of total internal reflection

Optical fibres

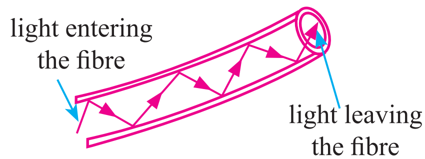
An optical fibre is a flexible transparent fibre made of glass or plastic. Light rays that enter through one end of an optical fibre travel through the fibre while undergoing total internal reflection and leave the fibre through the other end. Even if the fibre is many kilometers long, light will leave it without a significant loss of intensity.

The instrument called endoscope, which is used to observe the internal organs of the human body, makes use of optical fibres. Optical fibres are now widely used in telephone communication and in Internet connections. They are also used in decorations.



Endoscope

Endoscope



an optical fibre

Total internal reflection by prisms

A prism with one angle 90 degrees and the other two angles 45 degrees each can be used to produce total internal reflection. Such prisms are used in cameras, telescopes and binoculars. The critical angle of glass is 43 degrees. Therefore, if the incident angle inside glass is greater than 43 degrees, a light ray will undergo total internal refraction.

Figure 5.31 shows a light ray entering one face of a prism perpendicular to the surface. This ray is not refracted at that surface. Next if falls on the second face of the prism with an incident angle of 45 degrees. Because this incident angle is greater than the critical angle in glass, the light ray undergoes total internal refraction and travels perpendicular to the third face of the prism. The ray emerges from this face without bending. This technique allows us to bend a light ray by an angle of 90 degrees

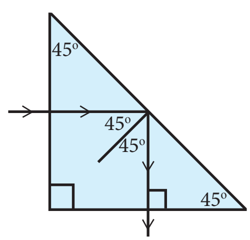


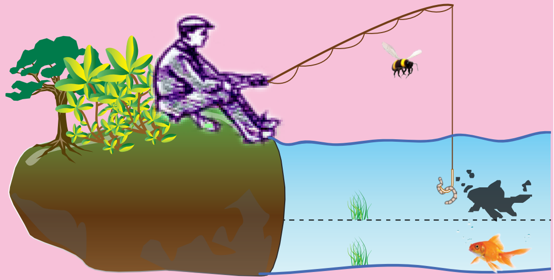
Figure 5.31 – Total internal reflection by a prism

5.1 Exercise

(1) The figure shows a man holding a fishing rod.

(i) The fish appears to the man at a slightly higher position. What is the reason for this?

(ii) Draw a ray diagram to show how the position appears to be raised.



5.4 Lenses

A lens is an optical device with curved surfaces, made of glass, plastic or any other transparent material. A lens alters the path of light rays that pass through it by refraction. Images on the retina of our eye are formed by a lens.

Lenses are used in telescopes and binoculars, which are instruments that help us see far away objects clearly. Lenses are also used in the microscope – the instrument that allows us to see very small objects that are not visible to the naked eye. The magnifying glass or the simple microscope that magnifies small objects is also a lens.

Some instruments with lenses

Many lenses are made of glass. But now plastic is increasingly used for making lenses. Any transparent material can be used to make lenses. Sometimes even liquids such as water are used to make lenses.

Figure 5.33 shows several types of lenses. Lenses with two convex surfaces are called **bi-convex** lenses. When a lens has one convex surface and the other plane, it is called a **plano-convex** lens. In a **bi-concave** lens, both surfaces are concave while a lens with a concave surface and plane surface is called a **plano-concave** lens.

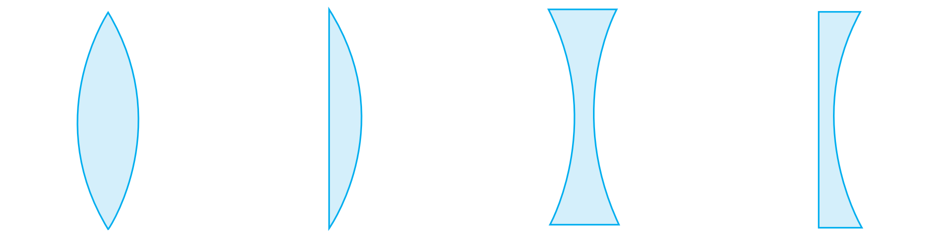


Figure 5.32 – several types of lenses.

5.4.1 Convex lenses

The two surfaces of a convex lens can be considered as parts of two imaginary spherical surfaces, as shown in figure 5.33.

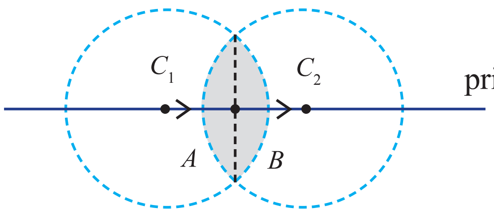


Figure 5.33 - surfaces of a convex lens

In figure 5.33 one surface of the convex lens is denoted as *A* and the other as *B*. The centre of the sphere that forms the surface *A* is denoted as C_2 and the centre of the sphere that forms the surface *B* is denoted as C_1. The line that joins these two centres C_1 and C_2 is called the principal axis of the lens. At the points where the principal axis intersects with the surfaces of the lens, the principal axis is perpendicular to the surfaces. Therefore, a light ray that enters the lens along the principal axis will leave the lens without bending. The mid point between the two surfaces of the lens is called the optical centre of the lens. It is possible to show that any light ray that travels through the optical centre passes through the lens without any bending, as shown in figure 5.34.

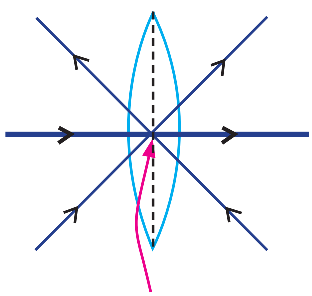


Fig. 5.34 – Light rays traveling through the optical centre.

Activity 5.5

- When there is bright Sun light, hold a convex lens to Sun light as shown in figure 5.35 and place a white paper in front. Adjust the distance between the paper and the lens until you get a very small patch of light on the paper.
- Because the Sun is very far from us, we can consider all rays of light coming from the Sun to be parallel. In this activity you will observe that, when parallel light from the Sun passes through the lens, all of the rays are focused to a single point.

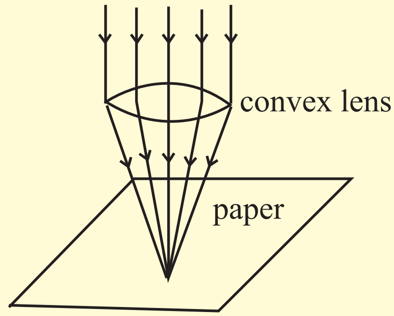


Figure 5.35 – Focusing of light with a convex lens

What will happen to the light rays travelling parallel to the principal axis of a convex lens? After refracting from the lens, they bend towards the principal axis (converge) and travel through a single point on the principal axis. This point is called the **focus** or the **focal point** of the lens.

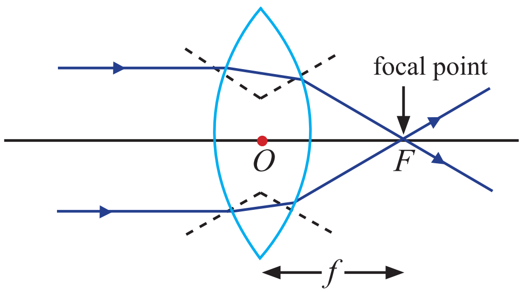


Fig. 5.36 – The way the rays parallel to the principal axis are refracted by a convex lens

In order to understand how the light rays entering a convex lens parallel to the principal axis, refract when they go through the lens, let us look at figure 5.36.

The broken lines in this figure are normals drawn to the lens surface at each point where a light ray crosses the surface.

- When such a ray enters the lens, they enter a denser medium from a rarer medium.
- Then this ray bends towards the normal to the surface. When this ray leaves the lens, it enters a rarer medium from a denser medium. Therefore it bends away from the normal.
- According to figure 5.36, in both cases the light ray bends towards the principal axis.
- It is possible to show that all rays that enter the lens parallel to the principal axis, after bending as discussed above travel through a single point on the principal axis.

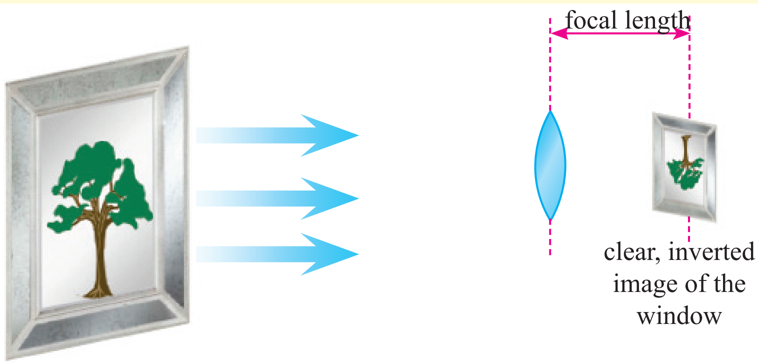
- This point is called the **focus or the focal point** of the lens. The distance from the optical centre of the lens to the focal point is called the **focal length** of the lens.

Because light can enter from either side of the lens, it is possible to identify two focal points for a lens. Both these points have the same distance to the optical centre of the lens. Normally, when ray diagrams are drawn, the focal point is denoted as *F* and the focal length is denoted by *f.*

• Images formed by convex lenses

Activity 5.6

- Open the window of a room.
- Hold a convex lens, turned towards the window.
- On the opposite side of the lens, hold a screen (or a white paper) and adjust the distance between the lens and the screen until a clear image of the scene outside the window is formed on the screen.
- Measure the distance between the lens and the screen when you get a very clear, up side down image on the screen.



This distance you measure will be the focal length of the lens.

The image in the above activity is formed when light rays coming from objects outside the window are refracted by the lens and come together on the screen. Because this image is formed by light rays that actually reach the screen, it is a real image.

• Drawing ray diagrams for images formed by convex lenses

The size, nature and position of the images formed by convex lenses depends on the distance between the lens and the object.

In drawing ray diagrams for images formed by convex lenses, it is convenient to use the specific rays shown in figure 5.37.A light ray passing through the optical axis is shown in figure 5.37 (a), This type of rays pass through the lens straight, without any refraction. A ray that enters a lens parallel to the principal axis, as shown in figure 5.37 (b), passes through the focal point after emerging from the lens. A light ray that passes through the focal point on one side of the lens, as shown in figure 5.37 (c) emerges parallel to the principal axis after refracting by the lens.

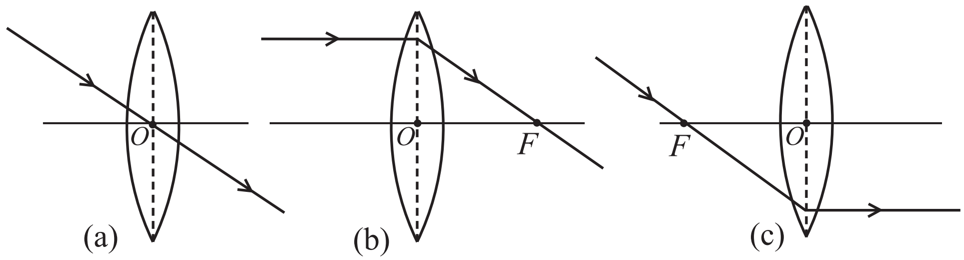


Figure 5.37 – A few special rays used in drawing ray diagrams

1. When the object is between the lens and its focal point

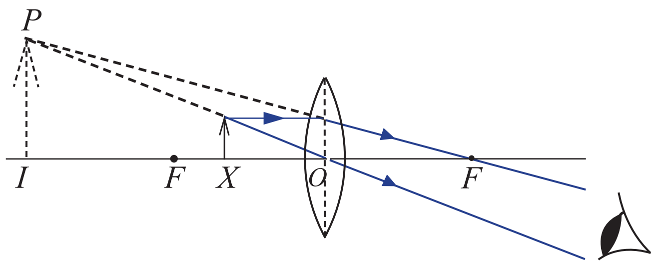


Figure 5.38 – When the object is between the lens and its focal point

Figure 5.38 shows an object placed at point *X* which is between the lens and the focal point *F*. A light ray coming from the top of the object and traveling parallel to the principal axis will go through the focal point *F* on the opposite side of the lens. Another ray coming from the top of the object and traveling through the optical axis *O* will go straight without any refraction. When these two rays are extended in the opposite direction, they will intersect at a point *P*. The top of the image will be at this point. Because the object is vertical, the image should also be vertical. Therefore, the image must be on the vertical line drawn to the principal axis from point *P*. This image is larger than the object and it is up right. This image can be seen when the eye is placed as shown in the figure. However, because the rays do not actually meet at point *P*, this image cannot be formed on a screen Therefore it is a virtual image.

2. When the object is on the focal point

Figure 5.39 shows a ray diagram for an image of an object places at the focal point of a convex lens. A light ray coming parallel to the principal axis, after going through the lens, travels through the focal point. A ray that goes through the optical centre (*O*) travels directly, without any refraction. Both these rays, when reaching the eye travel as parallel rays. Therefore, the image formed is at infinity. This image is larger than the object.

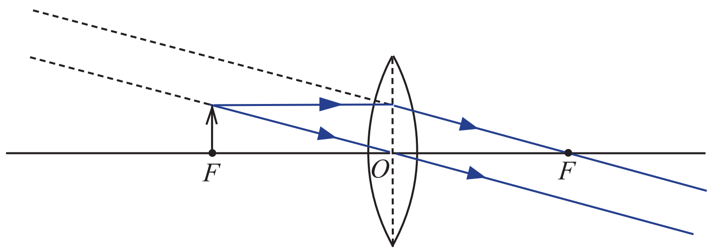


Figure 5.39 – Ray diagram for an image of an object on the focal point of a lens

3. When the object is between the focal length and twice the focal length

When the object is at a distance between *f* and 2*f*, the image is formed on the opposite side of the lens at a distance greater than 2*f*. As shown in figure 5.40, this image is a magnified inverted real image.

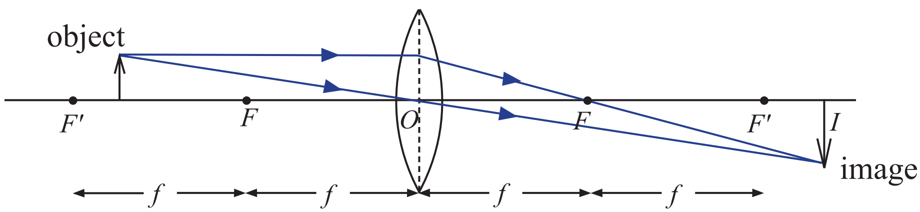


Figure 5.40 – The image of and object placed between distances *f* and 2*f*

4. When the object distance is equal to twice the focal length

The image formed in this case is at a distance 2*f* on the other side of the lens. The height of the image is equal to that of the object. It is a real, up side down image. The ray diagram is shown in figure 5.41

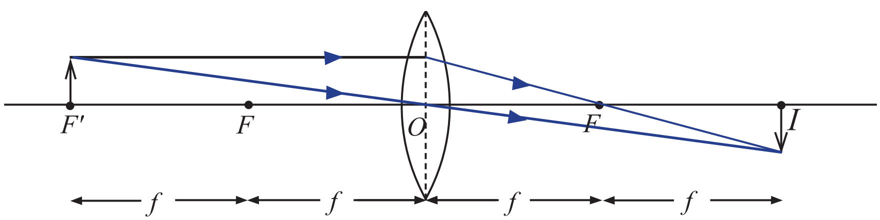


Figure 5.41 - Image of an object when the object distance is 2*f*

5. When the object distance is greater than twice the focal length

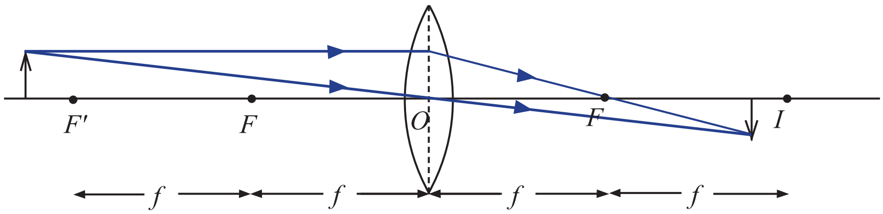


Figure 5.42 - Image of an object placed at a distance greater than $2f$

In this case, the image is formed on the opposite side of the lens, at a point between the focal length (f) and twice the focal length ($2f$). This image is diminished, real and up side down. The ray diagram is shown in figure 5.42.

The image becomes smaller as the object distance increases.

- The following table shows how images are formed by a biconvex lens. at different object distances.

table 5.2 - images formed by convex lens

Object distance	Position of the image	Real/ Virtual	Upright/ inverted	Size of the image
less than focal length	greater than object distance, on the same side as the object	virtual	upright	larger than the object
focal length	infinity			infinite
greater than focal length and less than twice the focal length	greater than twice the focal length, on the opposite side	real	inverted	larger than the object
twice the focal length	twice the focal length, on opposite side	real	inverted	same size as the object
greater than twice the focal length	greater than focal length and less than twice the focal length, on opposite side	real	inverted	smaller than the object
infinite	at focal point on the opposite side	real	inverted	much smaller than the object

5.4.2 Concave Lenses

Figure 5.44 shows how the surfaces of a concave lens can be understood as parts of spheres.

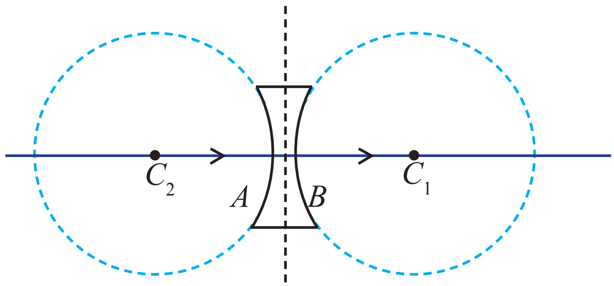


Figure 5.44 – Surfaces of a concave lens

The centre of the sphere that forms surface A is C_2 and the centre of the sphere that forms surface B is C_1. The line that joins these two centre points is called the principal axis of the lens. In both convex lenses and concave lenses, a light ray that travels through the principal axis passes through the lens without bending.

The centre point of the lens, labeled as O is called the optical centre. Any light ray that goes through the optical centre travels straight, without bending.

Next we have to consider light rays that enter a concave lens parallel to the principal axis. Such rays, as shown in figure 5.45, are refracted away from the principal axis after passing through the lens. That means they diverge. The point from which these divergent rays appear to come from is called the focal point of that lens.

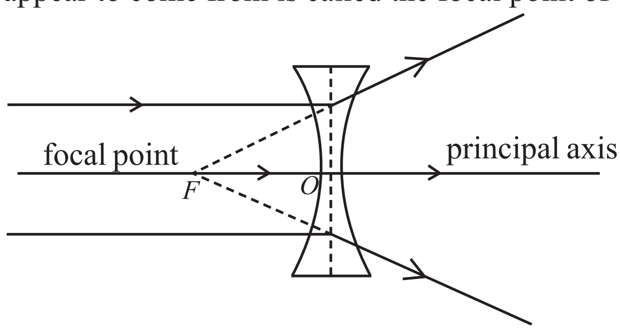


Figure 5.45 – Rays parallel to the principal axis, after passing through a concave lens, appear to come from a single point

• Images formed by concave lenses

In order to understand images formed by concave lenses, let us do acitivity 5.7.

Activity 5.7

- Place a bright object (eg: a lighted candle) in front of a concave lens.
- On the other side of the lens, place a screen and try to obtain a real image on the screen by suitably adjusting the lens.

You will find that concave lenses do not form real images. To obtain an image from a concave lens, you have to look at the object through the lens. Then you will see an image smaller than the object. This is a virtual image. Whatever the distance between the lens and the object, what you see will be an upright, diminished virtual image.

Figure 5.46 shows a ray diagram for an image formed by a concave lens.

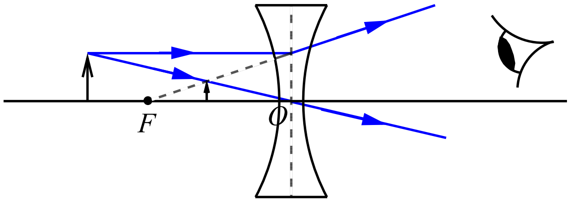


Figure 5.46 - A ray diagram for an image formed by a concave lens

5.4.3 Hand Lens or Simple Microscope

A convex lens makes an object look bigger when the object is placed in front of the lens at a distance less than the focal length of the lens. This property of convex lenses is used to view magnified images of objects.

A convex lens fitted with a handle is called a hand lens or a simple microscope. It is also commonly known as a magnifying lens. Figure 5.47 shows the ray diagram for a magnified lens. Magnifying glasses are commonly used for viewing small insects, parts of flowers etc.

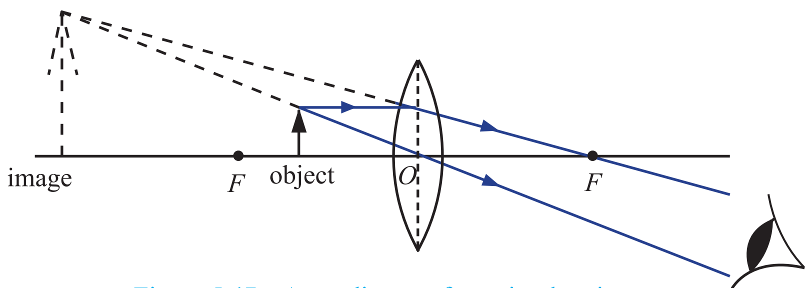
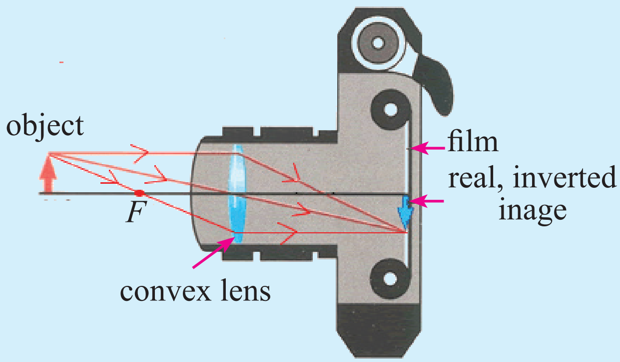


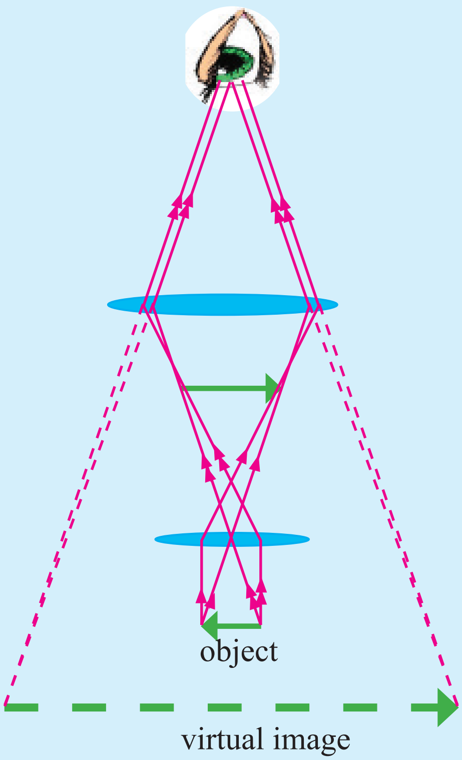
Figure 5.47 – A ray diagram for a simple microscope

For your knowledge

- In cameras, images are formed on a film using convex lenses. When one adjusts the lens, the distance between the screen and the lens changes. Clear images of objects at different distances can be obtained on the screen this way.



- The complex microscope is used to observe tiny objects which are not visible to the naked eye. It has two lenses called objective and eye piece. This combination of lenses produce a very high magnification.



5.2 Exercise

(1) (i) Name two types of mirrors that always produce virtual images.

(ii) Answer the following questions regarding the image formed when an object is placed between the mirror and the focal point of a concave mirror.

(a) Is the image upright or inverted?

(b) Is the image larger than the object or smaller than the object?

(c) Is the image real, or virtual?

(d) When the object is moved toward the pole of the mirror, will the image become smaller or larger?

(iii) At what object distance do you get the largest image from a concave mirror? Is that image upright or inverted?

(iv) Place an object in front of a convex lens at different positions and observe the image in each case. Write two properties common to all those images.

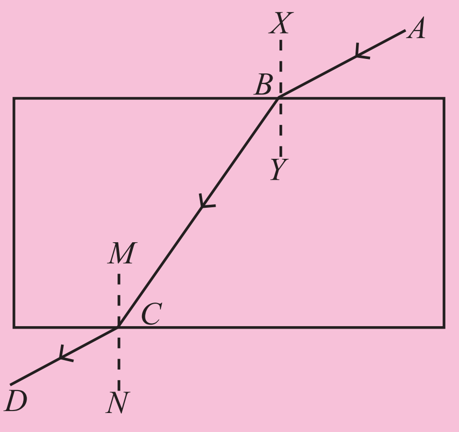
(2) (i) What is meant by the term refraction of light?

(ii) Draw ray diagrams to show how refraction occurs when light enters

(a) a dense medium from a rare medium,

(b) a rare medium from a dense medium.

(iii) Name the rays and the angles of the following ray diagram.



AB ray ....

BC ray ....

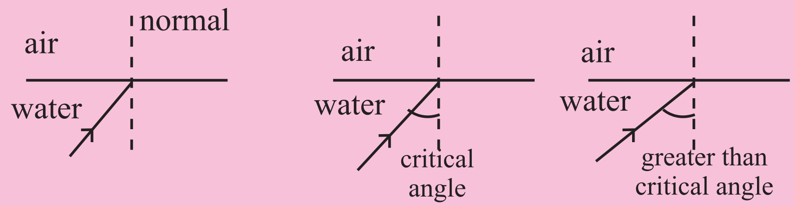
CD ray ....

ABX angle ....

YBC angle ....

NCD angle ....

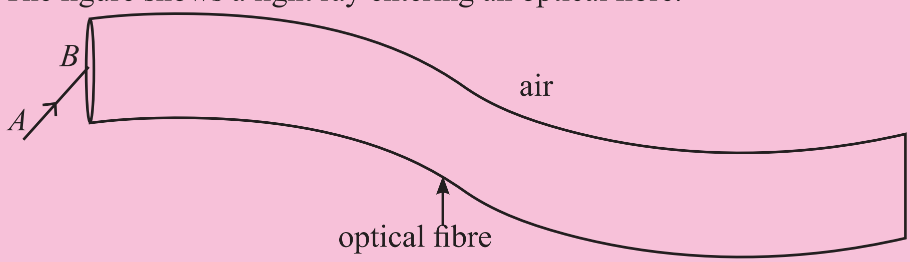
(3) The figure shows different light rays entering a rare medium from a dense medium.



(i) Copy these figures and complete the ray diagrams.
(ii) What is meant by the term *total internal reflection*?
(iii) Give an example for a situation where total internal reflection occurs.

(4) Draw a ray diagram to show how an image is formed when an object is placed in front of a convex lens, at a distance greater than twice the focal length.
(a) Is that image real or virtual?
(b) Describe a simple activity to find out whether the image is real virtual.
(c) Is that image smaller or larger than the object?

(5) (i) The figure shows a light ray entering an optical fibre.



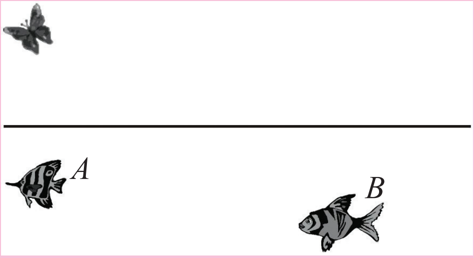
(a) Draw a ray diagram to show what happens to that ray inside the optical fibre.
(b) State what changes occur to the speed of the ray as it follows this path from the source. Calculations are not required.

(ii) (a) At what object distance do you get the largest real image when an object is placed in front of a convex lens?
(b) Write down two other properties of that image.
(c) At what object distance do you get the smallest real image when an object is placed in front of a convex lens?

(6) A bag contains lenses with focal lengths 10 cm, 20 cm and 25 cm which are not marked with their focal length. Describe a simple activity to identify the three types lenses.

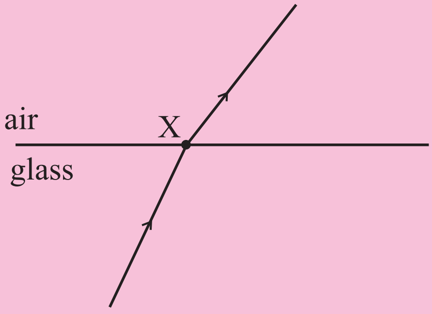
(7) (a) Light changes direction when it passes from air to water.
(i) Give the name of the process that produces this change of direction.
(ii) Explain why this change of direction occurs.

(b) The diagram shows some fish under water and a butterfly above water.



(i) Draw a ray to show the path of a light ray travelling from the butterfly to the eye of fish *B*.
(ii) Explain what critical angle is.
(iii) Explain how rays from fish *A* could reach the eye of fish *B* through two different paths. Draw rays in the diagram to show these two paths.

(8) A student carries out an experiment to investigate the refraction of light as it passes from glass into air. He shines a ray of light through a glass block and into the air as shown.



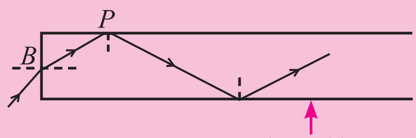
(a) Complete this diagram and show the angle of incidence i and the angle of refraction r . Measure these two angles.

i = ...

r = ...

(b) The student increases the angle of incidence and notices that, above a certain angle, the light no longer passes into air. Explain this observation.

(9) The figure shows a light signal travelling through an optical fibre made of glass.



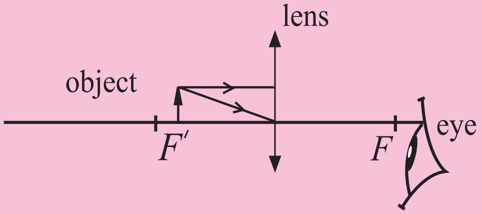
(a) State two changes light when it enters the fibre from air at point *B*.
(b) Explain why the light ray, after hitting point *P*, travels along the path shown.

(10) Lenses are used in many optical devices.
(a) Complete the table below by writing information about the images formed by each optical device.

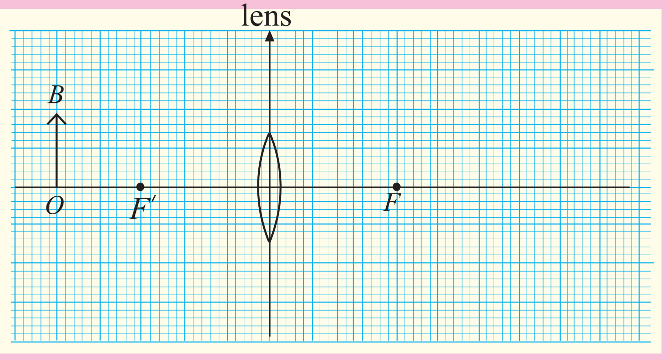
optical device	nature of image	size of image	position of image
eye	real		
projector		magnified	
magnifying glass			further from lens than the object

(b) The figure shows an object placed in front of a convex lens, at a distance less than its focal length.

(i) Complete the ray diagram and draw the image formed.
(ii) Use your ray diagram to describe three properties of the image.

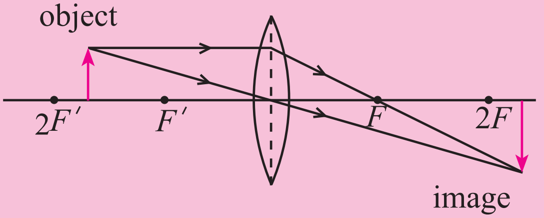


(11) The figure shows an object OB in front of a convex lens. The two focal points are marked as F and F'. An image of OB will be formed on the right of the lens.



(a) Draw two rays from the top of the object (B), that pass through the lens and reach the image.
(b) Draw the image formed and label it as I.
(c) Calculate the ratio of the image size to the object size.

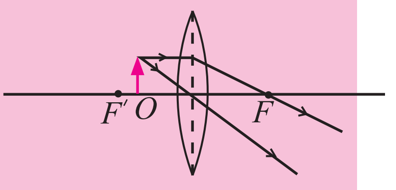
(12) The diagram shows a convex lens forming a real image of an object.



State two changes that occur to the image when the object is moved towards F.

(13) The diagram shows an object placed at O, in front of a convex lens. Focal length of the lens is 30 mm O is 20 mm from centre of lens and the object is 15 mm high.

(a) By drawing this diagram to a suitable scale find the position of the image.
(b) State two properties of the image.
(c) By measuring the heights of the image and the object, find the ratio of their heights.



Summary

- There are two types of mirrors - plane mirrors and curved mirrors. Curved mirrors can be either convex mirrors or concave mirrors.
- Images formed by plane mirrors are virtual and upright. They are the same size as the object.
- The incident ray, the reflected ray and the normal to the surface at the point of reflection lie on the same plane.
- When light is reflected from a mirror, the angle of incidence is equal to the angle of reflection.
- When an object is placed in front of a convex lens, the images are diminished, upright and virtual, irrespective of the object distance
- The bending of light when passing from one medium to another is called refraction of light
- When light travels from a rare medium to a dense medium, the ray bends towards the normal.
- When light travels from a dense medium to a rare medium, the ray bends away from the normal.
- When light undergoes refraction, the incident ray, the refracted ray and the normal to the surface at the point of refraction lie on the same plane.

$$\text{Index of refraction} = \frac{\text{Sine of the angle of incidence}}{\text{Sine of the angle of refraction}}$$

- When light travels from a denser medium to a rare medium, at a certain value of the angle of incidence, the refracted ray travels along the surface between the two media. The angle of incidence in this situation is called the critical angle (c).
- When a ray of light travels from a denser medium to a rare medium with an angle of incidence greater than the critical angle, the ray is reflected back into the denser medium. This is called total internal reflection.
- Light travels through optical fibers by undergoing total internal reflection.
- There are many types of lenses such as bi-convex lenses, bi-concave lenses, plano-convex lenses, and plano-concave lenses.
- When an object is placed in front of a bi-convex lens, the image is upright, diminished and virtual, irrespective of the object distance.

Glossary

Reflection	- පරාවර්තනය	- தெறிப்பு
Total internal reflection	- පූර්ණ අභ්‍යන්තර පරාවර්තනය	- முழுஅகதெறிப்பு
Mirrors	- දර්පණ	- ஆடிகள்
Apparent depth	- දෘශ්‍ය ගැඹුර	- தோற்ற ஆழம்
Binoculars	- දෙනෙතිය	- அரிய இருவிழியன்
Focal	- නාභිය	- குவிவு
Incident ray	- පතන කිරණය	- படுகதிர்
Angle of incidence	- පතන කෝණය	- படுகோணம்
Refraction	- වර්තනය	- முறிவு
Refractive index	- වර්තනාංකය	- முறிவுச் சுட்டி
Refracted	- වර්තිත	- முறிவடைதல்
Angle of refraction	- වර්තිත කෝණය	- முறிவுக் கோணம்
Convex lens	- උත්තල කාචය	- குவிவு வில்லைகள்
Concave lens	- අවතල කාචය	- குழிவு வில்லைகள்
Convex mirror	- උත්තල දර්පණය	- குவிவு ஆடி
Concave mirror	- අවතල දර්පණය	- குழிவு ஆடி
Real image	- තාත්වික ප්‍රතිබිම්බය	- உண்மை விம்பம்
Virtual image	- අතාත්වික ප්‍රතිබිම්බය	- மாய விம்பம்