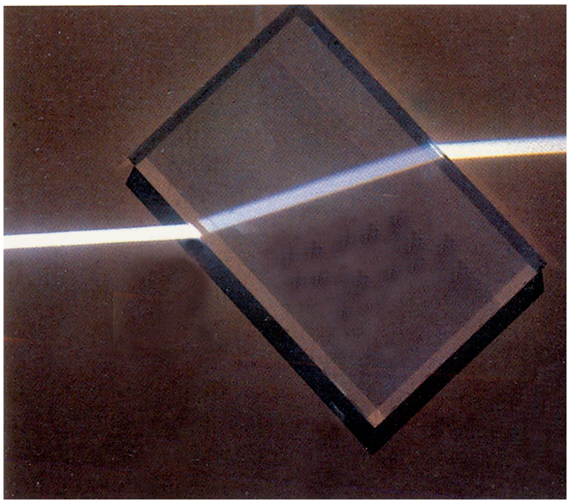
CHAPTER

5



Refraction of Light

We know that light travels in a straight line path. This is true as long as light rays are travelling in the same medium (or same substance) having the same density throughout. If, however, the light rays are made to go from one medium to another, the light rays change their direction (or bend) at the boundary between the two media. For example, when a ray of light travelling in 'air' goes *obliquely* into another medium 'glass', it changes the direction (or bends) on entering the glass block (see Figure 1). The change in direction of ray of light (or bending of ray of light) occurs again when it goes out from 'glass' into 'air' (see Figure 1). **The change in direction of light when it passes from one medium to another obliquely, is called refraction of light**. In other words, **the bending of light when it goes from one medium to another obliquely is called refraction of light.** The refraction of light takes place when light rays enter from *air* into *glass;* or from *glass* into *air.* The refraction of light takes place when light enters from *air* into *water* ; or from *water* into *air*. And the refraction of light also takes place when light enters from *water* into *glass*; or from *glass* into *water*. The optical instruments like camera, microscope, and telescope work on the refraction of light through glass lenses. We will now understand the refraction of light more clearly with the help of a diagram.

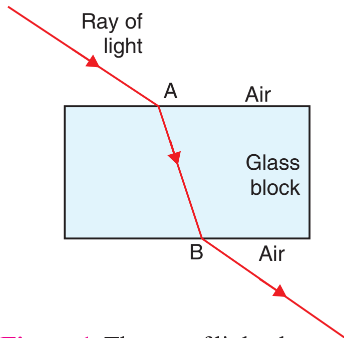


Figure 1. The ray of light changes direction (or refracts) at point *A* when it goes from air into glass. The ray of light changes direction (or refracts) again at point *B* when it goes from glass into air.

Consider a rectangular glass slab *PQRS* shown in Figure 2. Now, here we have two different media, one is air and the other is glass ('media' is the plural of 'medium'). Please note that glass is optically denser medium as compared to air (we will give the meaning of optically denser medium after a while). Now, a ray of light *AO* travelling in air is incident (or falls) obliquely on the glass slab at point *O* (see Figure 2). Since the glass slab is transparent, most of the incident light passes into the glass slab. Since glass is an optically denser medium than air, so when the ray of light *AO* passes from air into glass, its direction changes, it goes along the line *OB* inside the glass slab and we say that the light ray has been refracted (or bent). This is because *AO* and *OB* are not in the same straight line. Please note that **the refraction (or bending) of light takes place at the boundary between the two media.** For example, in Figure 2, the refraction of light (or bending of light) takes place at point *O* at the boundary of the two media : air and glass. We will now define the angle of incidence and the angle of refraction.

In Figure 2, for the light passing from air into glass, *AO* is the incident ray and *OB* is the refracted ray. Let us draw a normal *NON′* at the point of incidence *O*. Now, **the angle between incident ray and normal (at the point of incidence) is called the angle of incidence.** In Figure 2, the angle *AON* is the angle of incidence. The angle of incidence is denoted by the letter *i*. **The angle between the refracted ray and the normal (at the point of incidence) is called the angle of refraction.** In Figure 2, the angle *N′OB* is the angle of refraction. The angle of refraction is denoted by the letter *r*.

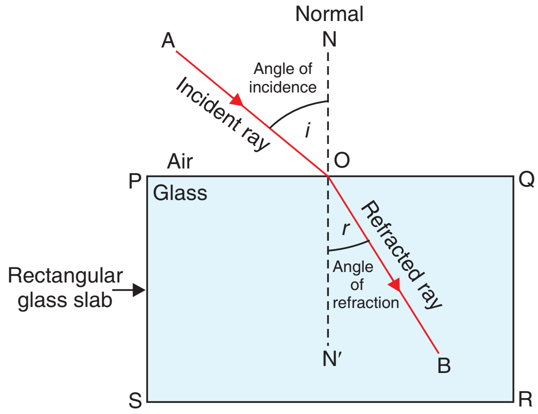


Figure 2. Diagram to show the refraction of light when it passes from air into glass. In this diagram, the light ray going along *AO* in air bends in the direction *OB* on entering the glass.

Please note that though in the reflection of light, the angle of reflection is always equal to the angle of incidence, but **in the refraction of light, the angle of refraction is usually not equal to the angle of incidence.** The angle of refraction is either *smaller* than the angle of incidence or *greater* than the angle of incidence. For example, in Figure 2, the angle of refraction (*r*) is not equal to the angle of incidence (*i*). In this case the angle of refraction (*r*) is smaller than the angle of incidence (*i*). We will give the reasons for this later on in this chapter. At the moment we will discuss why the refraction of light takes place on going from one medium to another.

Cause of Refraction

The speed of light is different in different media (or substances). For example, the speed of light in air is 3×10^8 m/s whereas that in glass is 2×10^8 m/s. It is clear from these values that the speed of light is more in air but less in glass. In other words, light travels faster in air but slower in glass. **The refraction of light is due to the change in the speed of light on going from one medium to another.** Thus, when light goes from one medium to another, its speed changes. And this change in speed of light causes the refraction of light. The refraction of light on going from air to glass takes place because the speed of light is different in air and glass : being more in air and lesser in glass. So, when light enters from air into glass, its speed changes (it gets reduced). And this change in speed of light in going from air to glass causes the refraction of light (or bending of light). Please note that **greater the difference in the speeds of light in the two media, greater will be the amount of refraction (or bending) of light.**

Why a Change in Speed of Light Causes Refraction of Light (or Bending of Light)

The refraction of light or change in direction of light on going from one medium to another can be explained by using the ***wave theory*** of light. A beam of light is made up of tiny waves. When a beam of light consisting of light waves and travelling in a certain medium falls obliquely (at an angle) on the boundary of another medium, then one part of the light waves enters into the other medium first and its speed changes first but the rest of waves enter the other medium a little later and hence its speed changes a little later. **The fact that the speed of light waves on one side of a beam of light changes a little before the change in speed of light waves on its other side, causes a change in the direction of light.** And this change in direction of light is called refraction of light or bending of light. This will become more clear from the following example in which a beam of light is entering from air into a glass slab obliquely and then emerging into air from its other side.

Light waves travel faster in air but slower in glass. Now, when a beam of light consisting of light waves and travelling in air falls on a glass slab obliquely then the part of light waves on the left side of the beam of light reaches the glass slab first (at point *A*) and slows down first on entering the glass slab (see Figure 3). The rest of light waves on the right side of the beam of light are still in air and have to travel more distance in air before reaching the glass slab (at point *B*) and hence slow down a little later on entering the glass slab (see Figure 3). **Since the speed of left side of the beam of light is reduced a little before its**

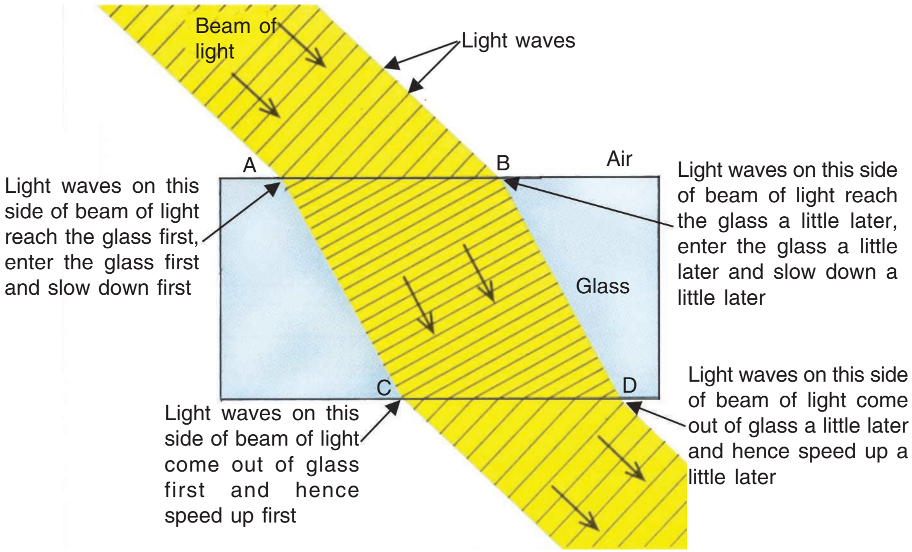


Figure 3. Diagram to explain the refraction of light on going from air into glass; and from glass into air.

right side, therefore, the direction of light changes (or bending of light occurs) on entering the glass slab (see Figure 3). Please note that a decrease in speed of light waves on going from air into glass causes bending of light towards left side (towards the normal) (see Figure 3).

When the beam of light travelling in glass slab comes out into air obliquely (at an angle), then the part of light waves on the left side of beam of light emerges out into air first (at point *C*) and speeds up first (see Figure 3). The part of light waves on the right side of beam of light emerges out into air (at point *D*) a little later and hence its speed increases a little later. **Since the speed of left side of the beam of light increases a little before its right side, therefore, the direction of light changes (or bending of light occurs) on coming out of glass slab into air** (see Figure 3). Please note that an increase in speed of light waves on coming out from glass into air causes bending of light towards the right side (away from the normal) (see Figure 3).

When light waves move from air into glass, their speed decreases and their wavelength also decreases (they become closer). On the other hand, when light waves come out from glass into air, their speed increases and their wavelength also increases (they become farther apart). Before we discuss the refraction of light in detail, we should know the meaning of the terms 'optically rarer medium' and 'optically denser medium'. This is described below.

Optically Rarer Medium and Optically Denser Medium

A transparent substance in which light travels is known as a medium. Air, glass, certain plastics, water, kerosene, alcohol, etc., are all examples of medium. Different media are said to have different optical densities. **A medium in which the speed of light is more is known as optically rarer medium** (or less dense medium). Air is an optically rarer medium as compared to glass and water. **A medium in which the speed of light is less, is known as optically denser medium.** Glass is an optically denser medium than air and water. Now, the speed of light in water is 2.25×10^8 m/s, which is less than that in air but more than that in glass. So, water is optically denser medium than air but it is optically rarer than glass. Please note that the refraction of light takes place whenever it goes from an optically rarer medium to an optically denser medium; or from a denser medium to a rarer medium. The optically rarer medium and optically denser medium can also be defined on the basis of their refractive index. We will learn this after a while. Keeping the above discussion in mind, we can now write down two rules which give the direction of bending of a ray of light when it goes from one medium to another.

It has been found that :

1. **When a ray of light goes from a rarer medium to a denser medium, it bends towards the normal** (at the point of incidence).

2. **When a ray of light goes from a denser medium to a rarer medium, it bends away from the normal** (at the point of incidence).

We will now understand these rules more clearly with the help of ray-diagrams.

Case 1 : Refraction of Light When it Goes From a Rarer Medium to a Denser Medium

Figure 4 shows a ray of light *AO* going from air (a rarer medium) into glass (which is a denser medium). In this case, the incident ray *AO* gets refracted at point *O* and bends towards the normal *ON′* and goes in the direction *OB* inside the glass slab. Thus, **when a ray of light goes from air into glass, it bends towards the normal** (at the point of incidence). In this case, the angle of refraction (*r*) is smaller than the angle of incidence (*i*).

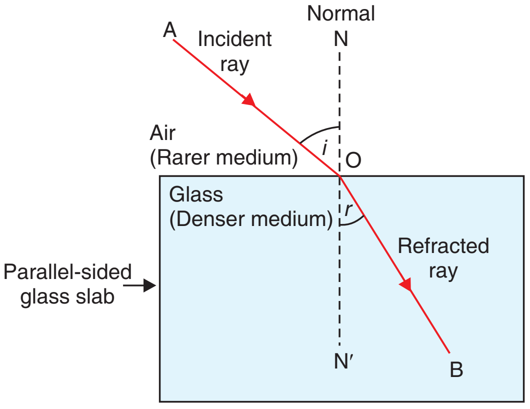


Figure 4.

Water is also an optically denser medium than air, so **when a ray of light goes from air into water, it bends towards the normal.** Thus, the refraction of light on going from air to water is similar to the refraction of light from air to glass (which has been shown in Figure 4). To show the path of a ray of light going from air into water, we can use Figure 4 but we will have to write 'water' in place of 'glass' and in place of glass slab we will have to show water by drawing some dotted lines. Please draw the diagram to show the refraction of a ray of light from air to water yourself.

Case 2 : Refraction of Light When it Goes From a Denser Medium to a Rarer Medium

Figure 5 shows a ray of light *AO* going from glass (a denser medium) into air (which is a rarer medium). In this case, the incident ray *AO* gets refracted at point *O* and bends away from the normal *ON′* in the direction *OB*. Thus, **when a ray of light goes from glass into air, it bends away from the normal** (at the point of incidence). In this case the angle of refraction (*r*) is greater than the angle of incidence (*i*).

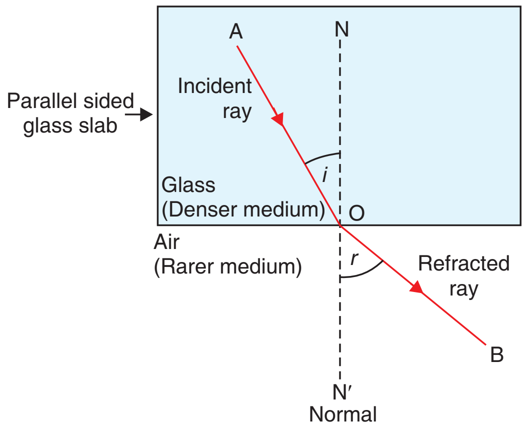


Figure 5.

Please note that water is also optically denser than air, so **when a beam of light travelling in water enters into air, it bends away from the normal.** We can show the refraction of light on going from water into air by using the ray-diagram given in Figure 5. All that we have to do is to write 'water' in place of 'glass' and show water by drawing some dotted lines. Please draw the diagram to show the refraction of a ray of light from water to air yourself. Please note that **a parallel-sided glass slab is also called rectangular glass block.**

When a ray of light goes from a rarer medium to a denser medium, its speed decreases or it slows down. On the other hand, when a ray of light goes from a denser medium to a rarer medium, then its speed increases or it speeds up. So, we can now say that a ray of light travelling from a rarer medium to a denser medium slows down and bends towards the normal but when a ray of light travels from a denser medium to a rarer medium, it speeds up and bends away from the normal.

The Case of Light Going From Air into Glass and Again into Air

We have just studied the refraction of light from air into glass (Figure 4), and from glass into air (Figure 5). We will now show these two types of refraction in the same diagram. In other words, we will now show the complete path of a ray of light when it passes from air into glass slab and again into air. This is shown in Figure 6.

A ray of light *AO* travelling in air is incident on a rectangular glass slab *PQRS* at point *O*. On entering the glass slab, it gets refracted along *OB* and bends towards the normal *ON′* (see Figure 6). A second change of direction takes place when the refracted ray of light *OB*, travelling in glass emerges (or comes out) into air at point *B*. Since the ray of light *OB* now goes from a denser medium 'glass' into the rarer medium 'air', it bends away from the normal BN_1' and goes in the direction *BC*. Please note that the incident ray *AO* and the emergent ray *BC* are parallel to each other (though the emergent ray has been displaced parallel to the incident ray). The incident ray *AO* and emergent ray *BC* are parallel to each other because the extent of bending of the ray of light at points *O* and *B* on the opposite, parallel faces (*PQ* and *SR*) of the rectangular glass slab is equal and opposite. The incident ray *AO* bends towards the normal at point *O* whereas the refracted ray *OB* bends away from the normal at point *B* by an equal amount. Thus, **the light emerges from a parallel-sided glass slab in a direction parallel with that in which it enters the glass slab.** Though the emergent ray *BC* is parallel to the incident ray *AO*, but the emergent ray has been sideways displaced (or laterally displaced) from the original path of the incident ray by a perpendicular distance *CD* (see Figure 6). In Figure 6, the original path of incident light is *AOD* but the emergent light goes along *BC,* the lateral displacement between them being *CD.* **The perpendicular distance between the original path of incident ray and the emergent ray coming out of the glass slab is called lateral displacement of the emergent ray of light**. Lateral displacement depends mainly on three factors : angle of incidence, thickness of glass slab, and refractive index of glass slab. Actually, lateral displacement is directly proportional to (*i*) angle of incidence (*ii*) thickness of glass slab, and (*iii*) refractive index of glass slab. Higher the values of these factors, greater will be the lateral displacement. Another point to be noted is that in this case the refraction (or bending) of light takes place twice : first at point *O* (when light enters from air into glass), and then at point *B* (when light goes out from glass into air).

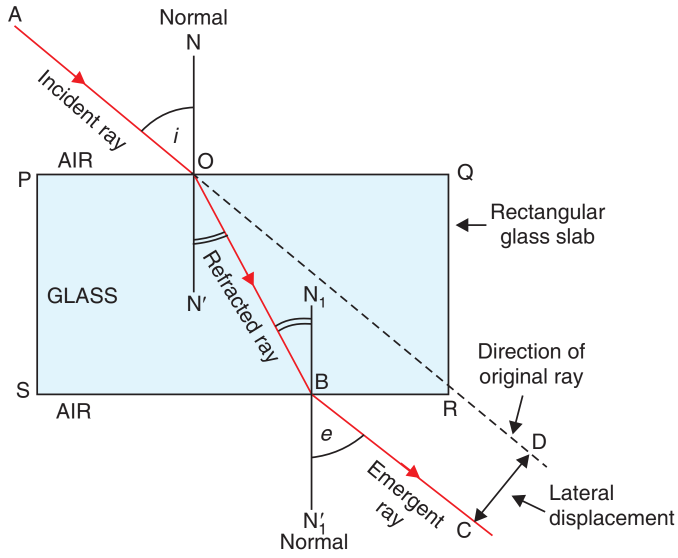


Figure 6.

The angle which the emergent ray makes with the normal is called the angle of emergence. In Figure 6, the angle $N_1'BC$ is the angle of emergence. Since the incident ray *AO* and the emergent ray *BC* are parallel to one another, so the angle of emergence (*e*) is equal to the angle of incidence (*i*). Please note that if a beam of light travelling in air passes into water and then emerges into air, we will get a ray-diagram similar to that shown in Figure 6. Draw it yourself by writing 'water' in place of 'glass'.

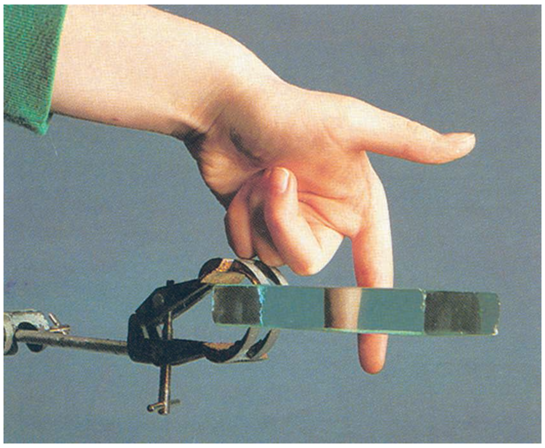


Figure 7. This picture shows the lateral displacement of a finger caused by the refraction of light through a glass slab.

The Case of Light Falling Normally (or Perpendicularly) on a Glass Slab

In all our discussions so far we have assumed that the incident ray of light falls *obliquely* to the surface of glass slab and bending of ray of light takes place. **If the incident ray falls normally (or perpendicularly) to the surface of a glass slab, then there is no bending of the ray of light, and it goes straight.** For example, in Figure 8, a ray of light *AO* travelling in air falls on a glass slab normally (or perpendicularly) at

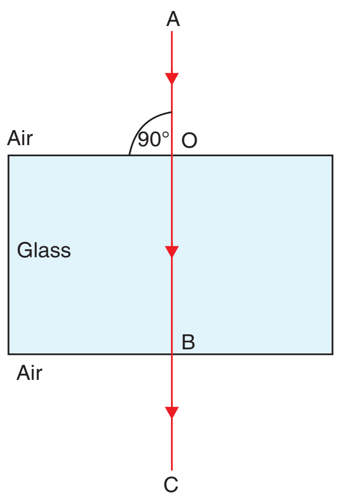


Figure 8.

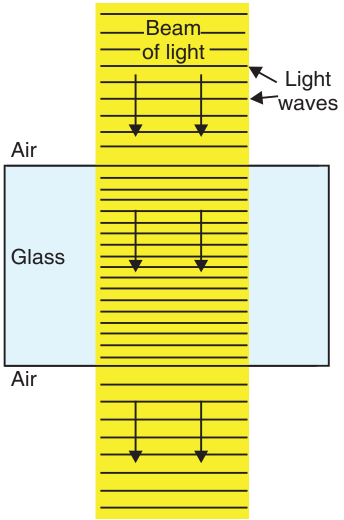


Figure 9.

point *O*, so it does not bend on entering the glass slab or on coming out of the glass slab. It goes straight in the direction *AOBC*. Since the incident ray goes along the normal to the surface, the angle of incidence in this case is zero (0) and the angle of refraction is also zero (0).

We can explain the case of *no refraction* (or *no bending*) of light on going perpendicularly from air to glass as follows : When a beam of light consisting of light waves and travelling in air falls perpendicularly (at right angles) to the surface of glass slab, then all the parts of light waves reach the glass slab at the same time, enter the glass slab at the same time and hence get slowed down at the same time (see Figure 9). Due to this no change in direction of light takes place. In other words, no refraction of light (no bending of light) takes place. Similarly, all the parts of the light waves of the beam of light travelling in glass slab come out of the glass slab into air at the same time and hence speed up at the same time. Due to this, no bending of light occurs when the light waves go out from glass slab into air (see Figure 9).

Please note that if a ray of light falls normally (or perpendicularly) to the surface of water, even then there is no bending of light ray, and it goes straight through water.

EFFECTS OF REFRACTION OF LIGHT

The refraction of light produces many effects which can be easily observed in our day to day life. We will now describe some of the important effects of the refraction of light. It is due to the refraction of light that :

(*i*) a stick (or pencil) held obliquely and partly immersed in water appears to be bent at the water surface.
(*ii*) an object placed under water appears to be raised.
(*iii*) a pool of water appears to be less deep than it actually is.
(*iv*) when a thick glass slab is placed over some printed matter, the letters appear raised when viewed from the top.
(*v*) a lemon kept in water in a glass tumbler appears to be bigger than its actual size, when viewed from the sides.
(*vi*) the stars appear to twinkle on a clear night.

All these effects are produced by the refraction of light (or change in direction of light) when it passes from one medium to another. Let us discuss some of these effects of refraction in detail.

1. A Stick Partly Immersed in Water Appears to be Bent at the Water Surface

When a straight stick is partly immersed in water and held obliquely to the surface, it appears to be bent at the point where it enters water (see Figure 10). This apparent bending of the stick is due to the refraction of light when it passes from water into air. Let us understand it more clearly with the help of a ray-diagram.

Figure 10 shows a straight stick *AO* whose lower portion *BO* is immersed in water. Though the stick is actually straight but on immersing in water, it appears to be bent at point *B*, in the direction *BI* (see Figure 10). This can be explained as follows : A ray of light *OC* coming from the lower end *O* of the stick passes from water into air at point *C* and gets refracted away from normal in the direction *CX* (because it passes from a denser medium water into a rarer medium air). Another ray of light *OD* gets refracted in the direction *DY*. The two refracted rays *CX* and *DY*, when produced backwards, appear to meet at point *I*, nearer to the water surface than point *O* (see Figure 10). Thus, *I* is the virtual image of the end *O* of the stick which is formed by the refraction of light on going from water to air. Thus, an eye at position *E* sees the end *O* of the stick at position *I* which is nearer to the water surface.

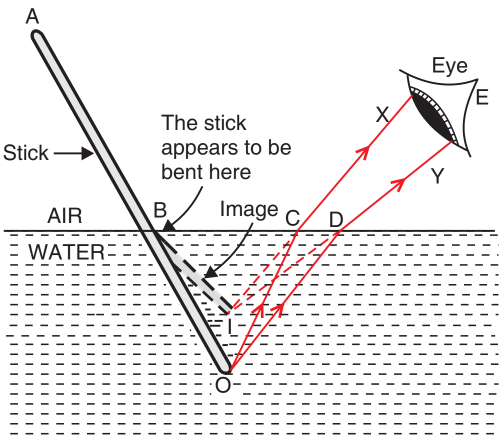


Figure 10. A straight stick *AO* appears bent at point *B* where it enters water.

We can extend this reasoning to all the points which make up part *BO* of the stick under water. Thus, due to the refraction of light, a virtual image of the part *BO* of the stick is formed at *BI*. So, what we see under water is actually the virtual image *BI* of the part *BO* of the stick under water. Since the part *AB* of the stick which is above water and the image *BI* under water are not in the same straight line, the stick *AO* appears to be bent at point B along *BI*. Thus, though the actual stick is *ABO*, it appears to be *ABI*. Please note that it is not the stick that is really bent. It is actually the light passing from water to air that is bent (or refracted) (see Figure 11).

Figure 11. The stick is partly immersed in water. Due to the refraction of light coming from the part of the stick that is under water, the stick appears bent.

Figure 12. The pencil is partly immersed in water. Because of the refraction of light coming from the part of the pencil that is under water, the pencil appears bent.

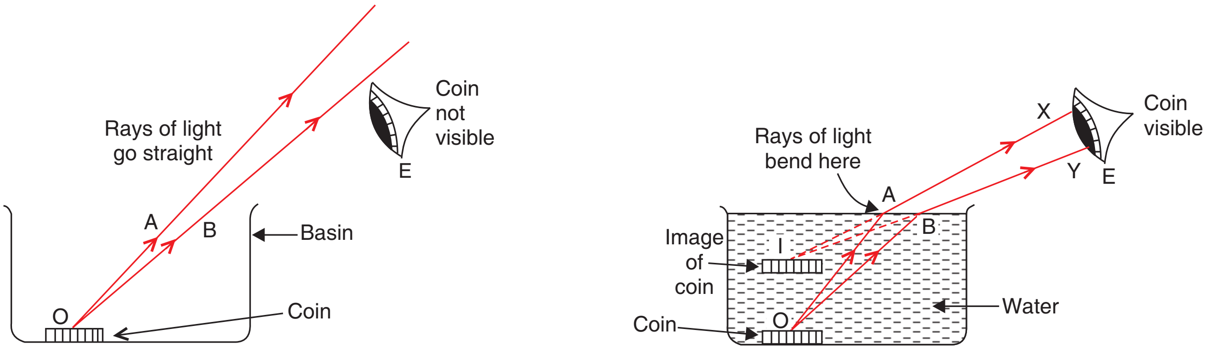
When a pencil is partly immersed in water and held obliquely to the surface, the pencil appears to bend at the water surface (when viewed from the side) (see Figure 12). This apparent bending of the pencil is due to the refraction of light when it passes from water into air. We can use Figure 10 for explaining the bending of pencil in water. Just make a pencil in place of stick.

2. An Object Placed Under Water Appears to be Raised

We will perform an experiment to show that an object placed under water appears to be raised. This can be done as follows : We place a coin at the bottom of an empty basin (a shallow vessel). Let us move our head away from the basin slowly, till the coin disappears from our view and we cannot see it [see

Figure 13(*a*)]. Now, without moving our head, we pour water into the basin. We will find that on adding water, the coin appears to rise and we are able to see it [see Figure 13(*b*)]. The coin under water appears to be raised (and becomes visible) due to the refraction of light which takes place when it goes from water into air. We will now understand all this more clearly with the help of a ray-diagram.

Figure 13(*a*) shows a coin *O* placed in an empty basin (having no water). In this case the rays of light *OA* and *OB* coming from the coin travel in straight line paths in air and do not enter our eye *E* (because the eye is at a lower level). Since the rays of light coming from the coin do not enter our eye, we cannot see the coin from this position of our eye.



(*a*) The coin placed in empty basin is not visible to the eye from this particular position.

(*b*) On adding water in the basin, the coin appears raised and becomes visible to the eye from the same position.

Figure 13.

When the coin is under water, then the rays *OA* and *OB* coming from the coin travel in water in straight line paths until they reach the surface of water. When the rays of light *OA* and *OB* travelling in water, go out into air, they get refracted (they change their directions). The ray of light *OA* gets refracted at point *A*, bends away from the normal, and goes in the direction *AX* [see Figure 13(*b*)]. Similarly, the ray of light *OB* gets refracted at point *B*, bends away from the normal, and goes in the direction *BY*.

If we extend the refracted rays *AX* and *BY* backwards (to the left side), then a virtual image of the coin is formed at point *I*, nearer to the surface of water [see Figure 13(*b*)]. The refracted rays *AX* and *BY*, which appear to be coming from the virtual image of the coin can enter our eye at position *E* due to which the coin becomes visible to us. Thus, **when the coin is under water then due to refraction of light, a virtual image of the coin is formed nearer to the water surface. And since the virtual image of coin which we see, is nearer to the water surface, so the coin appears to rise on adding water in the basin.** Thus, it is due to the refraction of light that a coin placed at the bottom of a container appears to rise as the container is slowly filled with water.

If instead of water, we take some other transparent liquid such as kerosene or turpentine in the above two experiments, then the bending of stick or raising of coin will appear to take place by different amounts than that in water. This is because light is refracted by different amounts in different liquids.

3. A Pool of Water Appears to be Less Deep than it Actually is

If we look into a pool of water (or tank of water), it appears to be less deep than it really is. This is due to the refraction of light which takes place when light rays pass from the pool of water into the air. Let us understand it more clearly with the help of a ray-diagram.

Figure 14 shows a pool of water (or a tank of water). Let us take any point *O* at the bottom of this pool. This point is under the surface of water. Our eye sees this point by the light rays coming from it. Now, a ray of light *OA* coming from the point *O* is travelling in water and it comes out into the air at point *A*. It gets refracted away from the normal in the direction *AX* (see Figure 14.) Similarly, another ray of light *OB*, coming from the point *O* gets refracted at point *B* and goes away from the normal in the direction *BY*. The two refracted rays AX and BY, when produced backwards, meet at point I under water. In fact, when the rays AX and BY enter the eye E, they appear to be coming from point I. So, point I is the virtual image of point O (which is at the bottom of the pool). It is clear from Figure 14 that the image I is nearer to the surface of water than the point O. Thus, a point O at the bottom of a pool appears to be much nearer at position I.

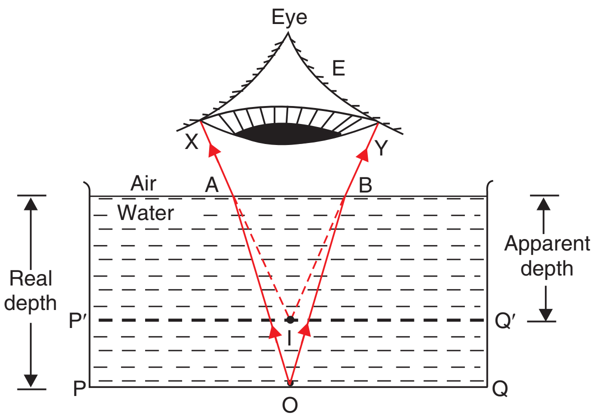


Figure 14. The bottom PQ of the pool of water appears to be raised at $P'Q'$ due to refraction of light. The pool thus appears to be less deep.

This reasoning can be applied to all the points which make up the bottom PQ of the pool, so that due to refraction of light, the bottom PQ of the pool will appear to be much nearer at the position $P'Q'$ (see Figure 14). Due to this, the pool of water will appear less deep than it actually is. Please note that **when we look into a pool of water, we do not see the actual bottom of the pool, we see a virtual image of the bottom of the pool which is formed by the refraction of light coming from the pool water into the air.** And since the image of the bottom of the pool is formed nearer to us, we feel that the pool is less deep. From this discussion we conclude that the bottom of a pool of water appears raised due to refraction of light. And the pool of water appears to be less deep than it actually is. *We should be careful while entering a swimming pool because the water in it will be deeper than it appears to be.*

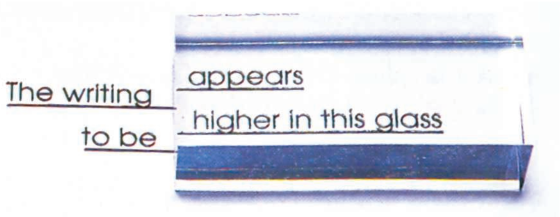


Figure 15. Those words of writing which are below the glass slab appear raised (or higher) due to refraction of light as it comes out of glass slab.

It is also due to the refraction of light that a thick glass slab appears to be less thick (when seen from above), than it actually is. Similarly, an ink mark or the writing on a piece of paper appears to be raised and much nearer than it actually is, when viewed by keeping a glass slab over it (see Figure 15). This also happens due to refraction of light. As we will study in the next Chapter, the stars appear to twinkle on a clear night due to the refraction of light in the atmosphere. Before we go further and discuss the laws of refraction of light, **please answer the following questions :**

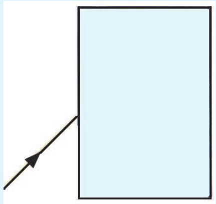
Very Short Answer Type Questions

1. If a ray of light goes from a rarer medium to a denser medium, will it bend towards the normal or away from it ?
2. If a ray of light goes from a denser medium to a rarer medium, will it bend towards the normal or away from the normal ?
3. A beam of light travelling in a rectangular glass slab emerges into air. Draw a ray-diagram indicating the change in its path.
4. A beam of light travelling in air is incident on water. Draw a ray-diagram indicating the change in its path in water.
5. A ray of light travelling in water emerges into air. Draw a ray-diagram indicating the change in its path.
6. A ray of light travelling in air is incident on a parallel-sided glass slab (or rectangular glass slab). Draw a ray-diagram indicating the change in its path in glass.
7. A ray of light travelling in glass emerges into air. State whether it will bend towards the normal or away from the normal.
8. A ray of light travelling in air enters obliquely into water. Does the ray of light bend towards the normal or away from the normal ? Why ?
9. A ray of light goes from water into air. Will it bend towards the normal or away from the normal ?
10. State two effects caused by the refraction of light.
11. Name the phenomenon due to which a swimming pool appears less deep than it really is.
12. When a ray of light passes from air into glass, is the angle of refraction greater than or less than the angle of incidence ?

13. A ray of light passes from air into a block of glass. Does it bend towards the normal or away from it ?
14. As light rays pass from water into glass, are they refracted towards the normal or away from the normal ?
15. In which material do you think light rays travel faster–glass or air ?
16. Which phenomenon of light makes the water to appear shallower than it really is ?
17. State whether the following statement is true or false :
Refraction occurs because light slows down in denser materials.
18. Why does a ray of light bend when it travels from one medium to another ?
19. Fill in the following blanks with suitable words :
(*a*) Light travelling along a normal is ....refracted.
(*b*) Light bends when it passes from water into air. We say that it is..............

Short Answer Type Questions

20. What is meant by 'refraction of light' ? Draw a labelled ray diagram to show the refraction of light.
21. A ray of light travelling in air is incident on a rectangular glass block and emerges out into the air from the opposite face. Draw a labelled ray diagram to show the complete path of this ray of light. Mark the two points where the refraction of light takes place. What can you say about the final direction of ray of light ?
22. Draw a labelled ray diagram to show how a ray of light is refracted when it passes :
(*a*) from air into an optically denser medium.
(*b*) from an optically denser medium into air.



23. The diagram given alongside shows a ray of light entering a rectangular block of glass.
(*a*) Copy the diagram and draw the normal at the point of entry.
(*b*) Draw the approximate path of the ray of light through the glass block and out of the other side.
24. What is meant by the 'angle of incidence' and the 'angle of refraction' for a ray of light ? Draw a labelled ray diagram to show the angle of incidence and the angle of refraction for a refracted ray of light.
25. Light travels more quickly through water than through glass.
(*a*) Which is optically denser : water or glass ?
(*b*) If a ray of light passes from glass into water, which way will it bend : towards the normal or away from the normal ?
26. Draw a labelled ray diagram to show how a ray of light passes through a parallel sided glass block :
(*a*) if it hits the glass block at 90° (that is, perpendicular to the glass block)
(*b*) if it hits the glass block at an angle other than 90° (that is, obliquely to the glass block).
27. When a light ray passes from air into glass, what happens to its speed ? Draw a diagram to show which way the ray of light bends.

Long Answer Type Questions

28. (*a*) Explain why, a stick half immersed in water appears to be bent at the surface. Draw a labelled diagram to illustrate your answer.
(*b*) A coin in a glass tumbler appears to rise as the glass tumbler is slowly filled with water. Name the phenomenon responsible for this effect.
29. (*a*) With the help of a labelled diagram, explain why a tank full of water appears less deep than it actually is.
(*b*) Name the phenomenon due to which a pencil partly immersed in water and held obliquely appears to be bent at the water surface.
30. (*a*) With the help of a diagram, show how when light falls obliquely on the side of a rectangular glass slab, the emergent ray is parallel to the incident ray.
(*b*) Show the lateral displacement of the ray on the diagram.
(*c*) State two factors on which the lateral displacement of the emergent ray depends.
31. Explain with the help of a labelled ray diagram, why a pencil partly immersed in water appears to be bent at the water surface. State whether the bending of pencil will increase or decrease if water is replaced by another liquid which is optically more dense than water. Give reason for your answer.

Multiple Choice Questions (MCQs)

32. Light travelling from a denser medium to a rarer medium along a normal to the boundary :
(*a*) is refracted towards the normal (*b*) is refracted away from the normal
(*c*) goes along the boundary (*d*) is not refracted

33. A ray of light passes from glass into air. The angle of refraction will be :
(*a*) equal to the angle of incidence (*b*) greater than the angle of incidence
(*c*) smaller than the angle of incidence (*d*) 45°

34. A ray of light travelling in air goes into water. The angle of refraction will be :
(*a*) 90° (*b*) smaller than the angle of incidence
(*c*) equal to the angle of incidence (*d*) greater than the angle of incidence

35. The speed of light in air is :
(*a*) 3×10^8 cm/s (*b*) 3×10^8 mm/s
(*c*) 3×10^8 km/s (*d*) 3×10^8 m/s

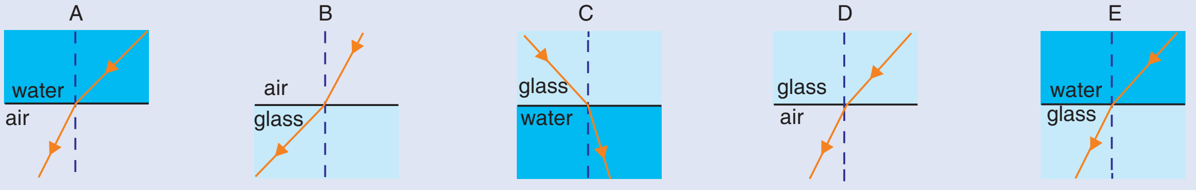
36. When a ray of light travelling in glass enters into water obliquely :
(*a*) it is refracted towards the normal (*b*) it is not refracted at all
(*c*) it goes along the normal (*d*) it is refracted away from the normal

37. A ray of light travelling in water falls at right angles to the boundary of a parallel-sided glass block. The ray of light :
(*a*) is refracted towards the normal (*b*) is refracted away from the normal
(*c*) does not get refracted (*d*) is reflected along the same path.

38. A ray of light passes from a medium *X* to another medium *Y*. No refraction of light occurs if the ray of light hits the boundary of medium *Y* at an angle of :
(*a*) 0° (*b*) 45° (*c*) 90° (*d*) 120°

Questions Based on High Order Thinking Skills (HOTS)

39. Which of the following diagrams shows the ray of light refracted correctly ?



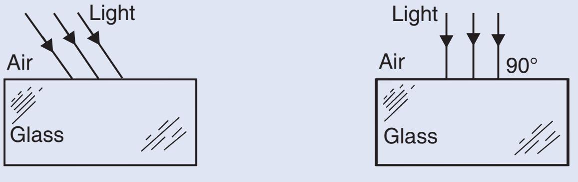
40. A vertical ray of light strikes the horizontal surface of some water :
(*a*) What is the angle of incidence ?
(*b*) What is the angle of refraction ?

41. How is the reflection of light ray from a plane mirror different from the refraction of light ray as it enters a block of glass ?

42. How does the light have to enter the glass :
(*a*) to produce a large amount of bending ?
(*b*) for no refraction to happen ?

43. (*a*) How can you bend light away from the normal ?
(*b*) How must light travel out of a substance if it is not going to be refracted ?

44. Draw and complete the following diagrams to show what happens to the beams of light as they enter the glass block and then leave it :



45. Why does a beam of light bend when it enters glass at an angle ? Why does it not bend if it enters the glass at right angles ?

ANSWERS

12. Angle of refraction is less than the angle of incidence **17.** True **19.** (*a*) not (*b*) refracted **28.** (*b*) Refraction of light (as it comes out from water into air) **31.** The bending of pencil will increase; The optically denser medium will cause more refraction (or more bending) of light rays **32.** (*d*) **33.** (*b*) **34.** (*b*) **35.** (*d*) **36.** (*d*) **37.** (*c*) **38.** (*c*) **39.** E **40.** (*a*) 0° (*b*) 0° **41.** The angle of reflection is equal to the angle of incidence but the angle of refraction is not equal to the angle of incidence **42.** (*a*) Obliquely ; Making a large angle of incidence (*b*) Perpendicularly (at right angles) to the glass surface **43.** (*a*) Make the light enter from a denser medium to a rarer medium (*b*) At right angles (90°) to the surface of substance.

LAWS OF REFRACTION OF LIGHT

The refraction of light on going from one medium to another takes place according to two laws which are known as the laws of refraction of light. These are given below.

1. According to the first law of refraction of light : **The incident ray, the refracted ray and the normal at the point of incidence, all lie in the same plane.** For example, in Figure 16, the incident ray *AO*, the refracted ray *OB*, and the normal *ON*, all lie in the same plane (which is the plane of the paper here).

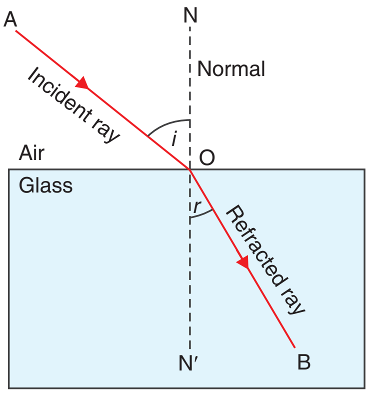


Figure 16.

2. The second law of refraction gives a relationship between the angle of incidence and the angle of refraction. This relationship was discovered by Snell experimentally in 1621, so the second law of refraction is called Snell's law of refraction. According to Snell's law of refraction of light : **The ratio of sine of angle of incidence to the sine of angle of refraction is constant for a given pair of media** (such as 'air and glass' or 'air and water'). That is :

$$\frac{\text{sine of angle of incidence}}{\text{sine of angle of refraction}} = \text{constant}$$

or

$$\frac{\sin i}{\sin r} = \text{constant}$$

This constant is called refractive index. We will now discuss the refractive index in somewhat detail.

Suppose a ray of light travelling in air enters into another medium and gets refracted. Let the angle of incidence in air be *i* and the angle of refraction in that medium be *r* (see Figure 16). **The value of the constant $\frac{\sin i}{\sin r}$ for a ray of light passing from air into a particular medium is called the refractive index of that medium.** The refractive index is usually denoted by the symbol *n*. So :

Refractive index, $n = \frac{\sin i}{\sin r}$

where $\sin i$ = sine of the angle of incidence (in air)

and $\sin r$ = sine of the angle of refraction (in medium)

Suppose the angle of incidence (*i*) for a ray of light in air is 37° and the angle of refraction (*r*) in glass be 24°. Then :

Refractive index of glass, $n = \frac{\sin 37°}{\sin 24°}$

Now, if we look up the sine tables we will find that the value of sin 37° = 0.60 and sin 24° = 0.40. Putting these values in the above relation, we get :

$$n = \frac{0.60}{0.40}$$

$$n = 1.50$$

Thus, the refractive index of this glass is 1.50.

Please note that **since the refractive index is a ratio of two similar quantities (the sines of angles), it has no units**. It is a pure number. The refractive index of a substance does not depend on the angle of incidence. When we talk of refractive index of a substance, say glass, we mean the value of $\frac{\sin i}{\sin r}$ for light passing from air to glass. Strictly speaking, it should mean the value of $\frac{\sin i}{\sin r}$ for light passing from vacuum to glass. But the difference in using air in place of vacuum is so small that it is ignored.

When light rays go from air (or vacuum) into another medium, then they bend (or refract) to some extent. Now, some media bend the light rays more than the others. **The refractive index of a medium gives an indication of the light-bending ability of that medium.** For example, the refractive index of glass is greater than the refractive index of water, therefore, the light rays bend more on passing from air into glass than from air into water. We will now solve one problem based on refractive index.

Sample Problem. A beam of light passes from air into a substance *X*. If the angle of incidence be 72° and the angle of refraction be 40°, calculate the refractive index of substance *X*. (Given : sin 72° = 0.951 and sin 40° = 0.642)

Solution. We know that :

$$\text{Refractive index} = \frac{\text{Sine of angle of incidence}}{\text{Sine of angle of refraction}}$$

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

Here, Angle of incidence, i = 72°

And, Angle of refraction, r = 40°

So, $$n = \frac{\sin 72°}{\sin 40°}$$

We are given that sin 72° = 0.951 and sin 40° = 0.642. So, putting these values of sin 72° and sin 40° in the above relation, we get :

$$n = \frac{0.951}{0.642}$$

or $$n = 1.48$$

Thus, the refractive index of substance *X* is 1.48.

So far we have denoted the refractive index of a substance just by the letter n. In its full form, the refractive index n has, however, two subscripts (lower words or letters) which show the two substances or media between which the light travels. For example, the refractive index for light going from *air* into *glass* is written as ${}_{air}n_{glass}$ (or ${}_{a}n_{g}$ where a = air and g = glass). We will discuss this in more detail after a while.

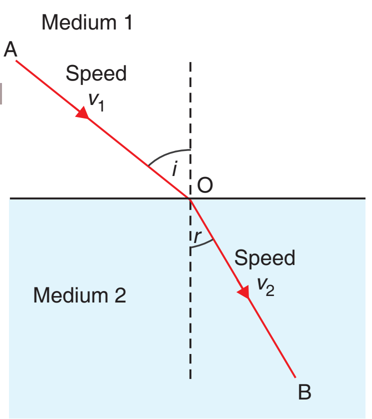


Figure 17.

Refractive Index and Speed of Light

The material (or substance) through which light travels is called medium. Light is refracted (or bent) in going from one medium to another because its speed changes (it slows down or speeds up). Due to this, **the refractive index (n) can also be written as a ratio of speeds of light in the two media.**

Look at Figure 17 in which a ray of light *AO* is going from medium 1 to medium 2 as *OB*. The speed of light in medium 2 is different from that in medium 1. Let the speed of light in medium 1 be v_1 and that in medium 2 be v_2. Now, **the refractive index of medium 2 with respect to medium 1 is equal to the ratio of speed of light in medium 1 to the speed of light in medium 2.**

This can be written as :

$$_{\text{medium 1}}n_{\text{medium 2}} = \frac{\text{Speed of light in medium 1}}{\text{Speed of light in medium 2}}$$

or $$_1n_2 = \frac{v_1}{v_2}$$

where $_1n_2$ = Refractive index of medium 2 with respect to medium 1

v_1 = Speed of light in medium 1

and v_2 = Speed of light in medium 2

Please note that the symbol $_{\text{medium 1}}n_{\text{medium 2}}$ or $_1n_2$ means that it is the refractive index of medium 2 with respect to medium 1 (for the light entering from medium 1 into medium 2). We have represented the refractive index of medium 2 with respect to medium 1 by the symbol $_1n_2$. In some books, however, the refractive index of medium 2 with respect to medium 1 is represented by the symbol n_{21} (read as n-two-one and not as n-twenty one). We have not used this notation because we find it a bit confusing.

When light is going from one medium (other than vacuum or air) to another medium, then the value of refractive index is called *relative* refractive index. For example, when the light is going from water into glass, then the value of refractive index will be the relative refractive index of glass with respect to water. The relative refractive index has always 'two subscripts' with its symbol n which indicate the two media in which the light travels. For example, for the light going from water to glass, the refractive index is written as $_{\text{water}}n_{\text{glass}}$ (or $_wn_g$). The symbol $_{\text{water}}n_{\text{glass}}$ means that it is the refractive index of glass with respect to water, that is, it is the refractive index of glass for light entering from water into glass.

When light is going from vacuum to another medium, then the value of refractive index is called the *absolute* refractive index. The absolute refractive index has only one subscript with its symbol n on its right side which indicates the name of the medium (the word vacuum is not written as a subscript). For example, for the light going from vacuum into glass, the absolute refractive index of glass is represented as n_{glass} (and not as $_{\text{vacuum}}n_{\text{glass}}$). The symbol n_{glass} means that it is the refractive index of glass with respect to vacuum, that is, it is the refractive index of glass for light entering from vacuum into glass. Please note that the symbol n_{glass} is also written in short as n_g.

The exact speed of light in vacuum is 2.9979×10^8 m/s and that in air is 2.9970×10^8 m/s. We can see that the speed of light in air is almost the same as that in vacuum, so for the purpose of determining refractive index we can also treat air as if it were vacuum. So, **the refractive index of a medium (or substance) with respect to air is also considered to be its *absolute* refractive index.** Thus, $_{\text{air}}n_{\text{glass}}$ can also be written as n_{glass}. The absolute refractive index of a medium (or substance) is just called its refractive index.

We will now write some simplified formulae for calculating the refractive index from the given values of the speed of light in the two media. These are given below.

The ratio of speed of light in vacuum to the speed of light in a medium, is called the refractive index of that medium. That is :

$$\text{Refractive index (of a medium)} = \frac{\text{Speed of light in vacuum}}{\text{Speed of light in medium}}$$

Since the speed of light in air is almost equal to the speed of light in vacuum, so for all practical purposes we can also say that : **The ratio of speed of light in air to the speed of light in a medium, is called refractive index of that medium.** That is :

$$\text{Refractive index (of a medium)} = \frac{\text{Speed of light in air}}{\text{Speed of light in medium}}$$

Let us take 'glass' as the medium and write a relation for its refractive index. Now, the speed of light in air is 3×10^8 m/s and the speed of light in common glass is 2×10^8 m/s. So :

$$\text{Refractive index of glass, } n_g = \frac{\text{Speed of light in air (or vacuum)}}{\text{Speed of light in glass}}$$

or $$n_g = \frac{3 \times 10^8}{2 \times 10^8}$$

or $$n_g = \frac{3}{2}$$

or $$n_g = 1.5$$

Thus, the refractive index of this glass is 1.5. **By saying that the refractive index of glass is 1.5 we mean that the ratio of the speed of light in air (or vacuum) to the speed of light in glass is equal to 1.5.** Let us solve one problem now.

Sample Problem. Light enters from air into a glass plate having refractive index 1.50. What is the speed of light in glass ? (The speed of light in vacuum is 3×10^8 m s^{-1}). **(NCERT Book Question)**

Solution. We know that :

$$\text{Refractive index of glass} = \frac{\text{Speed of light in air (or vacuum)}}{\text{Speed of light in glass}}$$

So, $$1.50 = \frac{3 \times 10^8}{\text{Speed of light in glass}}$$

or $$\text{Speed of light in glass} = \frac{3 \times 10^8}{1.50} \text{ m s}^{-1}$$

$$= 2 \times 10^8 \text{ m s}^{-1}$$

Thus, the speed of light in glass is 2×10^8 m s^{-1} (or 2×10^8 m/s).

The refractive index depends on the nature of the material of the medium and on the wavelength (or colour) of the light used. The value of refractive index of a substance is a characteristic property of that substance which can be used to identify it. The refractive indices of some of the common substances are given below (indices is the plural of index). These refractive index values have been obtained by using yellow sodium light of wavelength 589 nm (or 5.89×10^{-7} m).

Refractive Index of Some Common Substances

(with respect to air or vacuum)

Substance (or Medium)	*Refractive index (n)*	*Substance (or Medium)*	*Refractive index (n)*
1. Air	1.0003	8. Benzene	1.50
2. Ice	1.31	9. Crown glass	1.52
3. Water	1.33	10. Carbon disulphide	1.63
4. Alcohol	1.36	11. Dense flint glass	1.65
5. Sulphuric acid	1.43	12. Ruby	1.71
6. Kerosene	1.44	13. Sapphire	1.77
7. Turpentine oil	1.47	14. Diamond	2.42

Please note that different types of glass have different chemical compositions due to which they have somewhat different values of refractive indices. Because of this reason no single value can be given for the refractive index of all types of glass. The refractive index of glass usually varies from 1.5 to 1.9. Another point to be noted is that diamond has a very high refractive index of 2.42.

Figure 18. Diamonds sparkle partly because of their high refractive index. The shape to which they are cut also helps them to sparkle.

The construction of lenses of the optical instruments like cameras, microscopes and telescopes, etc., depends on an accurate knowledge of the refractive index of glass used for making lenses. Please note that **if any two media are optically exactly the same, then no bending occurs when light passes from one medium to another**. In other words, if the refractive indices of two media are equal, then there will be no bending of light rays when they pass from one medium to another. The ability of a substance to refract light is also expressed in terms of its optical density. The optical density of a substance (or medium) is the degree to which it retards (or slows down) the rays of light passing through it. **A substance having higher refractive index is optically denser than another substance having lower refractive index.** For example, the refractive index of one type of glass is 1.52 and that of water is 1.33. Since glass has a higher refractive index than water, therefore, glass is optically denser than water, and more bending of light rays takes place in glass than in water. From this we conclude that **higher the refractive index of a substance, more it will change the direction of a beam of light passing through it.**

Please note that **the optical density of a substance is different from its mass density.** A substance may have a higher optical density than another substance but its mass density may be less. For example, kerosene having a higher refractive index than water is optically denser than water though its mass density is less than that of water. We have been using the terms 'rarer medium' and 'denser medium' in our discussions. It actually means 'optically rarer medium' and 'optically denser medium'.

We will now show that **the refractive index for light going from medium 1 to medium 2 is equal to the reciprocal of the refractive index for light going from medium 2 to medium 1.** Suppose we have two media : medium 1 and medium 2. We can find out the refractive index in two ways : one for the light going from medium 1 to medium 2 (as shown in Figure 19) and the other for light going in the reverse direction, from medium 2 to medium 1 (as shown in Figure 20).

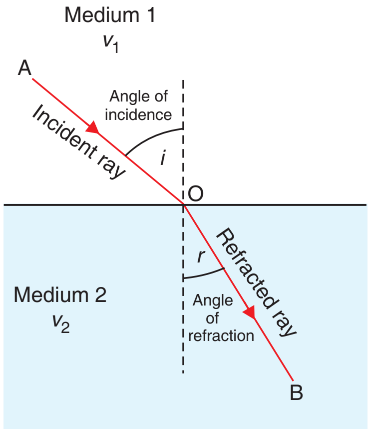


Figure 19. A ray of light going from medium 1 into medium 2

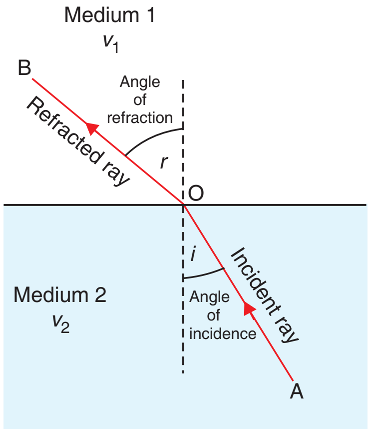


Figure 20. A ray of light going from medium 2 into medium 1

Suppose the speed of light in medium 1 is v_1 and that in medium 2 is v_2. Now :

(*i*) For the light going from medium 1 to medium 2 (Figure 19), the refractive index is given by :

$$ {}_1n_2 = \frac{v_1}{v_2} \qquad ....(1)$$

(*ii*) And for the light going from medium 2 to medium 1 (Figure 20), the refractive index is given by :

$$ {}_2n_1 = \frac{v_2}{v_1} $$

Let us take the reciprocal of this equation. This will give us :

$$\frac{1}{{}_2n_1} = \frac{v_1}{v_2} \qquad \text{.......(2)}$$

Now, if we compare equations (1) and (2), we find that their right hand sides are equal, so their left hand sides should also be equal. Thus,

$${}_1n_2 = \frac{1}{{}_2n_1}$$

This can also be written as :

$${}_{\text{medium 1}}n_{\text{medium 2}} = \frac{1}{{}_{\text{medium 2}}n_{\text{medium 1}}}$$

This means that the refractive index for light going from medium 1 to medium 2 is equal to the reciprocal of refractive index for light going from medium 2 to medium 1.

If medium 1 is air and medium 2 is glass, then the above relation can be written as :

$${}_{\text{air}}n_{\text{glass}} = \frac{1}{{}_{\text{glass}}n_{\text{air}}}$$

or

$${}_{\text{a}}n_{\text{g}} = \frac{1}{{}_{\text{g}}n_{\text{a}}}$$

Thus, the refractive index of glass for light going from *air* to *glass* is the reciprocal of the refractive index for light going from *glass* to *air.* Let us solve some problems now.

Sample Problem 1. If the refractive index of water for light going from air to water be 1.33, what will be the refractive index for light going from water to air ?

Solution. Here, $\quad {}_{\text{a}}n_{\text{w}} = 1.33$

Now,

$${}_{\text{w}}n_{\text{a}} = \frac{1}{{}_{\text{a}}n_{\text{w}}}$$

$$= \frac{1}{1.33}$$

$$= 0.75$$

Sample Problem 2. The refractive indices of kerosene, turpentine and water are 1.44, 1.47 and 1.33, respectively. In which of these materials does light travel fastest ? **(NCERT Book Question)**

Solution. We know that :

$$\text{Refractive index} = \frac{\text{Speed of light in air}}{\text{Speed of light in medium}}$$

So, $\quad \text{Speed of light in medium} = \frac{\text{Speed of light in air}}{\text{Refractive index}}$

It is obvious from the above relation that the speed of light will be the *maximum* in that medium (or substance) which has the *lowest* refractive index. Now, out of kerosene, turpentine and water, water has the lowest refractive index of 1.33. So, the light will have maximum speed in water or light will travel fastest in water.

We are now in a position to **answer the following questions :**

Very Short Answer Type Questions

1. What name is given to the ratio of sine of angle of incidence to the sine of angle of refraction ?
2. Write the relation between the angle of incidence and the angle of refraction for a medium.

3. What is the unit of refractive index ?
4. Which has higher refractive index : water or glass ?
5. Refractive indices of carbon disulphide and ethyl alcohol are 1.63 and 1.36 respectively. Which is optically denser ?
6. The refractive index of diamond is 2.42. What is the meaning of this statement in relation to the speed of light ?
7. If the refractive index for light going from air to diamond be 2.42, what will be the refractive index for light going from diamond to air ?
8. How is the refractive index of a material related to the speed of light in it ?
9. Fill in the following blank with a suitable word :

   When a ray of light goes from air into a clear material, you see the ray bend. How much the ray bends is determined by the.............of the material.

Short Answer Type Questions

10. Give three examples of materials that refract light rays. What happens to the speed of light rays when they enter these materials ?
11. Define Snell's law of refraction. A ray of light is incident on a glass slab at an angle of incidence of 60°. If the angle of refraction be 32.7°, calculate the refractive index of glass. (Given : sin 60° = 0.866, and sin 32.7° = 0.540).
12. The speed of light in vacuum and in two different glasses is given in the table below :

Medium	*Speed of light*
Vacuum	3.00×10^8 m/s
Flint glass	1.86×10^8 m/s
Crown glass	1.97×10^8 m/s

(*a*) Calculate the absolute refractive indexes of flint glass and crown glass.

(*b*) Calculate the relative refractive index for light going from crown glass to flint glass.

13. The speed of light in air is 3×10^8 m/s. In medium X its speed is 2×10^8 m/s and in medium Y the speed of light is 2.5×10^8 m/s. Calculate:

    (*a*) ${}_{\text{air}}n_X$ (*b*) ${}_{\text{air}}n_Y$ (*c*) ${}_{X}n_Y$
14. What is the speed of light in a medium of refractive index $\frac{6}{5}$ if its speed in air is 3,00,000 km/s ?
15. The refractive index of glass is 1.5. Calculate the speed of light in glass. The speed of light in air is 3.0×10^8 ms^{-1}.
16. The speed of light in water is 2.25×10^8 m/s. If the speed of light in vacuum be 3×10^8 m/s, calculate the refractive index of water.
17. Light enters from air into diamond which has a refractive index of 2.42. Calculate the speed of light in diamond. The speed of light in air is 3.0×10^8 ms^{-1}.

Long Answer Type Question

18. (*a*) State and explain the laws of refraction of light with the help of a labelled diagram.

    (*b*) What is meant by the refractive index of a substance ?

    (*c*) Light travels through air at 300 million ms^{-1}. On entering water it slows down to 225 million ms^{-1}. Calculate the refractive index of water.

Multiple Choice Questions (MCQs)

19. The refractive indices of four substances *P*, *Q*, *R* and *S* are 1.50, 1.36, 1.77 and 1.31 respectively. The speed of light is the maximum in the substance :

    (*a*) *P* (*b*) *Q* (*c*) *R* (*d*) *S*
20. The refractive indices of four materials A, B, C and D are 1.33, 1.43, 1.71 and 1.52 respectively. When the light rays pass from air into these materials, they refract the maximum in :

    (*a*) material A (*b*) material B (*c*) material C (*d*) material D

21. The refractive index of glass for light going from air to glass is $\frac{3}{2}$. The refractive index for light going from glass to air will be :

(*a*) $\frac{1}{3}$ (*b*) $\frac{4}{5}$ (*c*) $\frac{4}{6}$ (*d*) $\frac{5}{2}$

22. The refractive indices of four media A, B, C and D are 1.44, 1.52, 1.65 and 1.36 respectively. When light travelling in air is incident in these media at equal angles, the angle of refraction will be the minimum :

(*a*) in medium A (*b*) in medium B (*c*) in medium C (*d*) in medium D

23. The speed of light in substance X is 1.25×10^8 m/s and that in air is 3×10^8 m/s. The refractive index of this substance will be :

(*a*) 2.4 (*b*) 0.4 (*c*) 4.2 (*d*) 3.75

24. The refractive indexes of four substances *P, Q, R* and *S* are 1.77, 1.50, 2.42 and 1.31 respectively. When light travelling in air is incident on these substances at equal angles, the angle of refraction will be the maximum in :

(*a*) substance *P* (*b*) substance *Q* (*c*) substance *R* (*d*) substance *S*

25. The refractive index of water is :

(*a*) 1.33 (*b*) 1.50 (*c*) 2.42 (*d*) 1.36

26. The refractive index of water with respect to air is $\frac{4}{3}$. The refractive index of air with respect to water will be :

(*a*) 1.75 (*b*) 0.50 (*c*) 0.75 (*d*) 0.25

27. Refractive indices of water, sulphuric acid, glass and carbon disulphide are 1.33, 1.43, 1.53 and 1.63 respectively. The light travels slowest in :

(*a*) sulphuric acid (*b*) glass (*c*) water (*d*) carbon disulphide

28. The refractive index of glass with respect to air is $\frac{3}{2}$ and the refractive index of water with respect to air is $\frac{4}{3}$. The refractive index of glass with respect to water will be :

(*a*) 1.525 (*b*) 1.225 (*c*) 1.425 (*d*) 1.125

Questions Based on High Order Thinking Skills (HOTS)

29. The following table gives the refractive indices of a few media :

	1	2	3	4	5
Medium :	Water	Crown glass	Rock salt	Ruby	Diamond
Refractive index :	1.33	1.52	1.54	1.71	2.42

Use this table to give an example of :

(*i*) a medium pair so that light speeds up when it goes from one of these medium to another.

(*ii*) a medium pair so that light slows down when it goes from one of these medium to another.

30. Refractive indices of four media A, B, C and D are given below :

Medium	*Refractive index*
A	1.33
B	1.44
C	1.52
D	1.65

In which of these four media is the speed of light (*i*) maximum, and (*ii*) minimum ?

ANSWERS

7. 0.41 **9.** refractive index **11.** 1.60 **12.** (*a*) Flint glass : 1.61 ; Crown glass : 1.52 (*b*) 1.059 **13.** (*a*) 1.5 (*b*) 1.2 (*c*) 0.8 **14.** 2,50,000 km/s **15.** 2.0×10^8 ms^{-1} **16.** 1.33 **17.** 1.24×10^8 ms^{-1} **18.** (*c*) 1.33 **19.** (*d*) **20.** (*c*) **21.** (*c*) **22.** (*c*) **23.** (*a*) **24.** (*d*) **25.** (*a*) **26.** (*c*) **27.** (*d*) **28.** (*d*) **29.** (*i*) Crown glass to Water (*ii*) Water to Diamond **30.** (*i*) A (*ii*) D

REFRACTION OF LIGHT BY SPHERICAL LENSES

We have all seen a palmist using a lens (called magnifying glass) for seeing the details of the lines of a person's palm. A watch maker also uses a lens to see the extremely small parts of a watch clearly. In fact, lenses play a very important role in our everyday life. Lenses are used in making spectacles, cameras, microscopes, telescopes, film projectors, and many, many other optical instruments. We have already studied that the working of a mirror is based on the reflection of light rays from its surface. **The working of a lens is based on the refraction of light rays when they pass through it.** We will now study the formation of images by lenses in detail. Before we do that, we should know the various types of spherical lenses and the terms like optical centre, principal axis, principal focus (or just focus), and focal length, etc., which are used in the study of refraction of light by lenses. These are discussed below.

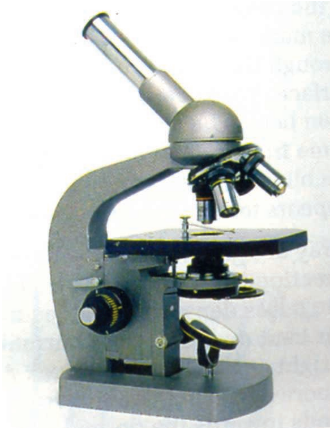
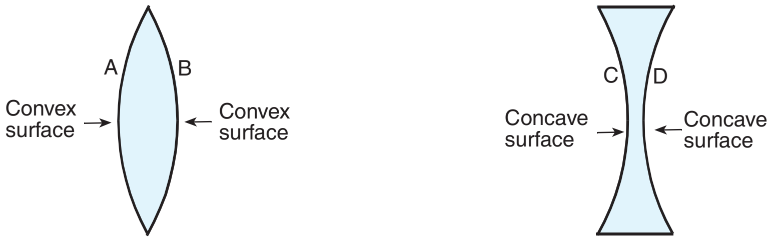


Figure 21. This is a microscope. Lenses are used in making microscopes.

A lens is a piece of transparent glass bound by two spherical surfaces. There are two types of lenses : Convex lens and Concave lens.

(*i*) A convex lens is thick at the centre but thinner at the edges. Figure 22(*a*) shows a convex lens in which the two surfaces *A* and *B* are convex or bulging out at the centre.



(*a*) Convex lens (*b*) Concave lens

Figure 22.

(*ii*) A concave lens is thin in the middle but thicker at the edges. Figure 22(*b*) shows a concave lens in which the two surfaces *C* and *D* are concave or bent inward.

Figure 22(*a*) shows the side view of a convex lens. When we look at a convex lens from the front side, it looks like a piece of transparent spherical glass (round glass) having a bulge in the middle [see Figure 23(*a*)]. We can feel the bulge in the middle of the convex lens by touching it. Similarly, Figure 22(*b*) shows the side view of a concave lens. When we look at a concave lens from the front side, it looks like a piece of transparent spherical glass (round glass) having a 'depression' in the middle [see Figure 23(*b*)]. We can feel the depression in the middle of a concave lens by touching it. Please note that the lenses (convex lens and concave lens) work on the refraction of light through them.

(*a*) Convex lens (*b*) Concave lens

Figure 23. Front view of spherical lenses.

Optical Centre and Principal Axis of a Lens

The centre point of a lens is known as its optical centre. The optical centre of a lens is usually denoted by the letter *C*. In Figure 24, *C* is the optical centre of the convex lens. The optical centre of a lens has a property that a ray of light passing through it does not suffer any deviation and goes straight. The optical centre of a lens is sometimes also denoted by the letter *O*.

The principal axis of a lens is a line passing through the optical centre of the lens and perpendicular

to both the faces of the lens. In Figure 24, the line *F′F* is the principal axis of the convex lens and it passes through the optical centre *C*.

Principal Focus and Focal Length of a Convex Lens

Suppose a parallel beam of light rays falls on a convex lens as shown in Figure 24. These light rays are parallel to one another and also parallel to the axis of the lens. The incident rays pass through the convex lens and get refracted (or bent) according to the laws of refraction. All the rays, after passing through the convex lens, converge at the same point *F* on the other side (right side) of the lens. The point *F* is called principal focus (or just focus) of the convex lens. We can now say that : **The principal focus of a convex lens is a point on its principal axis to which light rays parallel to the principal axis converge after passing through the lens.** In Figure 24, point *F* is the principal focus for the light rays coming from the left side. If the incident light rays fall on the convex lens from the right hand side, they will converge to a point *F′* on the left side of the lens. Thus, *F′* is the second focus of the convex lens. From this discussion we conclude that **a lens has two foci. The two foci of a lens are at equal distances from the optical centre, one on either side of the lens** (The word *'foci'* is the plural form of *'focus'*). The two foci of a lens are usually denoted by the letters *F* and *F′*. Since all the light rays actually pass through the focus of a convex lens, therefore, **a convex lens has real focus.**

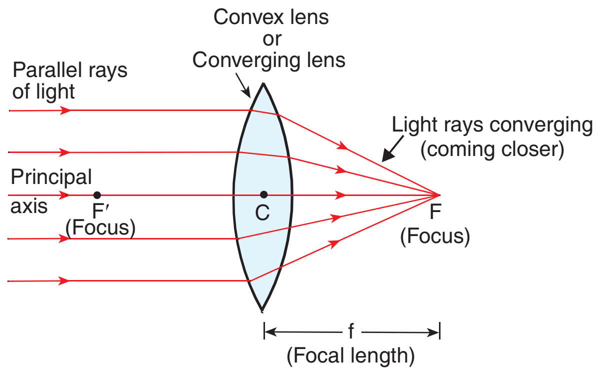


Figure 24. A convex lens converges (brings closer) a parallel beam of light rays to a point *F* on its other side (right side).

We are now in a position to define the focal length of a lens. **The focal length of a lens is the distance between optical centre and principal focus of the lens.** In Figure 24, the distance *CF* is the focal length of the convex lens. It should be noted that the distance *CF′* is also equal to the focal length of the lens. The focal length of a lens is denoted by the letter *f*. The focal length of a lens depends on the refractive index of the glass from which it is made, and the curvature of its two surfaces. Higher the refractive index, shorter will be the focal length. Similarly, more the curvature, shorter is the focal length.

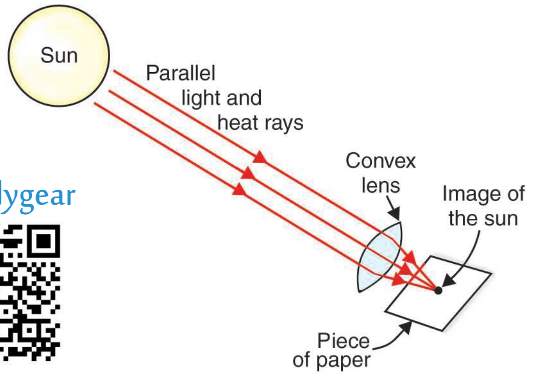


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Figure 25. A convex lens forms a real image of the sun on a piece of paper.

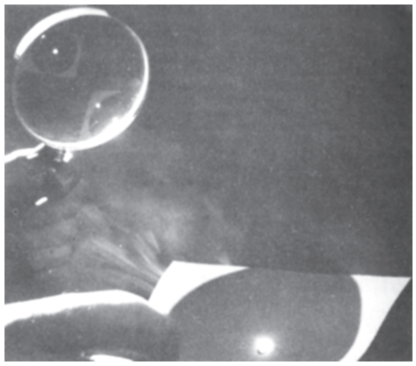


Figure 26. A picture showing the formation of image of the sun by a convex lens.

A convex lens is also known as a converging lens because it converges (brings to a point), a parallel beam of light rays passing through it (see Figure 24). The fact that a convex lens converges (or focusses) parallel rays of light to a single point can be shown as follows : Place a piece of paper on the ground in bright sunshine (see Figure 25). Hold a convex lens some distance above the piece of paper in such a way that a sharp image of the sun is formed on the piece of paper. Here the convex lens is converging the parallel rays of sunlight due to which the sun's rays get concentrated on a small part of the paper (where image is formed). The heat energy of focussed sunlight rays burns a hole in the piece of paper (where sun's image is formed). Please note that we should never look at the sun through a convex lens. It can damage our eyes permanently by focussing a lot of sunlight energy into our eyes.

Principal Focus and Focal Length of a Concave Lens

We have just studied that **a convex lens converges a parallel beam of light rays.** A concave lens has just the opposite effect on such rays of light. **A concave lens diverges a parallel beam of light rays.** The action of a concave lens on a parallel beam of light rays is shown in Figure 27. When a parallel beam of light rays falls on a concave lens, the rays will spread out (or diverge) after passing through the lens. Since the refracted rays are diverging away from one another, they do not actually meet at a point. The diverging rays when produced backwards (as shown by dotted lines in Figure 27) appear to meet at a point *F* on the left side of the lens. To a person on the right hand side, the refracted rays appear to be diverging (or coming) from a point *F* on the principal axis of the concave lens. This point is the principal focus of the concave lens. Thus, **the principal focus of a concave lens is a point on its principal axis from which light rays, originally parallel to the axis, appear to diverge after passing through the concave lens.** In Figure 27, the parallel rays of light appear to be diverging from point *F* after refraction. So, *F* is the principal focus of the concave lens for the light rays coming from the left side. Like a convex lens, a concave lens also has two foci, one on each side of the concave lens. For example, if the parallel rays fall on the concave lens from the right side, then they will appear to diverge from a point *F′*. Thus, *F′* is the second focus of the concave lens. **A concave lens is also known as a diverging lens because it diverges a parallel beam of light rays** (see Figure 27). Since the light rays do not actually pass through the focus of a concave lens, **a concave lens has a virtual focus.** In Figure 27, the distance *CF* is the focal length of concave lens. The distance *CF′* is also equal to the focal length.

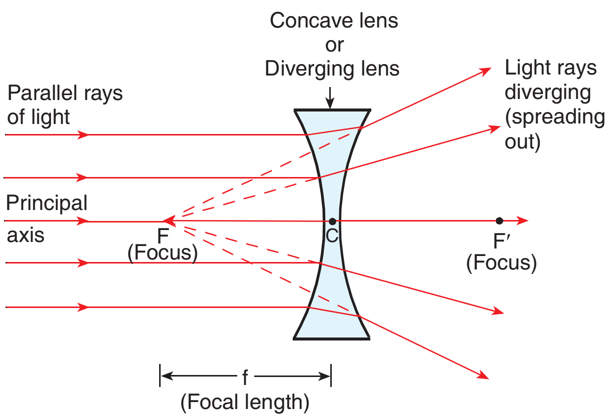


Figure 27. A concave lens diverges (spreads out) a parallel beam of light rays.

A yet another term which is used in the study of spherical lenses is 'aperture'. The aperture of a spherical lens (convex lens or concave lens) is the surface from which refraction of light takes place through the lens. The aperture of spherical lens is represented by its diameter. In most simple words, aperture tells us the size of the lens.

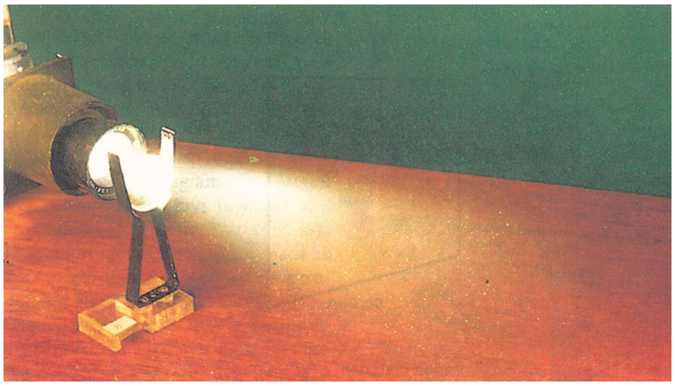


Figure 28. This picture shows that light diverges (or spreads) after passing through a concave lens.

Rules for Obtaining Images Formed by Convex Lenses

When an object is placed in front of a convex lens, an image is formed. **The image is formed at that point where at least two refracted light rays meet (or appear to meet).** To find out the position and nature of the image formed by a convex lens, we will use only those two rays of light (coming from the top of the object) whose paths after refraction from the lens are known to us and easy to draw (the bottom of the object is always assumed to be on the principal axis of the lens). Any two of the following rays of light are usually used to locate the images formed by convex lenses. We call them rules for obtaining images in convex lenses.

Rule 1. **A ray of light which is parallel to the principal axis of a convex lens, passes through its focus after refraction through the lens.** This is shown in Figure 29. Here we have a convex lens *L* and its principal axis is $X'Y'$. Now, a ray of light AD (coming from an object) is parallel to the principal axis of the convex lens. It enters the convex lens and gets refracted (or bends) at point D inside it. After refraction its path changes, it passes through focus F and goes in the direction DX (see Figure 29).

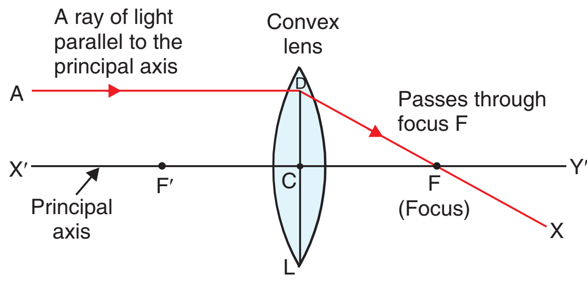


Figure 29.

Rule 2. **A ray of light passing through the optical centre of a convex lens goes straight after refraction through the lens.** It does not get deviated (or bent). This is shown in Figure 30. A ray of light AC is passing through the optical centre C of a convex lens. It goes straight in the direction CY after passing through the lens. It does not get deviated (or bent) from its original path (see Figure 30). Please note that a ray of light going along the principal axis of a convex lens also passes straight through the lens without any deviation. In Figure 30, the principal axis of the convex lens is $X'Y'$. So, a ray of light going along the principal axis $X'Y'$ of this convex lens will also go straight (without bending). We should keep this point in mind because in drawing ray-diagrams, an object is always placed above the principal axis of a lens so that a ray of light coming from its bottom always goes straight through the lens (along the principal axis).

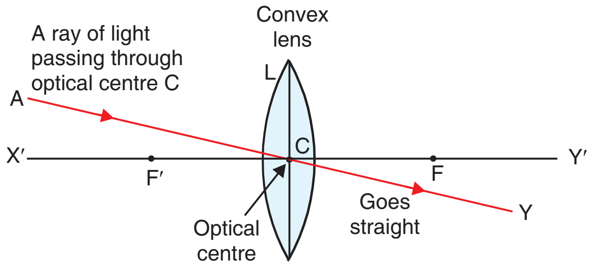


Figure 30.

Rule 3. **A ray of light passing through the focus of a convex lens becomes parallel to its principal axis after refraction through the lens.** This rule is just the reverse case of the first rule and it is shown in Figure 31. Here a ray of light AD (coming from the object) is passing through the focus F' of the convex lens. It enters the convex lens and gets refracted (or bends) at point D inside it. After passing through the convex lens, it becomes parallel to the principal axis of the lens and goes in the direction DX (see Figure 31). Please note that in this case the ray of light has to pass through the second focus F' of the convex lens which lies on its left side.

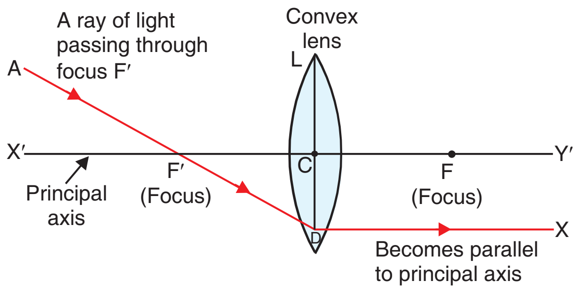


Figure 31.

We should remember the paths of the three rays of light described above because these will be used to construct ray-diagrams for finding the position and nature of images formed by convex lenses. At any given time, we will use only two of the above three types of light rays to find the position of image formed by a convex lens. We will now discuss the various positions at which an object can be placed in front of a convex lens to form images.

FORMATION OF DIFFERENT TYPES OF IMAGES BY A CONVEX LENS

The type of image formed by a convex lens depends on the position of the object in front of the lens. We can place the object at different positions (or distances) from a convex lens to get different types of images. We can place the object :

(*i*) between the optical centre (C) and focus (F') (see Figure 32)
(*ii*) at the focus (F')
(*iii*) between F' and $2F'$
(*iv*) at $2F'$
(*v*) beyond $2F'$, and
(*vi*) at infinity.

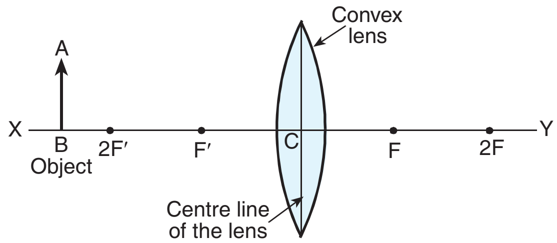


Figure 32.

We will consider all these six positions one by one.

Case 1. Image formed by a convex lens when the object is placed between optical centre and focus (Object between C and F′)

In Figure 33 we have a convex lens with optical centre *C* and two foci *F* and *F′*. The object *AB* has been placed between the optical centre *C* and focus *F′* so that it is at a distance less than the focal length *f* of the convex lens. In other words, the object *AB* is within the focus of the convex lens. A ray of light *AD* starting from the top of the object and parallel to the axis, passes through the other focus *F* after refraction through the lens and goes in the direction *DX*. Another ray of light *AC* passing through the optical centre *C* of the lens goes straight in the direction *CY*. The two refracted rays *DX* and *CY* diverge away from one another and, therefore, they cannot meet at a point on the right side to form a real image. We produce the refracted rays *DX* and *CY* backwards (to the left side) by dotted lines. They appear to meet at point *A′* on the left side. Thus, *A′* is the virtual image of point *A* of the object. To get the complete image of the object, we draw *A′B′* perpendicular to the axis from point *A′*. Thus, *A′B′* is the complete image of object *AB*. When our eye looks into the lens from the right side, it appears as if the light rays are coming from *A′* and *B′* instead of *A* and *B*. Thus, *A′B′* is the virtual image. It is erect, larger than the object and can be seen only by looking through the lens. It is formed on the same side of the lens as the object. From the above discussion we conclude that **when the object is placed within the focus of a convex lens, the image formed is :**

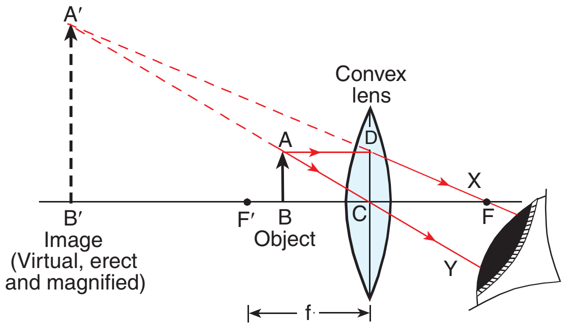


Figure 33. Formation of image by a convex lens when the object is placed between its optical centre (*C*) and focus (*F′*).

(*i*) behind the object (on the left side of lens),

(*ii*) virtual and erect, and

(*iii*) larger than the object (enlarged or magnified).

Figure 33 explains the use of a convex lens as a magnifying glass (or simple microscope). It should be noted that to use a convex lens as a magnifying glass, the object to be viewed should be placed within its focus, so that a magnified and erect image of the object is obtained. That is, the object should be placed at

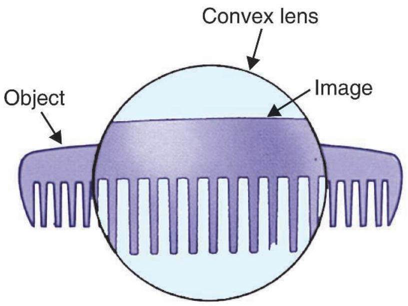


Figure 34. A convex lens is producing a magnified image of the middle part of the comb.

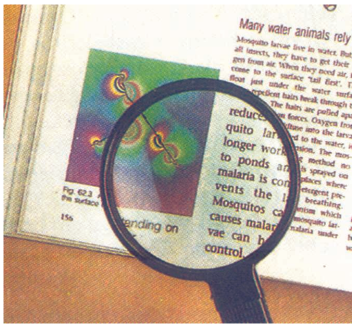


Figure 35. A convex lens being used as a magnifying glass to read the small print of a book.

a distance less than the focal length of the convex lens. For example, if the focal length of a convex lens is 5 centimetres, then the object to be magnified with it should be kept at a distance of less than 5 centimetres from this convex lens. So, if we look at a comb through this convex lens (by keeping the comb within 5 centimetres from it), then the part of comb seen through the convex lens appears much bigger in size than it actually is (see Figure 34). We actually see the magnified image of the comb through the convex lens. Figure 35 shows a convex lens being used as a magnifying glass to read the small print of a book.

Please note that **smaller the focal length of a convex lens, greater will be its magnifying power.** So, we should use a convex lens of short focal length as a magnifying glass. It will produce large magnification and hence the object will appear much bigger when seen through it. For example, a convex lens of 5 cm focal length will have a greater magnifying power than a convex lens of 50 cm focal length. So, we should use the convex lens having a shorter focal length of 5 cm as the magnifying glass. Thus, if we are given two convex lenses of focal lengths 5 cm and 50 cm respectively, then we should prefer to use the convex lens having 5 cm focal length as a magnifying glass (to see small things or read small letters of a dictionary).

Case 2. When the object is placed at the focus of a convex lens (Object at F′)

By saying that the object is at the focus of a convex lens, we mean that the object is at a distance equal to the focal length *f* of the lens. Figure 36 shows an object *AB* placed at the focus *F′* of a convex lens. A parallel ray of light *AD* passes through the focus *F* after refraction and goes along the path *DX*. Another ray *AC* passing through the centre *C* of the lens goes straight in the direction *CY*. The two refracted rays *DX* and *CY* are parallel to one another. These parallel rays will intersect (or meet) at a far off distance to form an image 'at infinity'. And since the image is formed at infinity, it is not possible to show it in our diagram. It will be real and inverted, and highly magnified or highly enlarged. From this discussion we conclude that **when an object is placed at the focus of a convex lens, the image formed is :**

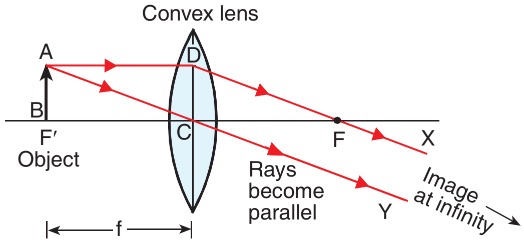


Figure 36. Formation of image by a convex lens when the object is placed at its focus (*F′*)

(*i*) **at infinity,**
(*ii*) **real and inverted,** and
(*iii*) **highly enlarged.**

Suppose we have a convex lens of focal length 5 cm, then its focus (*F′*) will be at a distance of 5 cm from it. So, by saying that the object is placed at the focus of this convex lens, we mean that the object is placed at a distance of 5 cm from the convex lens on its left side. In this case the convex lens converts the diverging rays of light coming from the object into a parallel beam of light rays which form an image at infinity (or very large distance).

Case 3. When the object is between F′ and 2F′ (Object between f and 2f)

By saying that the object is between *F′* and 2*F′*, we mean that the object is at a distance greater than focal length *f* but less than twice the focal length 2*f*. So, whether we say that the object is between *F′* and 2*F′* or between *f* and 2*f*, it means the same thing. Figure 37 shows an object *AB* placed between *F′* and 2*F′* of a convex lens. A ray of light *AD* which is parallel to the principal axis passes through the focus *F* after refraction and goes in the direction *DF* (see Figure 37). Another ray of light *AC* passing through the centre *C* of the lens goes straight and meets the first refracted ray at point *A′* on the right side of the lens. Thus, *A′* is the real image of point *A* of the object. Draw *A′B′* perpendicular to the axis to get the complete image *A′B′*. If we place a screen at *B′*, we can receive the image *A′B′* on the screen. It should be noted that the image is larger than the object (or magnified) and it is formed beyond 2*F* on the right side of the convex lens. From this discussion we conclude that **when an object is placed between *F′* and 2*F′* in front of a convex lens, the image formed is :**

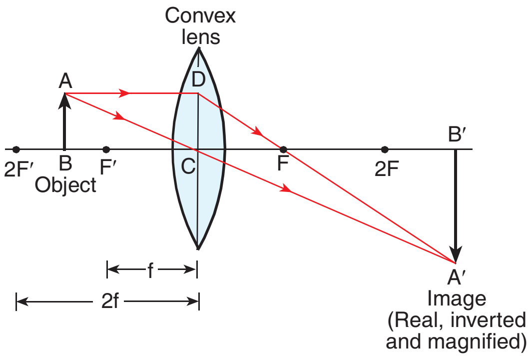


Figure 37. Formation of image by a convex lens when the object is placed between F′ and 2F′ (or between *f* and 2*f*)

(*i*) **beyond 2*F*,**
(*ii*) **real and inverted,** and
(*iii*) **larger than the object (or magnified).**

Figure 37 shows how a convex lens is used as a projection lens for the purpose of projecting a magnified real image of a slide (or a film) on a screen. The slide (or film) is kept between *F′* and 2*F′* of a convex lens and illuminated by a source of light (such as an electric lamp). A magnified image of the picture on the slide (or film) is produced on a screen placed on the other side of the convex lens.

Suppose we have a convex lens of 5 cm focal length, then its focus (*F′*) will be at a distance of 5 cm from it. So, by saying that the object is between *F′* and 2*F′* from this convex lens, we will mean that the object is between 5 cm and 2 × 5 = 10 cm from the convex lens on its left side. And by saying that the image is formed beyond 2*F* on the other side, we mean that the image is formed at a distance of more than 10 cm from convex lens on its right side.

Case 4. When the object is at 2F′ (Object at 2f)

By saying that the object is placed at 2*F′*, we mean that the object is at a distance equal to twice the focal length of the convex lens. In other words, the object is placed at a distance 2*f* from the convex lens. Figure 38 shows an object *AB* placed at a distance 2*f* (twice the focal length), from a convex lens. A ray of light *AD* which is parallel to the principal axis passes through the focus *F* after refraction and goes in the direction *DF* (see Figure 38). Another ray of light *AC* passing through the optical centre *C* of the lens, goes straight and meets the first refracted ray at point *A′*, on the right side of the lens. Thus, *A′* is the real image of point *A* of the object. We draw *A′B′* perpendicular to the axis to get the complete image *A′B′*. We find that the image *A′B′* is formed at 2*F*, at a distance 2*f* on the right side of the convex lens. So, in this case, the object and its image are at equal distance (2*f* each) from the convex lens, but they are on opposite sides of the lens. Thus, **when an object is placed at a distance 2*f* in front of a convex lens, then the image formed is :**

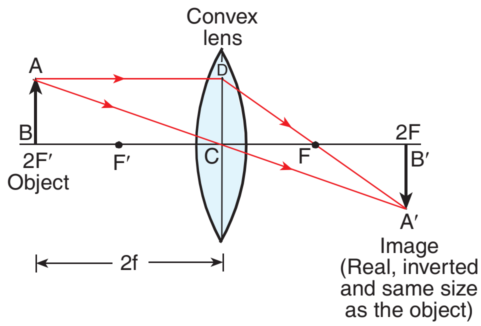


Figure 38. Formation of image by a convex lens when the object is placed at 2*F′* (at a distance 2*f* from the lens).

(*i*) **at a distance 2*f* on the other side of the lens,**
(*ii*) **real and inverted,** and
(*iii*) **of the same size as the object.**

Suppose we have a convex lens of focal length 5 cm, then its focus (*F′*) will be at a distance of 5 cm from it. So, by saying that the object is at 2*F′* of this convex lens, we will mean that the object is at a distance of 2 × 5 = 10 cm from this convex lens on its left side. And by saying that the image is formed at 2*F* on the other side, we will mean that the image is formed at a distance of 2 × 5 = 10 cm from the convex lens on its right side.

Case 5. When the object is beyond 2F′ (Object beyond 2f)

Figure 39 shows an object *AB* placed beyond 2*f* in front of a convex lens. To construct the ray diagram, we first take a ray of light *AD* parallel to the principal axis. After refraction, it will pass through focus *F* and go in the direction *DF*. A second ray of light *AC*, passing through the optical centre *C* will go straight in the direction *CA′*. The two refracted rays meet at point *A′*, so *A′* is the real image of point *A* of the object. To get the complete image, we draw *A′B′* perpendicular to the axis. Thus, *A′B′* is the complete image of the object *AB*. And it is formed between *f* and 2*f* on the other side of the lens. The image is real, inverted and smaller than the object. From the above discussion we conclude that **when an object is placed beyond 2*f* in front of a convex lens, then the image formed is :**

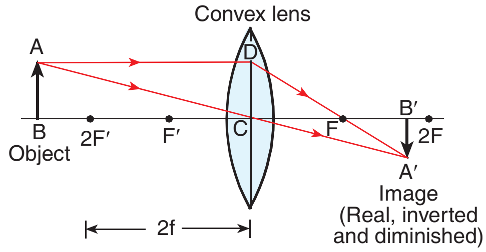


Figure 39. Formation of image by a convex lens when the object is placed beyond 2*F′* (at a distance more than 2*f*).

(*i*) **between *f* and 2*f* on the other side of the lens,**
(*ii*) **real and inverted,** and

(*iii*) smaller than the object (or diminished).

Figure 39 shows the action of a simple camera lens in producing a small, real and inverted image of an object on the film. A simple camera has a convex lens in it. The object to be photographed is at a distance of more than twice the focal length of the convex lens. The convex lens forms a real, inverted and small image (diminished image) of the object on the film.

Suppose we have a convex lens of focal length 5 cm. Then its focus (*F′*) will be at a distance of 5 cm on its left side, and its 2*F′* will be at a distance of 2 × 5 = 10 cm on the left side. So, by saying that the object is beyond 2*F′* of this convex lens, we will mean that the object is beyond 10 cm from convex lens on the left side. And by saying that the image is formed between *F* and 2*F* on the other side, we will mean that the image is formed at a distance between 5 cm and 10 cm from the convex lens on the right hand side of the lens. Figure 40 shows an actual picture of the formation of a real, inverted and diminished image by a convex lens of the filament of a lighted bulb on a screen.

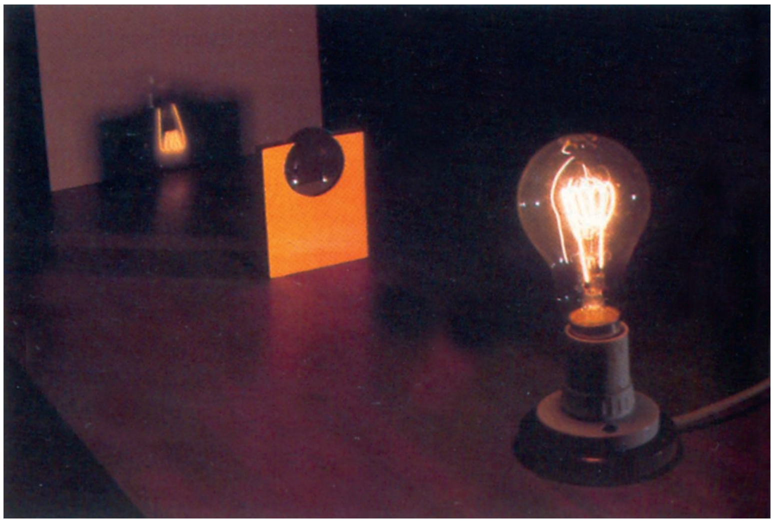


Figure 40. This picture shows a convex lens forming a real, inverted and diminished image of the filament of a light bulb. The bulb is placed at a distance more than twice the focal length from the convex lens.

Case 6. When the object is at infinity

When the object is at a considerable distance, we say that the object is at infinity. Suppose an object *AB* (in the form of an arrow pointing upwards) is at a considerable distance from a convex lens. Since the object is very far off from the lens, it has not been shown in Figure 41. Now, when the object is at infinity, then all the rays from a given point of the object, which are diverging in the beginning, become parallel to one another when they reach the lens after travelling a long distance. So, in Figure 41, we have two rays *AD* and *AC* coming from the same point *A* of the object. The incident rays *AD* and *AC* are parallel to one another but at an angle to the principal axis. The incident ray *AD* gets refracted along *DX*. The second ray *AC* passing through the optical centre C of the lens goes straight along *CY* and meets the first refracted ray at *A′*. Thus, *A′* is the real image of the top point *A* of the object. We draw *A′B′* perpendicular to the axis from *A′*. Thus, *A′B′* is the complete image of the object *AB* placed at infinity. It is clear from Figure 41, that the image is formed at the focus of the lens. It is real, inverted and much smaller than the object. From this discussion we conclude that **when an object is at infinity from a convex lens, then the image formed is :**

(*i*) at the focus,

(*ii*) real and inverted, and

(*iii*) much smaller than the object (or highly diminished).

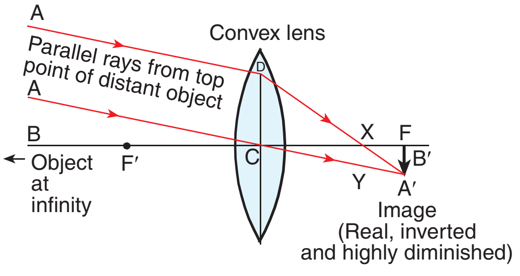


Figure 41. Formation of image by a convex lens when the object is placed at infinity (very large distance) from the lens.

Figure 41 represents the action of the objective lens of a telescope. Because in a telescope, the objective lens is a convex lens which forms a real, inverted and diminished image of the distant object at its focus. Please note that when the object kept at infinity in front of a convex lens is assumed to be a big arrow pointing upwards, then its image is formed at focus according to the ray-diagram shown in Figure 41. If, however, the object kept at infinity in front of a convex lens is round in shape (like the sun), then its image is formed at the focus according to the ray-diagram shown in Figure 24 on page 231.

To Determine the Focal Length of a Convex Lens Quickly but Approximately

When the object is at infinity, the distance of image from the lens will be equal to the focal length of the lens. This fact is used to find out the focal length of a convex lens quickly but approximately. Let us see how this is done.

To determine the focal length of a convex lens, we put the convex lens in a holder (or stand) and keep it in front of a distant object like a window (or a tree), so that the rays coming from the window pass through it. A cardboard screen is put behind the lens. We change the distance of the screen from the convex lens until a clear inverted image of the window is formed on the screen. Measure the distance of the screen from the lens with a scale. This distance will be the focal length of convex lens. For example, if the image of a distant window is formed at a distance of 20 cm from a convex lens, then the focal length of this convex lens will be 20 cm. And before we end this discussion, here is a summary of the images formed by a convex lens.

Summary of the Images Formed by a Convex Lens

Position of object	*Position of image*	*Size of image*	*Nature of image*
1. Between f and lens	On the same side as object	Enlarged	Virtual and erect
2. At f (at focus)	At infinity	Highly enlarged	Real and inverted
3. Between f and $2f$	Beyond $2f$	Enlarged	Real and inverted
4. At $2f$	At $2f$	Same size as object	Real and inverted
5. Beyond $2f$	Between f and $2f$	Diminished	Real and inverted
6. At infinity	At f (at focus)	Highly diminished	Real and inverted

Uses of Convex Lenses

(*i*) Convex lenses are used in spectacles to correct the defect of vision called hypermetropia (or long-sightedness).
(*ii*) Convex lens is used for making a simple camera.
(*iii*) Convex lens is used as a magnifying glass (or magnifying lens) (by palmists, watchmakers, etc.).
(*iv*) Convex lenses are used in making microscopes, telescopes and slide projectors (or film projectors).

We will now solve some problems based on the formation of images by a convex lens.

Sample Problem 1. Where should an object be placed so that a real and inverted image of the same size is obtained by a convex lens ?

(*a*) at the focus of the lens.

(*b*) at twice the focal length.

(*c*) at infinity.

(*d*) between the optical centre of lens and its focus. **(NCERT Book Question)**

Answer. (*b*) at twice the focal length.

Sample Problem 2. A convex lens has a focal length of 20 cm. Where should an object be placed in front of this convex lens so as to obtain an image which is real, inverted and same size as the object ? Draw the ray diagram to show the formation of image in this case. **(NCERT Book Question)**

Solution. When the image formed by a convex lens is real, inverted and *same size* as the object, then the distance of the object from the lens is $2f$ (twice the focal length). Here,

Focal length, $f = 20$ cm

So, $2f = 2 \times 20$ cm

$= 40$ cm

Thus, the object should be placed at a distance of 40 cm in front of the convex lens. (Please draw the ray diagram yourself).

Sample Problem 3. An object is placed at the following distances from a convex lens of focal length 10 cm :

(*a*) 8 cm (*b*) 15 cm (*c*) 20 cm (*d*) 25 cm

Which position of the object will produce :

(*i*) a diminished real image ?
(*ii*) a magnified real image ?
(*iii*) a magnified virtual image ?
(*iv*) an image of the same size as the object ?

Solution. The focal length of this convex lens is 10 cm. This means that $f = 10$ cm.

(*i*) A diminished real image is formed by a convex lens when the object is beyond $2f$, that is beyond 2×10 cm or beyond 20 cm. In this problem, the distance which is beyond 20 cm (or more than 20 cm) is 25 cm. Thus, 25 cm position of the object will produce a diminished real image.

(*ii*) A magnified real image is formed by a convex lens when the object is between f and $2f$, that is between 10 cm and 20 cm. In this problem, the distance which is between 10 cm and 20 cm is 15 cm. So, 15 cm position of the object will produce a magnified real image.

(*iii*) A magnified virtual image is formed by a convex lens when the object is within focus, at a distance less than the focal length f or less than 10 cm. In this problem, the distance which is less than the focal length of 10 cm is 8 cm. Thus, 8 cm position of object will produce a magnified virtual image.

(*iv*) An image of the same size as the object is formed by a convex lens when the object is at $2f$ or twice the focal length from lens. Here $2f = 2 \times 10 = 20$ cm. So, the 20 cm position of the object will produce an image of the same size as the object.

If this question is asked in the examination, then the answer can just be written as :

(*i*) 25 cm (*ii*) 15 cm (*iii*) 8 cm (*iv*) 20 cm

Sample Problem 4. Which of the following lens would you prefer to use while reading small letters found in a dictionary ?

(*a*) A convex lens of focal length 50 cm.
(*b*) A concave lens of focal length 50 cm.
(*c*) A convex lens of focal length 5 cm.
(*d*) A concave lens of focal length 5 cm. **(NCERT Book Question)**

Answer. (*c*) A convex lens of focal length 5 cm.

Before we go further and discuss sign convention for lenses and the lens formula, **please answer the following questions :**

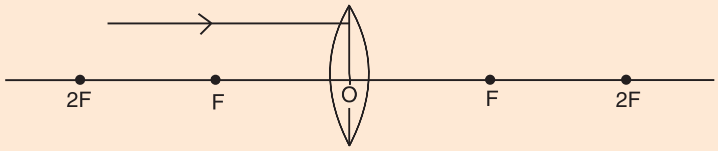
Very Short Answer Type Questions

1. Name the lens which can concentrate sun's rays to a point and burn a hole in a piece of paper.
2. Give the usual name for the following :
   A point inside a lens through which the light passes undeviated.
3. A 1 cm high object is placed at a distance of $2f$ from a convex lens. What is the height of the image formed ?
4. If the image formed by a convex lens is of the same size as that of the object, what is the position of the image with respect to the lens ?
5. If an object is placed at the focus of a convex lens, where is the image formed ?
6. Where should an object be placed in order to use a convex lens as a magnifying glass ?
7. Where should an object be placed in front of a convex lens so as to obtain its virtual, erect and magnified image ?
8. Where should an object be placed in front of a convex lens so as to obtain its real, inverted and magnified image ?

9. For what position of an object a real, diminished image is formed by a convex lens ?

10. If an object is at a considerable distance (or infinity) in front of a convex lens, where is the image formed ?

11. Draw the given diagram in your answer book and complete it for the path of a ray of light after passing through the lens.



12. What type of lens would you use as a magnifying glass ? How close must the object be to the lens ?

13. Name two factors on which the focal length of a lens depends.

14. State any two uses of convex lenses.

15. Fill in the following blanks with suitable words :

(*a*) Parallel rays of light are refracted by a convex lens to a point called the...........

(*b*) The image in a convex lens depends upon the distance of the...............from the lens.

Short Answer Type Questions

16. What is a lens ? Distinguish between a convex lens and a concave lens. Which of the two is a converging lens : convex lens or concave lens ?

17. (*a*) Explain with the help of a diagram, why the convex lens is also called a converging lens.

(*b*) Define principal axis, principal focus and focal length of a convex lens.

18. (*a*) Explain with the help of a diagram, why the concave lens is also called a diverging lens.

(*b*) Define the principal focus of a concave lens.

19. Draw a ray diagram to show the formation of a real magnified image by a convex lens. (In your sketch the position of object and image with respect to the principal focus of lens should be shown clearly).

20. Describe with the help of a ray-diagram, the formation of image of a finite object placed in front of a convex lens between f and $2f$. Give two characteristics of the image so formed.

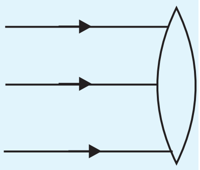
21. Describe with the help of a ray diagram the nature, size and position of the image formed when an object is placed in front of a convex lens between focus and optical centre. State three characteristics of the image formed.

22. An object is placed at a distance equal to $2f$ in front of a convex lens. Draw a labelled ray diagram to show the formation of image. State two characteristics of the image formed.

23. Describe with the help of a ray-diagram, the size, nature and position of the image formed by a convex lens when an object is placed beyond $2f$ in front of the lens.

24. Describe with the help of a ray diagram the nature, size and position of the image formed when an object is placed at infinity (considerable distance) in front of a convex lens. State three characteristics of the image so formed.

25. (*a*) What type of lens is shown in the diagram on the right ? What will happen to the parallel rays of light ? Show by completing the ray diagram.



(*b*) Your eye contains a convex lens. Why is it unwise to look at the sun ?

26. Where must the object be placed for the image formed by a converging lens to be :

(*a*) real, inverted and smaller than the object ?

(*b*) real, inverted and same size as the object ?

(*c*) real, inverted and larger than the object ?

(*d*) virtual, upright and larger than the object ?

27. Draw a diagram to show how a converging lens held close to the eye acts as a magnifying glass. Why is it usual to choose a lens of short focal length for this purpose rather than one of long focal length ?

28. How could you find the focal length of a convex lens rapidly but approximately ?

Long Answer Type Questions

29. (*a*) With the help of a labelled diagram explain how a convex lens converges a beam of parallel light rays. Mark the principal axis, optical centre, principal focus and focal length of the convex lens on the diagram.

(*b*) State whether convex lens has a real focus or a virtual focus.
(*c*) List some things that convex lens and concave mirror have in common.

30. (*a*) With the help of a labelled diagram, explain how a concave lens diverges a beam of parallel light rays. Mark the principal axis, optical centre, principal focus and focal length of the concave lens on the diagram.
(*b*) State whether concave lens has a real focus or a virtual focus.
(*c*) List some things that concave lens and convex mirror have in common.

31. Draw ray diagrams to represent the nature, position and relative size of the image formed by a convex lens for the object placed :
(*a*) at $2F_1$,
(*b*) between F_1 and the optical centre *O* of the lens.
Which of the above two cases shows the use of convex lens as a magnifying glass ? Give reasons for your choice.

32. (*a*) An object is placed well outside the principal focus of a convex lens. Draw a ray diagram to show how the image is formed, and say whether the image is real or virtual.
(*b*) What is the effect on the size and position of the image of moving the object (*i*) towards the lens, and (*ii*) away from the lens ?

33. (*a*) Explain what is meant by a virtual, magnified image.
(*b*) Draw a ray diagram to show the formation of a virtual magnified image of an object by a convex lens. In your diagram, the position of object and image with respect to the principal focus should be shown clearly.
(*c*) Three convex lenses are available having focal lengths of 4 cm, 40 cm and 4 m respectively. Which one would you choose as a magnifying glass and why ?

34. (*a*) Explain why, a real image can be projected on a screen but a virtual image cannot.
(*b*) Draw a ray diagram to show the formation of a real diminished image of an object by a convex lens. In your diagram, the position of object and image with respect to the principal focus should be shown clearly.
(*c*) Name one simple optical instrument in which the above arrangement of convex lens is used.

Multiple Choice Questions (MCQs)

35. A convex lens has a focal length of 10 cm. At which of the following position should an object be placed so that this convex lens may act as a magnifying glass ?
(*a*) 15 cm (*b*) 7 cm (*c*) 20 cm (*d*) 25 cm

36. Which one of the following materials cannot be used to make a lens ?
(*a*) Water (*b*) Glass (*c*) Plastic (*d*) Clay

37. A small bulb is placed at the focal point of a converging lens. When the bulb is switched on, the lens produces :
(*a*) a convergent beam of light (*b*) a divergent beam of light
(*c*) a parallel beam of light (*d*) a patch of coloured light

38. An illuminated object is placed at a distance of 20 cm from a converging lens of focal length 15 cm. The image obtained on the screen is :
(*a*) upright and magnified (*b*) inverted and magnified
(*c*) inverted and diminished (*d*) upright and diminished

39. An object is placed between *f* and 2*f* of a convex lens. Which of the following statements correctly describes its image ?
(*a*) real, larger than the object (*b*) erect, smaller than the object
(*c*) inverted, same size as object (*d*) virtual, larger than the object

40. Which of the following can make a parallel beam of light when light from a bulb falls on it ?
(*a*) concave mirror as well as concave lens (*b*) convex mirror as well as convex lens
(*c*) concave mirror as well as convex lens (*d*) convex mirror as well as concave lens

41. In order to obtain a real image twice the size of the object with a convex lens of focal length 15 cm, the object distance should be :
(*a*) more than 5 cm but less than 10 cm (*b*) more than 10 cm but less than 15 cm
(*c*) more than 15 cm but less than 30 cm (*d*) more than 30 cm but less than 60 cm

42. A converging lens is used to produce an image of an object on a screen. What change is needed for the image to be formed nearer to the lens ?

(*a*) increase the focal length of the lens

(*b*) insert a diverging lens between the lens and the screen

(*c*) increase the distance of the object from the lens

(*d*) move the object closer to the lens

43. A convex lens of focal length 8 cm forms a real image of the same size as the object. The distance between object and its image will be :

(*a*) 8 cm (*b*) 16 cm (*c*) 24 cm (*d*) 32 cm

44. A virtual, erect and magnified image of an object is to be obtained with a convex lens. For this purpose, the object should be placed :

(*a*) between 2F and infinity (*b*) between F and optical centre

(*c*) between F and 2F (*d*) at F

45. A burning candle whose flame is 1.5 cm tall is placed at a certain distance in front of a convex lens. An image of candle flame is received on a white screen kept behind the lens. The image of flame also measures 1.5 cm. If f is the focal length of convex lens, the candle is placed :

(*a*) at f (*b*) between f and $2f$ (*c*) at $2f$ (*d*) beyond $2f$

Questions Based on High Order Thinking Skills (HOTS)

46. A lens of focal length 12 cm forms an erect image three times the size of the object. The distance between the object and image is :

(*a*) 8 cm (*b*) 16 cm (*c*) 24 cm (*d*) 36 cm

47. If an object is placed 21 cm from a converging lens, the image formed is slightly smaller than the object. If the object is placed 19 cm from the lens, the image formed is slightly larger than the object. The approximate focal length of the lens is :

(*a*) 5 cm (*b*) 10 cm (*c*) 18 cm (*d*) 20 cm

48. An object is placed at the following distances from a convex lens of focal length 15 cm :

(*a*) 35 cm (*b*) 30 cm (*c*) 20 cm (*d*) 10 cm

Which position of the object will produce :

(*i*) a magnified real image ?

(*ii*) a magnified virtual image ?

(*iii*) a diminished real image ?

(*iv*) an image of same size as the object ?

49. When an object is placed at a distance of 36 cm from a convex lens, an image of the same size as the object is formed. What will be the nature of image formed when the object is placed at a distance of :

(*a*) 10 cm from the lens ? (*b*) 20 cm from the lens ?

50. (*a*) Draw a diagram to show how a converging lens focusses parallel rays of light.

(*b*) How would you alter the above diagram to show how a converging lens can produce a beam of parallel rays of light.

ANSWERS

2. Optical centre **3.** 1 cm **4.** At 2F (at twice the focal length) **5.** At infinity (very large distance) **6.** At a distance less than focal length **7.** Within focus **8.** Between F and 2F (or Between f and $2f$)

9. Beyond 2F **10.** At focus (F) **15.** (*a*) focus (*b*) object **26.** (*a*) Beyond 2F (*b*) At 2F (*c*) Between F and 2F (*d*) Between F and Optical centre **33.** (*c*) Convex lens having 4 cm focal length ; It will produce greatest magnification **34.** (*c*) A simple camera **35.** (*b*) **36.** (*d*) **37.** (*c*) **38.** (*b*) **39.** (*a*) **40.** (*c*) **41.** (*c*) **42.** (*c*) **43.** (*d*) **44.** (*b*) **45.** (*c*) **46.** (*b*) **47.** (*b*) **48.** (*i*) 20 cm (*ii*) 10 cm (*iii*) 35 cm (*iv*) 30 cm **49.** (*a*) Virtual, erect and magnified (*b*) Real, inverted and magnified **50.** (*b*) Place a source of light (say, a lighted bulb) at the focus of the converging lens.

SIGN CONVENTION FOR SPHERICAL LENSES

These days New Cartesian Sign Convention is used for measuring the various distances in the ray diagrams of spherical lenses (convex lenses and concave lenses). According to the New Cartesian Sign Convention :

(*i*) All the distances are measured from the *optical centre* of the lens.
(*ii*) The distances measured in the *same* direction as that of incident light are taken as *positive*.
(*iii*) The distances measured *against* the direction of incident light are taken as *negative*.
(*iv*) The distances measured *upward* and perpendicular to the principal axis are taken as *positive*.
(*v*) The distances measured *downward* and perpendicular to the principal axis are taken as *negative.*

The New Cartesian Sign Convention for lenses is shown in Figure 42. **The object is always placed on the left side of the lens** (as shown in Figure 42), so that the direction of incident light is from left to right. All the distances measured from the optical centre (*C*) of the lens to the right side will be considered positive (because they will be in the same direction as the incident light). On the other hand, all the distances measured from the optical centre (*C*) of the lens to the left side are considered negative (because they are measured against the direction of incident light). On the basis of New Cartesian Sign Convention, **the focal length of a convex lens is considered positive** (and written with a plus sign). On the other hand, **the focal length of a concave lens is considered negative** (and written with a minus sign). Please note that the sign convention for *spherical lenses* is very similar to the sign convention for *spherical mirrors* which we have already studied.

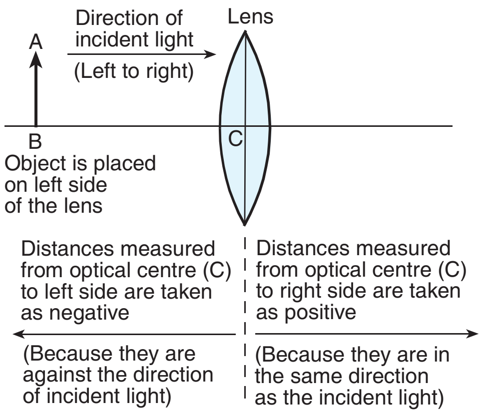


Figure 42. Sign convention for lenses.

Lens Formula

A formula which gives the relationship between image distance (*v*), object distance (*u*), and focal length (*f*) of a lens is known as the lens formula. The lens formula can be written as :

$$\frac{1}{v}-\frac{1}{u}=\frac{1}{f}$$

where v = image distance

u = object distance

and f = focal length

This lens formula applies to both types of spherical lenses : convex lenses as well as concave lenses. Please note that the lens formula differs from the mirror formula only in the sign between $\frac{1}{v}$ and $\frac{1}{u}$. The mirror formula is $\frac{1}{v}+\frac{1}{u}=\frac{1}{f}$ whereas the lens formula is $\frac{1}{v}-\frac{1}{u}=\frac{1}{f}$. It is clear that the mirror formula has a plus sign (+) between $\frac{1}{v}$ and $\frac{1}{u}$ whereas the lens formula has a minus sign (–) between $\frac{1}{v}$ and $\frac{1}{u}$. The values of *v* and *u* should be substituted in the lens formula with their proper signs.

Magnification Produced by Lenses

The size of image formed by a lens depends on the position of the object from the lens. For example, the image formed by a convex lens can be smaller than the object, equal to the object or bigger than the object. The size of the image relative to the object is given by the linear magnification. **The linear magnification is the ratio of the height of the image to the height of the object.** That is :

$$\text{Magnification} = \frac{\text{height of image}}{\text{height of object}}$$

or $m = \frac{h_2}{h_1}$

where m = magnification

h_2 = height of image

and h_1 = height of object

We will now write another formula for the magnification produced by a lens in terms of the image distance and object distance.

The linear magnification produced by a lens is equal to the ratio of image distance to the object distance. That is :

$$\text{Magnification} = \frac{\text{Image distance}}{\text{Object distance}}$$

or $m = \frac{v}{u}$

where m = magnification

v = image distance

and u = object distance

It should be noted that this second magnification formula for lenses differs only in sign from the magnification formula for mirrors. The magnification formula for the mirrors is, $m = -\frac{v}{u}$ whereas that for lenses is, $m = \frac{v}{u}$. It is clear that the magnification formula for mirrors has a minus (–) sign but the magnification formula for lenses has no minus sign.

If the magnification m has a positive value, the image is virtual and erect. And if the magnification m has a negative value, the image will be real and inverted. Since a convex lens can form virtual images as well as real images, therefore, the magnification produced by a convex lens can be either positive or negative. A concave lens, however, forms only virtual images, so the magnification produced by a concave lens is always positive. A convex lens can form images which are smaller than the object, equal to the object or bigger than the object, therefore, the magnification (m) produced by a convex lens can be less than 1, equal to 1 or more than 1. On the other hand, a concave lens forms images which are always smaller than the object, so the magnification (m) produced by a concave lens is always less than 1.

Numerical Problems Based On Convex Lenses

We will now solve some numerical problems based on convex lenses by using the lens formula and the magnification formulae. Here are some examples.

Sample Problem 1. A convex lens of focal length 10 cm is placed at a distance of 12 cm from a wall. How far from the lens should an object be placed so as to form its real image on the wall ?

Solution. Here, the real image is formed on the wall which is at a distance of 12 cm from the convex lens. This means that the distance of image from the convex lens or image distance will be 12 cm. Since a real image is formed on the right side of the lens, so this image distance will be positive.

Now, Image distance, $v = +12$ cm (A real image)

Object distance, $u = ?$ (To be calculated)

Focal length, $f = +10$ cm (It is a convex lens)

Putting these values in the lens formula :

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$$

we get : $$\frac{1}{12} - \frac{1}{u} = \frac{1}{10}$$

$$\frac{1}{12} - \frac{1}{10} = \frac{1}{u}$$

$$\frac{5-6}{60} = \frac{1}{u}$$

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

So, Object distance, $u = -60$ cm

Thus, the object should be placed at a distance of 60 cm in front of the convex lens. The minus sign shows that the object is on the left side of the lens.

Sample Problem 2. If an object of 7 cm height is placed at a distance of 12 cm from a convex lens of focal length 8 cm, find the position, nature and height of the image.

Solution. First of all we will find out the position of the image. By the position of image we mean the distance of image from the lens.

Here, Object distance, $u = -12$ cm (It is to the left of lens)

Image distance, $v = ?$ (To be calculated)

Focal length, $f = +8$ cm (It is a convex lens)

Putting these values in the lens formula :

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$$

we get : $$\frac{1}{v} - \frac{1}{-12} = \frac{1}{8}$$

or $$\frac{1}{v} + \frac{1}{12} = \frac{1}{8}$$

$$\frac{1}{v} = \frac{1}{8} - \frac{1}{12}$$

$$\frac{1}{v} = \frac{3-2}{24}$$

$$\frac{1}{v} = \frac{1}{24}$$

So, Image distance, $v = +24$ cm

Thus, the image is formed at a distance of 24 cm from the convex lens. The plus sign for image distance shows that the image is formed on the right side of the convex lens. Only a real and inverted image is formed on the right side of a convex lens, so the image formed is real and inverted.

Let us calculate the magnification now. We know that for a lens :

Magnification, $m = \frac{v}{u}$

Here, Image distance, $v = 24$ cm

Object distance, $u = -12$ cm

So, $$m = \frac{24}{-12}$$

or $$m = -2$$

Since the value of magnification is more than 1 (it is 2), so the image is larger than the object or magnified. The minus sign for magnification shows that the image is formed below the principal axis. Hence the image is real and inverted. Let us calculate the size of the image by using the formula :

$$m = \frac{h_2}{h_1}$$

Here, Magnification, $m = -2$ (Found above)

Height of object, $h_1 = +7$ cm (Measured upwards)

Height of image, $h_2 = ?$ (To be calculated)

Now, putting these values in the above formula, we get :

$$-2 = \frac{h_2}{7}$$

or $$h_2 = -2 \times 7$$

Thus, Height of image, $h_2 = -14$ cm

Thus, the height or size of the image is 14 cm. The minus sign shows that this height is in the downward direction, that is, the image is formed below the axis. Thus, the image is real and inverted.

Sample Problem 3. The magnification produced by a spherical lens is +2.5. What is the :

(*a*) nature of image ?

(*b*) nature of lens ?

Answer. (*a*) When the magnification is positive, then the image is virtual and erect. In this case, the magnification has a positive sign, so the nature of image is virtual and erect.

(*b*) The value of magnification given here is 2.5 (which is more than 1). So, the image is larger than the object or magnified. A virtual, erect and magnified image can be formed only by a convex lens, therefore, the nature of lens is convex.

We are now in a position to **answer the following questions and problems :**

Very Short Answer Type Questions

1. Write the formula for a lens connecting image distance (v), object distance (u) and the focal length (f). How does the lens formula differ from the mirror formula ?

2. Write down the magnification formula for a lens in terms of object distance and image distance. How does this magnification formula for a lens differ from the corresponding formula for a mirror ?

3. What is the nature of the image formed by a convex lens if the magnification produced by the lens is +3 ?

4. What is the nature of the image formed by a convex lens if the magnification produced by the lens is, – 0.5 ?

5. What is the position of image when an object is placed at a distance of 10 cm from a convex lens of focal length 10 cm ?

6. Describe the nature of image formed when an object is placed at a distance of 30 cm from a convex lens of focal length 15 cm.

7. At what distance from a converging lens of focal length 12 cm must an object be placed in order that an image of magnification 1 will be produced ?

Short Answer Type Questions

8. State and explain the New Cartesian Sign Convention for spherical lenses.

9. An object 4 cm high is placed at a distance of 10 cm from a convex lens of focal length 20 cm. Find the position, nature and size of the image.

10. A small object is so placed in front of a convex lens of 5 cm focal length that a virtual image is formed at a distance of 25 cm. Find the magnification.

11. Find the position and nature of the image of an object 5 cm high and 10 cm in front of a convex lens of focal length 6 cm.

12. Calculate the focal length of a convex lens which produces a virtual image at a distance of 50 cm of an object placed 20 cm in front of it.

13. An object is placed at a distance of 100 cm from a converging lens of focal length 40 cm.

(*i*) What is the nature of image ?

(*ii*) What is the position of image ?

14. A convex lens produces an inverted image magnified three times of an object placed at a distance of 15 cm from it. Calculate focal length of the lens.

15. A converging lens of focal length 5 cm is placed at a distance of 20 cm from a screen. How far from the lens should an object be placed so as to form its real image on the screen ?

16. An object 5 cm high is held 25 cm away from a converging lens of focal length 10 cm. Find the position, size and nature of the image formed. Also draw the ray diagram.

17. At what distance should an object be placed from a convex lens of focal length 18 cm to obtain an image at 24 cm from it on the other side ? What will be the magnification produced in this case ?

18. An object 2 cm tall is placed on the axis of a convex lens of focal length 5 cm at a distance of 10 m from the optical centre of the lens. Find the nature, position and size of the image formed. Which case of image formation by convex lenses is illustrated by this example ?

19. The filament of a lamp is 80 cm from a screen and a converging lens forms an image of it on a screen, magnified three times. Find the distance of the lens from the filament and the focal length of the lens.

20. An erect image 2.0 cm high is formed 12 cm from a lens, the object being 0.5 cm high. Find the focal length of the lens.

21. A convex lens of focal length 0.10 m is used to form a magnified image of an object of height 5 mm placed at a distance of 0.08 m from the lens. Calculate the position, nature and size of the image.

22. A convex lens of focal length 6 cm is held 4 cm from a newspaper which has print 0.5 cm high. By calculation, determine the size and nature of the image produced.

23. Determine how far an object must be placed in front of a converging lens of focal length 10 cm in order to produce an erect (upright) image of linear magnification 4.

24. A lens of focal length 20 cm is used to produce a ten times magnified image of a film slide on a screen. How far must the slide be placed from the lens ?

25. An object placed 4 cm in front of a converging lens produces a real image 12 cm from the lens.

(*a*) What is the magnification of the image ?

(*b*) What is the focal length of the lens ?

(*c*) Draw a ray diagram to show the formation of image. Mark clearly F and 2F in the diagram.

Long Answer Type Questions

26. (*a*) An object 2 cm tall stands on the principal axis of a converging lens of focal length 8 cm. Find the position, nature and size of the image formed if the object is :

(*i*) 12 cm from the lens

(*ii*) 6 cm from the lens

(*b*) State one practical application each of the use of such a lens with the object in position (*i*) and (*ii*).

27. (*a*) An object 3 cm high is placed 24 cm away from a convex lens of focal length 8 cm. Find by calculations, the position, height and nature of the image.

(*b*) If the object is moved to a point only 3 cm away from the lens, what is the new position, height and nature of the image ?

(*c*) Which of the above two cases illustrates the working of a magnifying glass ?

28. (*a*) Find the nature, position and magnification of the images formed by a convex lens of focal length 0.20 m if the object is placed at a distance of :

(*i*) 0.50 m (*ii*) 0.25 m (*iii*) 0.15 m

(*b*) Which of the above cases represents the use of convex lens in a film projector, in a camera, and as a magnifying glass ?

Multiple Choice Questions (MCQs)

29. A spherical mirror and a spherical lens each have a focal length of, –15 cm. The mirror and the lens are likely to be :

(*a*) both concave.

(*b*) both convex.

(*c*) the mirror is concave but the lens is convex.

(*d*) the mirror is convex but the lens is concave.

30. Linear magnification produced by a convex lens can be :

(*a*) less than 1 or more than 1

(*b*) less than 1 or equal to 1
(*c*) more than 1 or equal to 1
(*d*) less than 1, equal to 1 or more than 1

31. Magnification produced by a concave lens is always :
(*a*) more than 1 (*b*) equal to 1 (*c*) less than 1 (*d*) more than 1 or less than 1

32. In order to obtain a magnification of, – 3 (minus 3) with a convex lens, the object should be placed :
(*a*) between optical centre and F (*b*) between F and 2F
(*c*) at 2F (*d*) beyond 2F

33. A convex lens produces a magnification of +5. The object is placed :
(*a*) at focus (*b*) between *f* and 2*f*
(*c*) at less than *f* (*d*) beyond 2*f*

34. If a magnification of, –1 (minus 1) is obtained by using a converging lens, then the object has to be placed :
(*a*) within *f* (*b*) at 2*f*
(*c*) beyond 2*f* (*d*) at infinity

35. To obtain a magnification of, – 0.5 with a convex lens, the object should be placed :
(*a*) at F (*b*) between optical centre and F
(*c*) between F and 2F (*d*) beyond 2F

36. An object is 0.09 m from a magnifying lens and the image is formed 36 cm from the lens. The magnification produced is :
(*a*) 0.4 (*b*) 1.4 (*c*) 4.0 (*d*) 4.5

37. To obtain a magnification of, –2 with a convex lens of focal length 10 cm, the object should be placed :
(*a*) between 5 cm and 10 cm (*b*) between 10 cm and 20 cm
(*c*) at 20 cm (*d*) beyond 20 cm

38. A convex lens of focal length 15 cm produces a magnification of + 4. The object is placed :
(*a*) at a distance of 15 cm (*b*) between 15 cm and 30 cm
(*c*) at less than 15 cm (*d*) beyond 30 cm

39. If a magnification of, –1 is to be obtained by using a converging lens of focal length 12 cm, then the object must be placed :
(*a*) within 12 cm (*b*) at 24 cm (*c*) at 6 cm (*d*) beyond 24 cm

40. In order to obtain a magnification of, – 0.75 with a convex lens of focal length 8 cm, the object should be placed :
(*a*) at less than 8 cm (*b*) between 8 cm and 16 cm
(*c*) beyond 16 cm (*d*) at 16 cm

Questions Based on High Order Thinking Skills (HOTS)

41. A student did an experiment with a convex lens. He put an object at different distances 25 cm, 30 cm, 40 cm, 60 cm and 120 cm from the lens. In each case he measured the distance of the image from the lens. His results were 100 cm, 24 cm, 60 cm, 30 cm and 40 cm, respectively. Unfortunately his results are written in wrong order.
(*a*) Rewrite the image distances in the correct order.
(*b*) What would be the image distance if the object distance was 90 cm ?
(*c*) Which of the object distances gives the biggest image ?
(*d*) What is the focal length of this lens ?

42. A magnifying lens has a focal length of 100 mm. An object whose size is 16 mm is placed at some distance from the lens so that an image is formed at a distance of 25 cm in front of the lens.
(*a*) What is the distance between the object and the lens ?
(*b*) Where should the object be placed if the image is to form at infinity ?

43. A lens forms a real image 3 cm high of an object 1 cm high. If the separation of object and image is 15 cm, find the focal length of the lens.

44. An object 50 cm tall is placed on the principal axis of a convex lens. Its 20 cm tall image is formed on the screen placed at a distance of 10 cm from the lens. Calculate the focal length of the lens.

ANSWERS

3. Virtual and erect **4.** Real and inverted **5.** At infinity **6.** Real and inverted. **7.** 24 cm **9.** $v = -20$ cm ; The image is 20 cm in front of convex lens (on its left side) ; Virtual and erect; 8 cm **10.** +6 **11.** $v = +15$ cm ; The image is formed 15 cm behind the convex lens (on its right side); Real and inverted **12.** 33.3 cm **13.** (*i*) Real and inverted (*ii*) $v = +66.6$ cm ; The image is formed 66.6 cm behind the convex lens (on its right side) **14.** 11.2 cm **15.** 6.6 cm **16.** $v = +16.6$ cm ; The image is 16.6 cm behind the convex lens ; 3.3 cm ; Real and inverted **17.** 72 cm from convex lens ; $-\frac{1}{3}$ **18.** Real and inverted ; $v = +5$ cm ; The image is formed 5 cm behind the convex lens ; 0.01 cm **19.** 20 cm ; + 15 cm **20.** + 4.0 cm **21.** $v = -0.40$ m ; The position of image is 0.40 m from the lens on the same side as the object (on the left of lens) ; The nature of image is virtual and erect ; The size of image is 25 mm **22.** 1.5 cm high ; Virtual, erect and magnified (3 times) **23.** 7.5 cm **24.** 220 cm behind the lens **25.** (*a*) 3 (*b*) + 3 cm **26.** (*a*) (*i*) $v = +24$ cm ; The image is 24 cm behind the lens ; Real and inverted ; 4 cm (*ii*) $v = -24$ cm ; The image is 24 cm in front of the lens ; Virtual and erect ; 8 cm (*b*) (*i*) Used in film projector (*ii*) Used as a magnifying glass **27.** (*a*) $v = +12$ cm ; The image is formed 12 cm behind the lens ; 1.5 cm high ; Real and inverted (*b*) $v = -4.8$ cm ; The image is formed 4.8 cm in front of the lens (on its left side); 4.8 cm high ; Virtual and erect (*c*) Case *b* **28.** (*a*) (*i*) $v = +0.33$ m ; The image is formed 0.33 m behind the lens ; $m = -0.66$; Real and inverted (*ii*) $v = +1.00$ m ; The image is formed 1.00 m behind the lens ; $m = -4.0$; Real and inverted (*iii*) $v = -0.60$ m ; The image is formed 0.60 m in front of the lens ; $m = +4.0$; Virtual and erect (*b*) Film projector : Case (*ii*) ; Camera : Case (*i*) ; Magnifying glass : case (*iii*) **29.** (*a*) **30.** (*d*) **31.** (*c*) **32.** (*b*) **33.** (*c*) **34.** (*b*) **35.** (*d*) **36.** (*c*) **37.** (*b*) **38.** (*c*) **39.** (*b*) **40.** (*c*) **41.** (*a*) 100 cm ; 60 cm ; 40 cm ; 30 cm ; 24 cm (*b*) 25.7 cm (*c*) 25 cm (*d*) 20 cm **42.** (*a*) 7.14 cm (*b*) 10 cm **43.** + 2.81 cm **44.** 7.14 cm

RULES FOR OBTAINING IMAGES FORMED BY CONCAVE LENSES

We have already studied some rules for the formation of images by convex lenses. There are similar rules for constructing ray-diagrams for obtaining images with concave lenses. These are given below.

Rule 1. **A ray of light which is parallel to the principal axis of a concave lens, appears to be coming from its focus after refraction through the lens.** This is shown in Figure 43. Here we have a concave lens *L* and its principal axis is *X′Y′*. A ray of light *AD* parallel to the principal axis enters the concave lens, gets refracted at point *D* and goes in the direction *DX*. To a person looking into the concave lens from the right side, the refracted ray of light *DX* appears to be coming from the focus *F* of concave lens situated on its left side (as shown by dotted line) (see Figure 43).

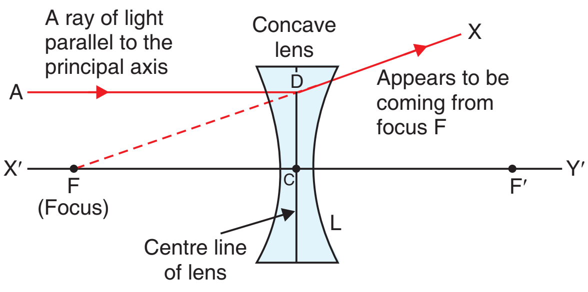


Figure 43.

Rule 2. **A ray of light passing through the optical centre of a concave lens goes straight after passing through the lens.** This is shown in Figure 44. The ray of light *AC* is passing through the optical centre *C* of concave lens. This ray of light goes straight in the direction *CY* after passing through the concave lens. It does not bend at all. Please note that a ray of light along the principal axis of a conave lens also goes straight.

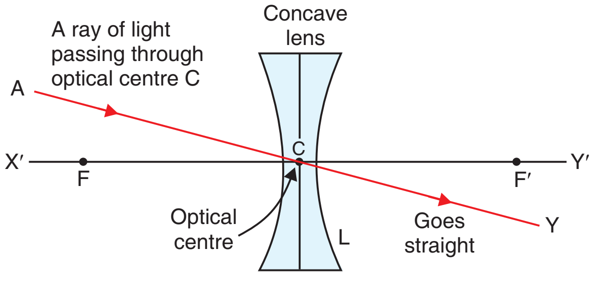


Figure 44.

Rule 3. **A ray of light going towards the focus of a concave lens, becomes parallel to its principal axis after refraction through the lens.** This rule is just the reverse case of the first rule and it is shown in Figure 45. Here a ray of light *AD* (coming from the object) is going towards the focus *F′* of the concave lens. It enters the concave lens and gets refracted (or bends) at point *D*. After passing through the concave lens, it becomes parallel to the principal axis of the lens and goes in the direction *DX* (see Figure 45).

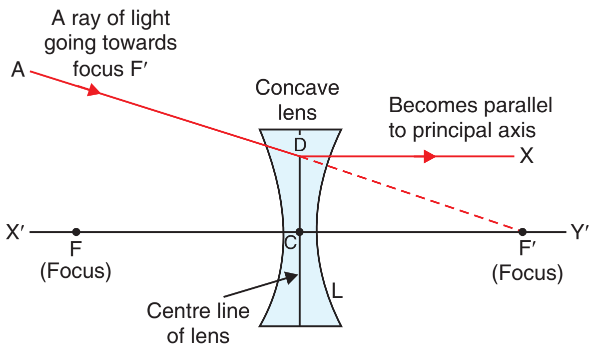


Figure 45.

At any given time, we will use only two of the above three types of light rays to draw the ray-diagrams to find the position of image formed by a concave lens.

Please note that **no matter where the object is placed in front of a concave lens, the concave lens always forms a virtual, erect and diminished image of the object.** When the distance of an object from a concave lens is changed, then only the position and size of the image changes. There are two main positions of an object in the case of a concave lens from the point of view of position and size of image. The object can be :

(*i*) anywhere between optical centre (*C*) and infinity, and

(*ii*) at infinity.

We will discuss both these cases one by one. Let us first describe the formation of image by a concave lens when the object is anywhere between optical centre (*C*) and infinity.

Formation of Image by a Concave Lens

In Figure 46, we have a concave lens with optical centre *C*. And *F* is the focus of this lens. The arrow *AB* pointing upwards represents the object. Now, we want to find out the position, nature and size of the image of this object which will be formed by the concave lens. The method used for obtaining the images with concave lenses is very similar to the one we have used in the case of convex lenses. This is as follows.

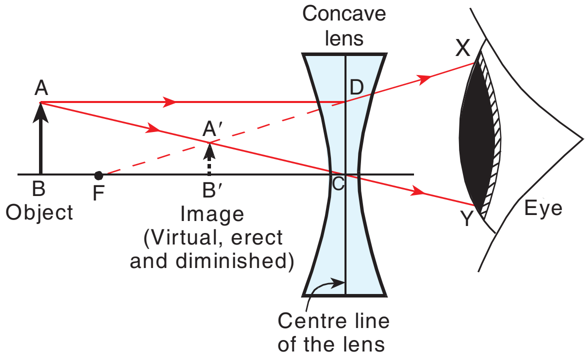


Figure 46. Diagram to show the formation of image by a concave lens.

Starting from the upper point *A* of the object *AB*, we draw a line *AD* parallel to the principal axis. Now, according to the first rule of image formation, this parallel ray *AD* should appear to be coming from focus *F* after refraction. So, we join *DF* by a dotted line and produce *FD* upwards in the direction *DX* by a solid line. Now, *DX* is the first refracted ray which appears to be coming from focus *F* of the concave lens.

We have now to draw a second ray of light starting from the same point *A* and passing through the optical centre *C*. For this we join the points *A* and *C* by a line. Thus, the line *AC* represents a ray of light passing through the optical centre *C* of the lens. Now, according to the second rule of image formation, this ray should go straight. So, we extend the line *AC* further in the direction *CY*. Thus, *CY* is the second refracted ray. The two refracted rays *DX* and *CY* are diverging rays and appear to intersect at point *A′* on the left side of the lens, only when they are produced backwards. So, to an eye placed on the right side of the concave lens (as shown in Figure 46), the top of arrow appears to be at *A′*. Thus, *A′* is the virtual image of the top point *A* of the object. To get the complete image of the object, we draw *A′B′* perpendicular to the axis from point *A′*. Thus, *A′B′* is the image of the object *AB*. The image is virtual, erect and smaller than the object. It is situated between

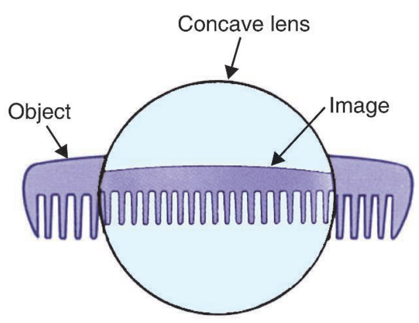


Figure 47. A concave lens always produces a smaller image than the object. Here a concave lens is producing a smaller image of the middle part of the comb.

the optical centre and focus (in front of the concave lens). From the above discussion we conclude that : **When an object is placed anywhere between optical centre (*C*) and infinity in front of a concave lens, the image formed is :**

(*i*) **between optical centre (*C*) and focus (*F*),**

(*ii*) **virtual and erect,** and

(*iii*) **diminished (smaller than the object).**

If we move the object more and more away from the optical centre of the concave lens, the image becomes smaller and smaller in size and moves away from the lens towards its focus. And when the object is at infinity, the image is formed at the focus (see Figure 27 on page 232). From this discussion we conclude that : **When an object is at infinity from a concave lens, the image formed is :**

(*i*) **at focus (*F*),**

(*ii*) **virtual and erect,** and

(*iii*) **highly diminished (much smaller than the object).**

And before we conclude this discussion, here is a summary of the images formed by a concave lens.

Summary of the Images Formed by a Concave Lens

Position of object	*Position of image*	*Size of image*	*Nature of image*
1. Anywhere between optical centre (*C*) and infinity.	Between optical centre (*C*) and focus (*F*)	Diminished	Virtual and erect
2. At infinity	At focus (*F*)	Highly diminished	Virtual and erect

How to Distinguish Between a Convex Lens and a Concave Lens Without Touching Them

We keep the lens close to the page of a book and see the image of the writing of the book through it. If the letters of the book appear enlarged, then it is a convex lens; and if the letters appear diminished, then it is a concave lens. This is due to the fact that when an object is within the focus of a convex lens, it produces an enlarged image. But a concave lens produces a diminished image for all positions of the object. So, in this case the object (the book) has been placed within focus of the lens.

Uses of Concave Lenses

(*i*) Concave lenses are used in spectacles to correct the defect of vision called myopia (or short-sightedness).

(*ii*) Concave lens is used as eye-lens in Galilean telescope.

(*iii*) Concave lenses are used in combination with convex lenses to make high quality lens systems for optical instruments.

(*iv*) Concave lens is used in wide-angle spyhole in doors.

Before we go further and discuss the mirror formula and magnification formulae for a concave lens, **please answer the following questions :**

Very Short Answer Type Questions

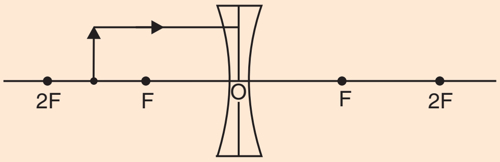
1. If the image formed by a lens is always diminished and erect, what is the nature of the lens ?
2. Copy and complete the diagram below to show what happens to the rays of light when they pass through the concave lens :

3. Which type of lenses are :
(*a*) thinner in the middle than at the edges ?
(*b*) thicker in the middle than at the edges ?

4. A ray of light is going towards the focus of a concave lens. Draw a ray diagram to show the path of this ray of light after refraction through the lens.

5. (*a*) What type of images can a convex lens make ?
(*b*) What type of image is always made by a concave lens ?

6. Take down this figure into your answer book and complete the path of the ray.



7. Fill in the following blanks with suitable words :
(*a*) A convex lens...........rays of light, whereas a concave lens............rays of light.
(*b*) Lenses refract light to form images : a.............lens can form both real and virtual images, but a diverging lens forms only..............images.

8. Things always look small on viewing through a lens. What is the nature of the lens ?

Short Answer Type Questions

9. An object lies at a distance of 2*f* from a concave lens of focal length *f*. Draw a ray-diagram to illustrate the image formation.

10. Show by drawing a ray-diagram that the image of an object formed by a concave lens is virtual, erect and diminished.

11. Give the position, size and nature of image formed by a concave lens when the object is placed :
(*a*) anywhere between optical centre and infinity.
(*b*) at infinity.

12. Which type of lens is : (*a*) a converging lens, and which is (*b*) a diverging lens ? Explain your answer with diagrams.

13. With the help of a diagram, explain why the image of an object viewed through a concave lens appears smaller and closer than the object.

14. How would a pencil look like if you saw it through (*a*) a concave lens, and (*b*) a convex lens ? (Assume the pencil is close to the lens). Is the image real or virtual ?

Long Answer Type Questions

15. (*a*) An object is placed 10 cm from a lens of focal length 5 cm. Draw the ray diagrams to show the formation of image if the lens is (*i*) converging, and (*ii*) diverging.
(*b*) State one practical use each of convex mirror, concave mirror, convex lens and concave lens.

16. (*a*) Construct ray diagrams to illustrate the formation of a virtual image using (*i*) a converging lens, and (*ii*) a diverging lens.
(*b*) What is the difference between the two images formed above ?

Multiple Choice Questions (MCQs)

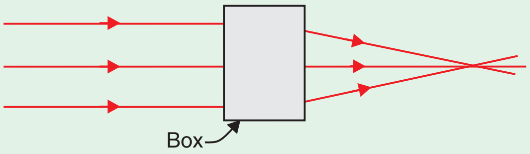
17. A diverging lens is used in :
(*a*) a magnifying glass
(*b*) a car to see objects on rear side
(*c*) spectacles for the correction of short sight
(*d*) a simple camera

18. When an object is kept at any distance in front of a concave lens, the image formed is always :
(*a*) virtual, erect and magnified
(*b*) virtual, inverted and diminished.
(*c*) virtual, erect and diminished
(*d*) virtual, erect and same size as object

19. When sunlight is concentrated on a piece of paper by a spherical mirror or lens, then a hole can be burnt in it. For doing this, the paper must be placed at the focus of :

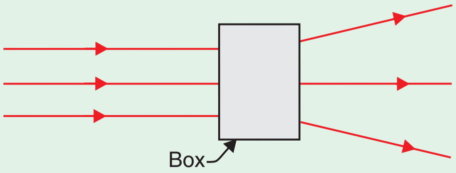
(*a*) either a convex mirror or convex lens (*b*) either a concave mirror or concave lens
(*c*) either a concave mirror or convex lens (*d*) either a convex mirror or concave lens

20. A beam of parallel light rays is incident through the holes on one side of a box and emerges out through the holes on its opposite side as shown in the diagram below :



Which of the following could be inside the box ?
(*a*) a rectangular glass block (*b*) a concave lens
(*c*) a convex lens (*d*) a glass prism

21. A beam of light is incident through the holes on one side of a box and emerges out through the holes on its opposite side as shown in the following figure :



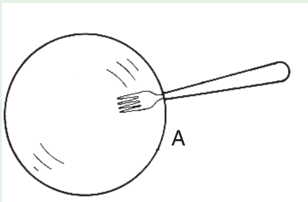
The box contains :
(*a*) a glass prism (*b*) a concave lens
(*c*) a convex lens (*d*) a parallel-sided glass slab

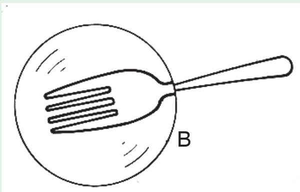
22. Which of the following can form a virtual image which is always smaller than the object ?
(*a*) a plane mirror (*b*) a convex lens
(*c*) a concave lens (*d*) a concave mirror

Questions Based on High Order Thinking Skills (HOTS)

23. When an object is placed 10 cm in front of lens *A*, the image is real, inverted, magnified and formed at a great distance. When the same object is placed 10 cm in front of lens *B*, the image formed is real, inverted and same size as the object.
(*a*) What is the focal length of lens *A* ?
(*b*) What is the focal length of lens *B* ?
(*c*) What is the nature of lens *A* ?
(*d*) What is the nature of lens *B* ?

24. When a fork is seen through lenses *A* and *B* one by one, it appears as shown in the diagrams. What is the nature of (*i*) lens *A*, and (*ii*) lens *B* ? Give reason for your answer.





25. What kind of lens can form :
(*a*) an inverted magnified image ?
(*b*) an erect magnified image ?
(*c*) an inverted diminished image ?
(*d*) an erect diminished image ?

ANSWERS

1. Concave lens **3.** (*a*) Concave lenses (*b*) Convex lenses **5.** (*a*) Real and Virtual (*b*) Virtual **7.** (*a*) converges; diverges (*b*) converging ; virtual **8.** Concave lens **14.** (*a*) Smaller (*b*) Bigger ; Virtual **16.** (*b*) The virtual image formed by a converging lens is magnified whereas that formed by a diverging lens is diminished **17.** (*c*) **18.** (*c*) **19.** (*c*) **20.** (*c*) **21.** (*b*) **22.** (*c*) **23.** (*a*) 10 cm (*b*) 5 cm (*c*) Convex lens (*d*) Convex lens **24.** (*i*) Concave lens (*ii*) Convex lens **25.** (*a*) Convex lens (*b*) Convex lens (*c*) Convex lens (*d*) Concave lens.

LENS FORMULA AND MAGNIFICATION FORMULAE FOR A CONCAVE LENS

The lens formula for a concave lens is the same as that for a convex lens, which is :

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$$

The magnification formulae for a concave lens are also just the same as that for convex lens, which are :

$$m = \frac{h_2}{h_1} \quad \text{and} \quad m = \frac{v}{u}$$

Numerical Problems Based on Concave Lenses

We will now solve some numerical problems based on concave lenses by using the lens formula and the magnification formulae. Here are some examples.

Sample Problem 1. An object is placed at a distance of 50 cm from a concave lens of focal length 20 cm. Find the nature and position of the image.

Solution. First of all we will find out the position of image which is given by the image distance v.

Here, Object distance, $u = -50$ cm (It is to the left of lens)

Image distance, $v = ?$ (To be calculated)

Focal length, $f = -20$ cm (It is a concave lens)

Putting these values in the lens formula :

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$$

we get : $$\frac{1}{v} - \frac{1}{-50} = \frac{1}{-20}$$

or $$\frac{1}{v} + \frac{1}{50} = -\frac{1}{20}$$

or $$\frac{1}{v} = -\frac{1}{20} - \frac{1}{50}$$

or $$\frac{1}{v} = \frac{-5-2}{100}$$

or $$\frac{1}{v} = \frac{-7}{100}$$

or $$v = -\frac{100}{7}$$

So, Image distance, $v = -14.3$ cm

Thus, the image is formed at a distance of 14.3 cm from the concave lens. The minus sign for image distance shows that the image is formed on the left side of the concave lens. We know that a concave lens always forms a virtual and erect image, so the nature of image is virtual and erect.

Sample Problem 2. An object placed 50 cm from a lens produces a virtual image at a distance of 10 cm in front of the lens. Draw a diagram to show the formation of image. Calculate focal length of the lens and magnification produced.

Solution. First of all we will find out the focal length of the lens. We know that the object is always placed in front of the lens on the left side, so the object distance is always taken as negative. Here the image is also formed in front of the lens on the left side, so the image distance will also be negative. Thus,

Object distance, $u = -50$ cm (To the left of lens)

Image distance, $v = -10$ cm (To the left of lens)

Focal length, $f = ?$ (To be calculated)

Putting these values in the lens formula :

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$$

we get :

$$\frac{1}{-10} - \frac{1}{-50} = \frac{1}{f}$$

$$-\frac{1}{10} + \frac{1}{50} = \frac{1}{f}$$

$$\frac{-5+1}{50} = \frac{1}{f}$$

$$-\frac{4}{50} = \frac{1}{f}$$

$$f = -\frac{50}{4}$$

So, Focal length, $f = -12.5$ cm

The minus sign for focal length shows that it is a concave lens. Please draw the ray diagram yourself.

We will now calculate the magnification produced by concave lens. We know that for a lens :

$$\text{Magnification, } m = \frac{v}{u}$$

Here, Image distance, $v = -10$ cm

And, Object distance, $u = -50$ cm

So,

$$m = \frac{-10}{-50}$$

$$m = +\frac{1}{5}$$

$$m = +0.2$$

Thus, the magnification produced by this concave lens is + 0.2. Since the value of magnification is less than 1 (it is 0.2), therefore, the image is smaller than the object (or diminished). The plus sign for the magnification shows that the image is virtual and erect.

Sample Problem 3. The magnification produced by a spherical lens is + 0.75. What is the :

(*a*) nature of image ?

(*b*) nature of lens ?

Answer. (*a*) When the magnification is positive, the nature of image is virtual and erect. In this case, the magnification is positive, so the nature of image is virtual and erect.

(*b*) The value of magnification given here is 0.75 (which is less than 1), so the image is smaller than the object or diminished. A virtual, erect and diminished image can be formed only by a concave lens, so the nature of lens is concave.

We are now in position to **answer the following questions and problems :**

Very Short Answer Type Questions

1. The lens *A* produces a magnification of, – 0.6 whereas lens *B* produces a magnification of + 0.6.
   (*a*) What is the nature of lens *A* ?
   (*b*) What is the nature of lens *B* ?
2. A 50 cm tall object is at a very large distance from a diverging lens. A virtual, erect and diminished image of the object is formed at a distance of 20 cm in front of the lens. How much is the focal length of the lens ?

Short Answer Type Questions

3. An object is placed at a distance of 4 cm from a concave lens of focal length 12 cm. Find the position and nature of the image.

4. A concave lens of focal length 15 cm forms an image 10 cm from the lens. How far is the object placed from the lens ? Draw the ray-diagram.

5. An object 60 cm from a lens gives a virtual image at a distance of 20 cm in front of the lens. What is the focal length of the lens ? Is the lens converging or diverging ? Give reasons for your answer.

6. A concave lens of 20 cm focal length forms an image 15 cm from the lens. Compute the object distance.

7. A concave lens has focal length 15 cm. At what distance should the object from the lens be placed so that it forms an image at 10 cm from the lens ? Also find the magnification produced by the lens.

8. Calculate the image distance for an object of height 12 mm at a distance of 0.20 m from a concave lens of focal length 0.30 m, and state the nature and size of the image.

9. A concave lens has a focal length of 20 cm. At what distance from the lens a 5 cm tall object be placed so that it forms an image at 15 cm from the lens ? Also calculate the size of the image formed.

10. An object is placed 20 cm from (*a*) a converging lens, and (*b*) a diverging lens, of focal length 15 cm. Calculate the image position and magnification in each case.

11. A 2.0 cm tall object is placed 40 cm from a diverging lens of focal length 15 cm. Find the position and size of the image.

Long Answer Type Questions

12. (*a*) Find the position and size of the virtual image formed when an object 2 cm tall is placed 20 cm from :

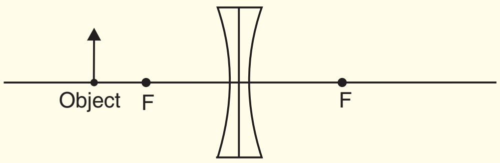
(*i*) a diverging lens of focal length 40 cm.

(*ii*) a converging lens of focal length 40 cm.

(*b*) Draw labelled ray diagrams to show the formation of images in cases (*i*) and (*ii*) above (The diagrams may not be according to scale).

13. (*a*) A small object is placed 150 mm away from a diverging lens of focal length 100 mm.

(*i*) Copy the figure below and draw rays to show how an image is formed by the lens.



(*ii*) Calculate the distance of the image from the lens by using the lens formula.

(*b*) The diverging lens in part (*a*) is replaced by a converging lens also of focal length 100 mm. The object remains in the same position and an image is formed by the converging lens. Compare two properties of this image with those of the image formed by the diverging lens in part (*a*).

Multiple Choice Questions (MCQs)

14. A concave lens produces an image 20 cm from the lens of an object placed 30 cm from the lens. The focal length of the lens is :

(*a*) 50 cm (*b*) 40 cm (*c*) 60 cm (*d*) 30 cm

15. Only one of the following applies to a concave lens. This is :

(*a*) focal length is positive
(*b*) image distance can be positive or negative
(*c*) height of image can be positive or negative
(*d*) image distance is always negative

16. The magnification produced by a spherical mirror and a spherical lens is + 0.8.

(*a*) The mirror and lens are both convex
(*b*) The mirror and lens are both concave
(*c*) The mirror is concave but the lens is convex
(*d*) The mirror is convex but the lens is concave

17. The magnification produced by a spherical lens and a spherical mirror is + 2.0.

(*a*) The lens and mirror are both concave
(*b*) The lens and mirror are both convex
(*c*) The lens is convex but the mirror is concave
(*d*) The lens is concave but the mirror is convex

Questions Based on High Order Thinking Skills (HOTS)

18. A camera fitted with a lens of focal length 50 mm is being used to photograph a flower that is 5 cm in diameter. The flower is placed 20 cm in front of the camera lens.

(*a*) At what distance from the film should the lens be adjusted to obtain a sharp image of the flower ?

(*b*) What would be the diameter of the image of the flower on the film ?

(*c*) What is the nature of camera lens ?

19. An object is 2 m from a lens which forms an erect image one-fourth (exactly) the size of the object. Determine the focal length of the lens. What type of lens is this ?

20. An image formed on a screen is three times the size of the object. The object and screen are 80 cm apart when the image is sharply focussed.

(*a*) State which type of lens is used.

(*b*) Calculate focal length of the lens.

ANSWERS

1. (*a*) Convex lens (*b*) Concave lens **2.** 20 cm **3.** $v = -3$ cm ; The image is formed at 3 cm in front of the concave lens (on its left side) ; Virtual and erect **4.** $u = -30$ cm ; The object is at 30 cm from the concave lens on its left side **5.** $f = -30$ cm ; Diverging lens : Negative sign of focal length **6.** 60 cm on left side of lens **7.** $u = -30$ cm ; $m = +0.33$ **8.** $v = -0.12$ m ; Virtual and erect ; 7.2 mm tall **9.** $u = -60$ cm ; 1.25 cm **10.** (*a*) $v = +60$ cm; $m = -3$ (*b*) $v = -8.5$ cm; $m = +0.42$; **11.** $v = -10.90$ cm ; 0.54 cm tall **12.** (*a*) (*i*) $v = -13.3$ cm ; 1.33 cm tall (*ii*) $v = -40$ cm ; 4 cm tall **13.** (*a*) (*ii*) $v = -60$ mm (*b*) $v = +300$ mm ; The image formed by converging lens is real, inverted and magnified (2 times). It is formed behind the converging lens. On the other hand, the image formed by diverging lens is virtual, erect and diminished. It is formed in front of the diverging lens. **14.** (*c*) **15.** (*d*) **16.** (*d*) **17.** (*c*) **18.** (*a*) $v = +6.66$ cm ; The film should be at a distance of 6.66 cm behind the camera lens (*b*) 1.66 cm (*c*) Convex lens **19.** $f = -66.7$ cm ; Concave lens **20.** (*a*) Convex lens (*b*) + 15 cm

POWER OF A LENS

A convex lens converges the light rays falling on it whereas a concave lens diverges the light rays falling on it. **The power of a lens is a measure of the degree of convergence or divergence of light rays falling on it.** If a convex lens converges a beam of parallel light rays more strongly by focussing them closer to the optical centre, it is said to have greater power (than another convex lens which focusses the same parallel light rays at a greater distance from the optical centre). Similarly, a concave lens which diverges a parallel beam of light rays more strongly is said to have a greater diverging power than another concave lens which diverges the light rays less strongly. *The power of a lens depends on its focal length*. We can define the power of a lens as follows :

The power of a lens is defined as the reciprocal of its focal length in metres.

Thus, $$\text{Power of a lens} = \frac{1}{\text{focal length of the lens } (\textit{in metres})}$$

or $$P = \frac{1}{f}$$

where P = Power of the lens

and f = focal length of the lens (*in metres*)

Since the power of a lens is *inversely proportional* to its focal length, therefore, **a lens of short focal length has more power whereas a lens of long focal length has less power**. For example, a lens of 5 cm focal length will have more power than a lens of 20 cm focal length. A more powerful lens is one that bends the light rays more ; and has a shorter focal length (see Figure 48).

The unit of the power of a lens is dioptre, which is denoted by the letter D. **One dioptre is the power of a lens whose focal length is 1 metre.** The power of a lens can be measured directly by using an instrument called dioptremeter. It is used by opticians to measure the power of spectacle lenses (see Figure 49). A convex lens has a positive focal length, so **the power of a convex lens is positive** (and written with a

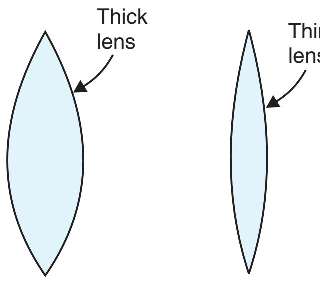


Figure 48. A thick lens has short focal length but more power. A thin lens has large focal length but less power.

Figure 49. An optician measuring the power of a spectacle lens by using an instrument called dioptremeter.

+ sign). A concave lens has a negative focal length, so **the power of a concave lens is negative** [and written with a minus (–) sign]. Since a convex lens is also known as a converging lens and a concave lens is also known as a diverging lens, we can also say that the power of a converging lens is positive whereas the power of a diverging lens is negative. When an optician, after testing the eyes of a person, prescribes the corrective lenses of say, + 2.0 D and + 1.5 D for the left eye and right eye, respectively, he actually refers to the power of convex lenses required for making eye-glasses or spectacles to make him see clearly.

In order to calculate the power of a lens, we need its focal length in metres. In many problems, the focal length of a lens is usually given to us in 'centimetres'. So, to calculate the power of such a lens, we should first convert the focal length of the lens into 'metres' by dividing the given 'centimetre' value by 100. If, however, the focal length is already in metres, then there is no need to change it. We will now solve some problems based on the calculation of power of lenses.

Sample Problem 1. A convex lens is of focal length 10 cm. What is its power ?

Solution. Here, the focal length of the lens is given in 'centimetres' so to calculate the power of this lens, we should first convert the focal length into 'metres' because our formula uses the focal length in 'metres'.

Now, $$10 \text{ cm} = \frac{10}{100} \text{ m}$$

$$= 0.1 \text{ m}$$

So, Focal length, $f = 0.1$ m (A convex lens has positive focal length)

Now, putting this value of focal length in the formula for the power of a lens :

$$P = \frac{1}{f \text{ (in metres)}}$$

we get : $$P = \frac{1}{0.1}$$

or $$P = \frac{1 \times 10}{1}$$

Thus, Power, $P = +10$ dioptres (or +10 D)

Thus, the power of this convex lens is +10 dioptres which is also written as +10 D. The plus sign with the power indicates that it is a converging lens or convex lens.

Sample Problem 2. A person having a myopic eye uses a concave lens of focal length 50 cm. What is the power of the lens ?

Solution. Here we have a concave lens. Now, the focal length of a concave lens is considered negative, so it is to be written with a minus sign.

Thus, Focal length, $f = -50$ cm

$$= -\frac{50}{100} \text{ m}$$

$$= -0.5 \text{ m}$$

Now, Power, $P = \dfrac{1}{f \text{ (in metres)}}$

$$P = \frac{1}{-0.5}$$

$$P = -\frac{1 \times 10}{5}$$

$P = -2$ dioptres (or -2 D)

Thus, the power of this concave lens is, – 2 dioptres which can also be written as, – 2 D. The minus sign with the power indicates that it is a diverging lens or concave lens.

Sample Problem 3. A thin lens has a focal length of, – 25 cm. What is the power of the lens and what is its nature ?

Solution. Since the focal length is negative, it is a concave lens or diverging lens. Calculate the power yourself as shown in the above question. The power will be, – 4 D.

Sample Problem 4. The power of a lens is + 2.5 D. What kind of lens it is and what is its focal length ?

Solution. The power of this lens has positive sign, so it is a convex lens. Now,

Power, $P = \dfrac{1}{f \text{ (in metres)}}$

So, $+2.5 = \dfrac{1}{f}$

and $f = \dfrac{1}{2.5}$ m

$$= \frac{1}{2.5} \times 100 \text{ cm}$$

So, Focal length, $f = 40$ cm (or + 40 cm)

Sample Problem 5. A lens has a power of, – 2.5 D. What is the focal length and nature of the lens ?

Solution. The power of this lens has minus sign, so it is a concave lens. Calculate the focal length yourself as shown in the above question. The focal length will be, – 40 cm.

Sample Problem 6. Find the power of a concave lens of focal length 2 m. **(NCERT Book Question)**

Solution. A concave lens has negative focal length, so it is to be written with a minus sign. Thus,

Focal length, $f = -2$ m (It is in metres)

Now, Power, $P = \dfrac{1}{f \text{ (in metres)}}$

$$P = \frac{1}{-2}$$

$$P = -0.5 \text{ D}$$

Thus, the power of this concave lens is, – 0.5 dioptre.

Sample Problem 7. A convex lens forms a real and inverted image of a needle at a distance of 50 cm from the lens. If the image is of the same size as the needle, where is the needle placed in front of the lens? Also, find the power of the lens. **(NCERT Book Question)**

Solution. (*i*) In this case needle is the object. Since the image is real, inverted and of same size as the needle (or object), the needle must be at the same distance (50 cm) in front of lens, as the image is behind the lens. Thus, the needle is placed at a distance of 50 cm from lens in the front.

(*ii*) When the image formed by a convex lens is of the same size as the needle (or object), then the distance of needle from the lens is $2f$ (twice the focal length). In this case :

$$2f = 50 \text{ cm}$$

So, $$f = \frac{50}{2} \text{ cm}$$

$$f = 25 \text{ cm}$$

Thus, the focal length of this convex lens is +25 cm. This is equal to $\frac{+25}{100}$ m or + 0.25 m. Now,

$$\text{Power, } P = \frac{1}{f\,(\text{in metres})}$$

$$= \frac{1}{+0.25} = +4.0 \text{ D}$$

So, the power of this convex lens is + 4.0 dioptres.

Power of a Combination of Lenses

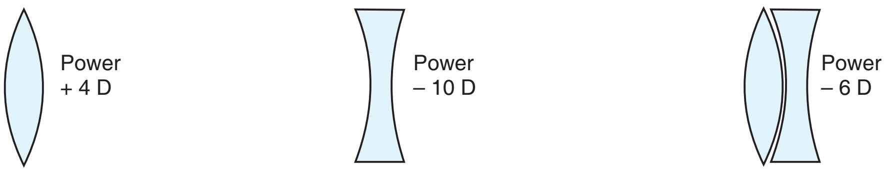
If a number of lenses are placed in close contact, then the power of the combination of lenses is equal to the algebraic sum of the powers of individual lenses. Thus, if two lenses of powers p_1 and p_2 are placed in contact with each other, then their resultant power P is given by :

$$P = p_1 + p_2$$

For example, if a convex lens of power, + 4 D and a concave lens of power, –10 D are placed in contact with each other, then their resultant power will be :

$$P = p_1 + p_2$$
$$= +4 + (-10)$$
$$= 4 - 10$$
$$= -6 \text{ D}$$

This shows that a combination of convex lens of power + 4 D and a concave lens of power, – 10 D has a resultant power of , – 6 D. So, this combination of convex lens and concave lens behaves like a concave lens (of power, – 6 dioptres). This is shown clearly in the Figure given below :



(*a*) Convex lens (*b*) Concave lens (*c*) Combination of convex lens and concave lens

Figure 50. A combination of convex lens of power +4 D and a concave lens of power, –10 D kept in close contact has a resultant power of, – 6 D.

In general, if a number of thin lenses having powers p_1, p_2, p_3, ...etc., are placed in close contact with one another, then their resultant power P is given by :

$$P = p_1 + p_2 + p_3 + \ldots\ldots\ldots\ldots$$

Please note that the individual powers p_1, p_2, p_3, etc., of the lenses should be put in the above formula with their proper signs.

The use of powers of lenses (instead of their focal lengths) makes the work of opticians very simple and straightforward. For example, when an optician places two convex lenses of powers +2.0 D and +0.25 D in front of a person's eye during eye-testing, he immediately knows that this convex lens combination is equivalent to a single convex lens of power +2.25 D.

The lens systems consisting of several lenses in contact are used in designing the optical instruments like cameras, microscopes and telescopes, etc. The use of a combination of lenses increases the sharpness of the image. The image produced by using a combination of lenses is also free from many defects which otherwise occur while using a single lens. We will now solve a problem based on combination of lenses.

Sample Problem. Two thin lenses of power, + 3.5 D and, – 2.5 D are placed in contact. Find the power and focal length of the lens combination. **(NCERT Book Question)**

Solution. We know that :

Power of combination of lenses, $P = p_1 + p_2$

So, $P = +3.5 + (-2.5)$

$P = +3.5 - 2.5$

$P = +1.0$ D

Thus, the power of this combination of lenses is, +1.0 dioptre.

We will now calculate the focal length of this combination of lenses. We know that :

Power, $P = \frac{1}{f}$

or $+1 = \frac{1}{f}$

And, $f = +1$ m

So, the focal length of this combination of lenses is, +1 metre.

We are now in a position to **answer the following questions and problems :**

Very Short Answer Type Questions

1. The lens *A* has a focal length of 25 cm whereas another lens *B* has a focal length of 60 cm. Giving reason state, which lens has more power : *A* or *B*.
2. Which causes more bending (or more refraction) of light rays passing through it : a convex lens of long focal length or a convex lens of short focal length ?
3. Name the physical quantity whose unit is dioptre.
4. Define 1 dioptre power of a lens.
5. Which type of lens has (*a*) a positive power, and (*b*) a negative power ?
6. Which of the two has a greater power : a lens of short focal length or a lens of large focal length ?
7. How is the power of a lens related to its focal length ?
8. Which has more power : a thick convex lens or a thin convex lens, made of the same glass ? Give reason for your choice.
9. The focal length of a convex lens is 25 cm. What is its power ?
10. What is the power of a convex lens of focal length 0.5 m ?
11. A converging lens has a focal length of 50 mm. What is the power of the lens ?
12. What is the power of a convex lens whose focal length is 80 cm ?
13. A diverging lens has a focal length of 3 cm. Calculate the power.
14. The power of a lens is + 0.2 D. Calculate its focal length.
15. The power of a lens is, – 2 D. What is its focal length ?
16. What is the nature of a lens having a power of + 0.5 D ?
17. What is the nature of a lens whose power is, – 4 D ?
18. The optician's prescription for a spectacle lens is marked + 0.5 D. What is the :
    (*a*) nature of spectacle lens ?
    (*b*) focal length of spectacle lens ?
19. A doctor has prescribed a corrective lens of power, –1.5 D. Find the focal length of the lens. Is the prescribed lens diverging or converging ?

20. A lens has a focal length of, –10 cm. What is the power of the lens and what is its nature ?

21. The focal length of a lens is +150 mm. What kind of lens is it and what is its power ?

22. Fill in the following blanks with suitable words :

(*a*) The reciprocal of the focal length in metres gives you the ....of the lens, which is measured in.........

(*b*) For converging lenses, the power is............while for diverging lenses, the power is..............

Short Answer Type Questions

23. An object of height 4 cm is placed at a distance of 15 cm in front of a concave lens of power, –10 dioptres. Find the size of the image.

24. An object of height 4.25 mm is placed at a distance of 10 cm from a convex lens of power +5 D. Find (*i*) focal length of the lens, and (*ii*) size of the image.

25. A convex lens of power 5 D and a concave lens of power 7.5 D are placed in contact with each other. What is the :

(*a*) power of this combination of lenses ?

(*b*) focal length of this combination of lenses ?

26. A convex lens of focal length 25 cm and a concave lens of focal length 10 cm are placed in close contact with one another.

(*a*) What is the power of this combination ?

(*b*) What is the focal length of this combination ?

(*c*) Is this combination converging or diverging ?

27. The power of a combination of two lenses *X* and *Y* is 5 D. If the focal length of lens *X* be 15 cm :

(*a*) calculate the focal length of lens *Y*.

(*b*) state the nature of lens *Y*.

28. Two lenses *A* and *B* have focal lengths of + 20 cm and, –10 cm, respectively.

(*a*) What is the nature of lens *A* and lens *B* ?

(*b*) What is the power of lens *A* and lens *B* ?

(*c*) What is the power of combination if lenses *A* and *B* are held close together ?

Long Answer Type Questions

29. (*a*) What do you understand by the power of a lens ? Name one factor on which the power of a lens depends.

(*b*) What is the unit of power of a lens ? Define the unit of power of a lens.

(*c*) A combination of lenses for a camera contains two converging lenses of focal lengths 20 cm and 40 cm and a diverging lens of focal length 50 cm. Find the power and focal length of the combination.

30. (*a*) Two lenses *A* and *B* have power of (*i*) + 2 D and (*ii*) – 4 D respectively. What is the nature and focal length of each lens ?

(*b*) An object is placed at a distance of 100 cm from each of the above lenses *A* and *B*. Calculate (*i*) image distance, and (*ii*) magnification, in each of the two cases.

Multiple Choice Questions (MCQs)

31. The focal lengths of four convex lenses *P*, *Q*, *R* and *S* are 20 cm, 15 cm, 5 cm and 10 cm, respectively. The lens having greatest power is :

(*a*) *P* (*b*) *Q* (c) *R* (*d*) *S*

32. A converging lens has a focal length of 50 cm. The power of this lens is :

(*a*) + 0.2 D (*b*) – 2.0 D (*c*) + 2.0 D (*d*) – 0.2 D

33. A diverging lens has a focal length of 0.10 m. The power of this lens will be :

(*a*) + 10.0 D (*b*) + 1.0 D (*c*) – 1.0 D (*d*) – 10.0 D

34. The power of a lens is + 2.0 D. Its focal length should be :

(*a*) 100 cm (*b*) 50 cm (*c*) 25 cm (*d*) 40 cm

35. If a spherical lens has a power of, – 0.25 D, the focal length of this lens will be :

(*a*) – 4 cm (*b*) – 400 mm (*c*) – 4 m (*d*) – 40 m

36. The power of a concave lens is 10 D and that of a convex lens is 6 D. When these two lenses are placed in contact with each other, the power of their combination will be :

(*a*) + 16 D (*b*) + 4 D (*c*) –16 D (*d*) – 4 D

37. The power of a converging lens is 4.5 D and that of a diverging lens is 3 D. The power of this combination of lenses placed close together is :

(*a*) + 1.5 D (*b*) + 7.5 D (*c*) – 7.5 D (*d*) – 1.5 D

38. A convex lens of focal length 10 cm is placed in contact with a concave lens of focal length 20 cm. The focal length of this combination of lenses will be :

(*a*) + 10 cm (*b*) + 20 cm (*c*) – 10 cm (*d*) – 20 cm

Questions Based on High Order Thinking Skills (HOTS)

39. The optical prescription for a pair of spectacles is :

Right eye : – 3.50 D Left eye : – 4.00 D

(*a*) Are these lenses thinner at the middle or at the edges ?

(*b*) Which lens has a greater focal length ?

(*c*) Which is the weaker eye ?

40. A person got his eyes tested by an optician. The prescription for the spectacle lenses to be made reads :

Left eye : + 2.50 D Right eye : + 2.00 D

(*a*) State whether these lenses are thicker in the middle or at the edges.

(*b*) Which lens bends the light rays more strongly ?

(*c*) State whether these spectacle lenses will converge light rays or diverge light rays.

ANSWERS

1. Lens *A* has more power ; It has shorter focal length. **2.** Convex lens of short focal length **6.** Lens of short focal length **8.** Thick convex lens ; It has shorter focal length **9.** + 4 D **10.** + 2 D **11.** + 20 D **12.** + 1.25 D **13.** – 33.3 D **14.** + 5 m **15.** – 50 cm **16.** Convex lens **17.** Concave lens **18.** (*a*) Convex lens (*b*) 2 m **19.** – 66.6 cm ; Diverging lens **20.** –10 D ; Concave lens **21.** Convex lens ; + 6.6 D **22.** (*a*) power ; dioptres (*b*) positive ; negative **23.** 1.6 cm **24.** (*i*) 20 cm (*ii*) 8.50 mm **25.** (*a*) –2.5 D (*b*) – 40 cm **26.** (*a*) – 6 D (*b*) –16.66 cm (*c*) Diverging **27.** (*a*) – 60 cm (*b*) Concave lens **28.** (*a*) Lens *A* is convex ; Lens *B* is concave (*b*) Power of lens *A* = + 5 D ; Power of lens *B* = – 10 D (*c*) – 5 D **29.** (*c*) *P* = + 5.5 D ; *f* = + 18.18 cm **30.** (*a*) Lens *A* is convex ; *f* = + 50 cm ; Lens *B* is concave ; *f* = – 25 cm (*b*) Lens *A* : *v* = +100 cm ; *m* = – 1 ; Lens B : *v* = –20 cm ; *m* = 0.2 **31.** (*c*) **32.** (*c*) **33.** (*d*) **34.** (*b*) **35.** (*c*) **36.** (*d*) **37.** (*a*) **38.** (*b*) **39.** (*a*) Thinner at the middle (*b*) Lens of lower power : – 3.50 D (*c*) Left eye **40.** (*a*) Thicker in the middle (*b*) Lens having greater power of + 2.50 D (*c*) Converge light rays.