SEMESTER-ONE

PERIOD-1

P12CH1

TOPIC 1

Refraction and Dispersion of Light

In earlier grades you have studied about propagation of light and reflection of light. In this unit we will study about refraction of light.

1.1 BENDING OF LIGHT BETWEEN ADJACENT MEDIA

The change in direction of light when it passes from one medium to another is called refraction of light. In other words, the bending of light between adjacent media is called refraction of light.

ACTIVITY 1.1

Demonstrating refraction of light using air-water medium

Materials required

A coin, opaque bowl or cup and water

Procedure

- Place a large shallow bowl on a table and put a coin in it.
- Move away slowly from the bowl. Stop when the coin just disappears from your sight.
- Ask a friend to pour water gently into the bowl without disturbing the coin.
- Keep looking for the coin from your position.

Fig. 1.1

Questions:

- Does the coin become visible again from your position?
- How could this happen?

The coin becomes visible again on pouring water into the bowl. This happens because the coin appears slightly raised above its actual position due to refraction of light.

Note: The diagrams used here show the container as transparent so that you can see the coin inside, whereas you will actually be using an opaque container.

ACTIVITY 1.2

Estabilishing experimentally the laws of refraction of light

- Fix a sheet of white paper on a drawing board using drawing pins.
- Place a rectangular glass slab over the sheet in the middle.
- Draw the outline of the slab with a pencil. Let us name the outline as ABCD.Take four identical pins.
- Fix two pins, say E and F vertically such that the line joining the pins is inclined to the edge AB.
- Look for the images of the pins E and F through the opposite edge. Fix two other pins, say G and H, such that these pins and the images of E and F lie on a straight line.
- Remove the pins and the slab.
- Join the positions of tip of the pins E and F and produce the line up to AE. Let EF meet AB at O. Similarly, join the positions of tip of the pins G and H and produce it up to the edge CD. Let HG meet CD at Q.
- Join O and O′. Also produce EF up to P, as shown by a dotted line in Fig. 1.2.

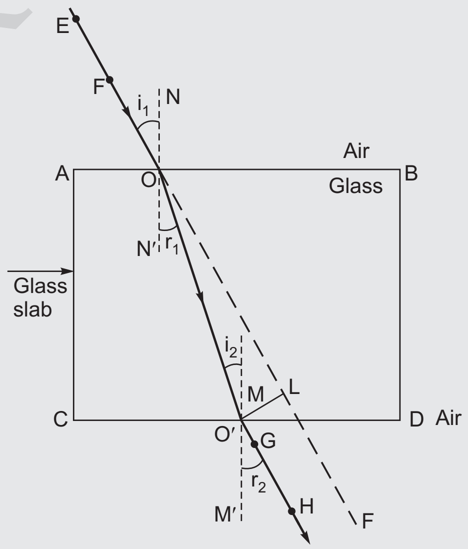


Fig. 1.2. Refraction of light through a rectangular glass slab

In this activity, you will note, the light ray has changed its direction at points *O* and *O′*. Note that both the points *O* and *O′* lie on surfaces separating two transparent media. Draw a perpendicular *NN′* to *AB* at *O* and another perpendicular *MM′* to *CD* at *O′*. The light ray at point *O* has entered from a rarer medium to a denser medium, that is, from air to glass. Note that the light ray has bent towards the normal. At *O′*, the light ray has entered from glass to air, that is, from a denser medium to a rarer medium. The light here has bent away from the normal. Compare the angle of incidence with the angle of refraction at both refracting surfaces *AB* and *CD*.

In Fig 1.2, *EO* is the incident ray, *OO′* is the refracted ray and *O′H* is the emergent ray. You may observe that the emergent ray is parallel to the direction of the incident ray. Why does it happen so? The extent of bending of the ray of light at the opposite parallel faces *AB* (air glass interface) and CD (glass air interface) of the rectangular glass slab is equal and opposite. This is why the ray emerges parallel to the incident ray. However, the light ray is shifted sideward slightly. What happens when a light ray is incident normally to the interface of two media? Try and find out.

Now you are familiar with the refraction of light. Refraction is due to change in the speed of light as it enters from one transparent medium to another. Experiments show that refraction of light occurs according to certain laws.

The following are the laws of refraction of light.

(*i*) *The incident ray, the refracted ray and the normal to the interface of two transparent media at the point of incidence, all lie in the same plane.*

(*ii*) *The ratio of sine of angle of incidence to the sine of angle of refraction is a constant for the light of a given color and for the given pair of media. This law is also known as Snell's law of refraction.*

If i is the angle of incidence and r is the angle of refraction, then,

$$\frac{\sin i}{\sin r} = \text{constant (denoted by } \mu \text{ or } n)$$

This constant value is called the refractive index of the second medium with respect to the first.

1.2 VERIFICATION OF SNELL'S LAW

ACTIVITY 1.3

Verifying Snell's law

Materials required

- A rectangular glass slab, white sheet of paper, drawing board and Pins.

Procedure

- Place a rectangular glass slab on a white sheet of paper fixed on a drawing board.
- Trace the boundary ABCD of the glass slab.
- Remove the glass slab and draw a normal N_1N_2 at O.
- Draw a straight line IO inclined at an angle say 30° with the normal. IO is the incident ray.
- Fix two pins P and Q on the incident ray IO.
- Place the glass slab within its boundary ABCD.

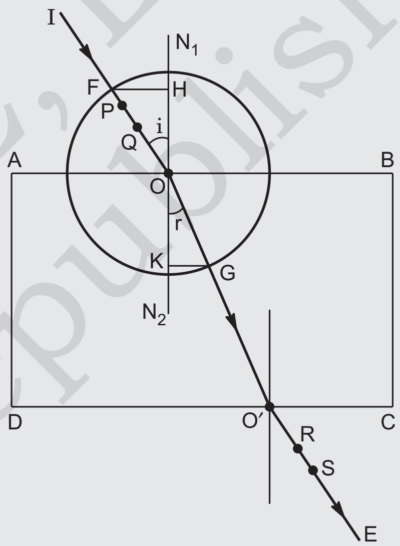


Fig. 1.3

- Looking from the other side of the glass slab fix two other pins R and S such that P, Q, R and S appear to lie on the same straight line.
- Remove the glass slab and the pins. Mark the pin points P, Q, R and S.
- Join the pins R and S and produce the line on both sides. The ray $O'E$ is the emergent ray.
- Join OO'. It is the refracted ray.
- With O as centre, draw a circle of a convenient radius 'r' in such a way that it cuts the incident and the refracted rays at F and G respectively.

- From F and G draw perpendiculars to the normal N_1N_2.
- DFHO and DGKO are right-angled triangles.

∴ $$\sin i = \frac{FH}{OF}, \quad \sin r = \frac{GK}{OG}$$

$$\mu = \frac{\sin i}{\sin r} = \frac{FH}{OF} \times \frac{OG}{GK}$$

But $OG = OF = r$

So, $$\mu = \frac{FH}{OG} \times \frac{OG}{GK} \quad \text{or} \quad \mu = \frac{FH}{GK}$$

- Measure the length of FH and GK.
- Repeat the experiment for different values of angle of incidence.
- Record the result in tabular form.

Sl. No.	i	FH	GK	$\frac{FH}{GK}$
1.				
2.				
3.				
4.				
5.				

- Find the value of $\frac{FH}{GK}$ for different values of i.
- $\frac{FH}{GK}$ will be equal to a constant verifying Snell's law.

1.3 REFRACTIVE INDEX

ACTIVITY 1.4

Measuring refractive index of a glass block

Materials required

Glass block, light box (laser) styrofoam.

Procedure

1. Place glass block on a sheet of paper.
2. Trace the outline of the block on the sheet.

3. Remove the block.
4. 1/3 down the outline mark a tick on the page.
5. Using a protractor mark an angle such as 30° or 45°. This is your angle of incidence.
6. Complete lines to show the angles.
7. Set up the ray box so as a ray shines along this line.
8. On the other side of the block make a mark where the refracted ray leaves the block.

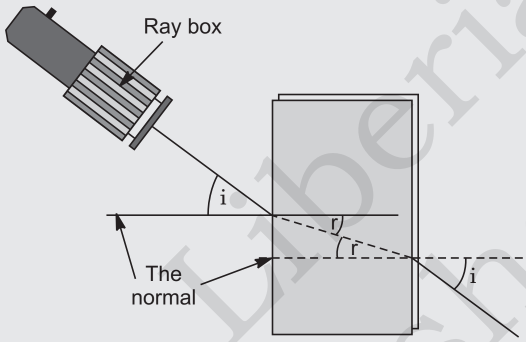


Fig. 1.4

9. Remove the block and complete the line from the point the light entered to where it left. This is the direction of the refracted ray.
10. Draw a normal and measure the angle *r*.
11. Having calculated *r*, calculate values of sin *i* and sin *r* using calculator.
12. Put the values in the following formula to get out the refractive index of glass block. Refractive index = sin i/sin r = n

1.4 REFRACTION OF LIGHT THROUGH LAYERS OF PARALLEL MEDIA

Consider a ray of light travelling from medium 1 into medium 2, as shown in Fig. 1.5. Let v_1 be the speed of light in medium 1 and v_2 be the speed of light in medium 2. The refractive index of medium 2 with respect to medium 1 is given by the ratio of the speed of light in medium 1 and the speed of light in medium 2. This is usually represented by the symbol n_{21}. This can be expressed in an equation form as,

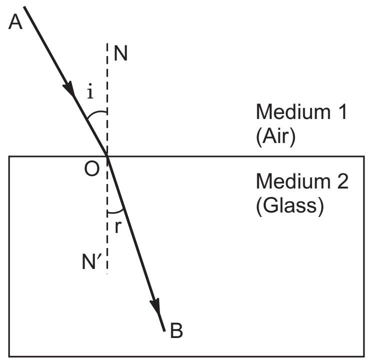


Fig. 1.5

$$n_{21} = \frac{\text{Speed of light in medium 1}}{\text{Speed of light in medium 2}} = \frac{v_1}{v_2}$$

By the same argument, the refractive index of medium 1 with respect to medium 2 is represented as n_{12}. It is given by

$$n_{12} = \frac{\text{Speed of light in medium 2}}{\text{Speed of light in medium 1}} = \frac{v_2}{v_1}$$

If medium 1 is vacuum or air, then the refractive index of medium 2 is considered with respect to vacuum. This is called the absolute refractive index of the medium. It is simply represented as n_2. If c is the speed of light in air and v is the speed of light in the medium, then, the refractive index of the medium n_m is given by

$$n_m = \frac{\text{Speed of light in air}}{\text{Speed of light in the medium}} = \frac{c}{v}$$

The absolute refractive index of a medium is simply called its refractive index. The refractive index of several media is given in Table 1.1. From the Table you can know that the refractive index of water, n_w = 1.33. This means that the ratio of the speed of light in air and the speed of light in water is equal to 1.33. Similarly, the refractive index of crown glass, n_g = 1.52.

Table 1.1 Absolute refractive index of some material media

Material medium	Refractive index
Air	1.0003
Ice	1.31
Water	1.33
Alcohol	1.36
Kerosene	1.44
Fused quartz	1.46
Turpentine oil	1.47
Benzene	1.50
Crown glass	1.52
Diamond	2.42

1.5 TOTAL INTERNAL REFLECTION OF LIGHT

ACTIVITY 1.5

Demonstrating total internal reflection of light

Materials required

A laser torch or pointer, a glass beaker with clear water and a glass test tube.

Procedure

1. Take a glass beaker with clear water in it. Stir the water a few times with a piece of soap, so that it becomes a little turbid. Take a laser pointer and shine its beam through the turbid water. You will find that the path of the beam inside water shines brightly.
2. Shine the beam from below the beaker such that it strikes at the upper water surface at the other end. Do you find that it undergoes partial reflection (which is seen as a spot and partial refraction [which comes out in the air and is seen as a spot on the roof; [Fig. 1.6 (*a*)]?

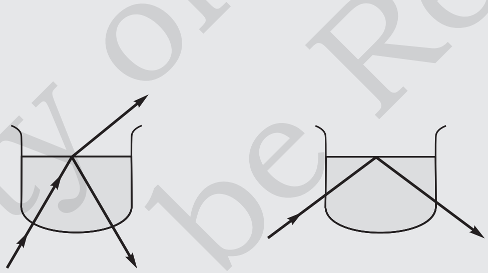


Fig. 1.6. Observing total internal reflection in water with a laser beam (refraction due to glass of beaker neglected being very thin).

3. Now direct the laser beam from one side of the beaker such that it strikes the upper surface of water more obliquely [Fig. 1.6 (*b*)]. Adjust the direction of laser beam until you find the angle for which the refraction above the water surface is totally absent and the beam is totally reflected back to water. This is total internal reflection at its simplest.
4. Pour this water in a long test tube and shine the laser light from top, as shown in Fig. 1.6 (*c*). Adjust the direction of the laser

beam such that it is totally internally reflected every time it strikes the walls of the tube. This is similar to what happens in optical fibres.

Caution: Take care not to look into the laser beam directly and not to point it at anybody's face.

1.5.1 Critical Angle

It is that angle of incidence for which a ray of light while moving from a denser to a rarer medium just grazes over the surface of separation of the two media (that is, angle of refraction = 90°).

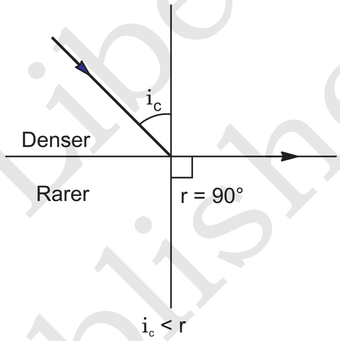


Fig. 1.7

1.5.2 Total Internal Reflection

If the angle of incidence of a ray of light traveling from a denser medium to rarer medium is greater than the critical angle for the two media, then the ray is reflected into denser medium and this phenomenon is described as **total internal reflection**.

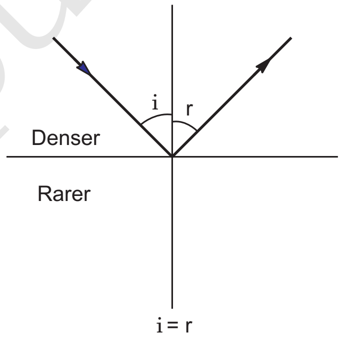


Fig. 1.8

Conditions to be satisfied for total internal reflection to take place

The conditions to be satisfied for total internal reflection to take place are:

- The ray of light must travel from a denser medium to a rarer medium.
- The angle of incidence must be greater than the critical angle for those two mediums.

Table 1.2 Critical angle of some transparent media with respect to air.

Substance medium	Refractive index	Critical angle
Water	1.33	48.75°
Crown glass	1.52	41.14°
Dense flint glass	1.62	37.31°
Diamond	2.42	24.41°

1.6 APPLICATIONS OF TOTAL INTERNAL REFLECTION

Total internal reflection has the following applications.

1.6.1 Optical Fibres

An optical fibre is a thin rod of high-quality glass. Very little light is absorbed by the glass. Light getting in at one end undergoes repeated total internal reflection, even when the fibre is bent, and emerges at the other end.

- Optical fibres are used in endoscopes that allow surgeons to see inside their patients.
- Optical fibres can also carry enormous amounts of information as pulses of light.

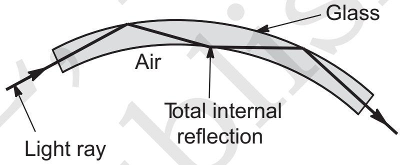


Fig. 1.9. Optical fibres

1.6.2 Diamond

The brilliance of diamond is due to total internal reflection. The critical angle for diamond-air interface (24.4°) is very small, therefore once light enters a diamond, it undergoes total internal reflection inside it. The faces of the diamond are so cut that a ray of light entering the diamond fall at angle greater than 24.4°. This results in multiple, total internal reflections

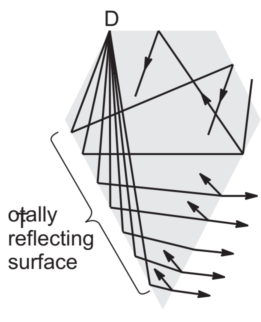


Fig. 1.10. Total internal reflection in diamond

at various angles and remains within the diamond. Hence diamond sparkles.

1.6.3 Prism

ACTIVITY 1.6

Illustrating total internal reflection of light using a right-angled prism.

A right angled glass prism can be used to change the direction of a light ray by 90 degrees or 180 degrees. Such prisms make use of total internal reflection [Fig. 1.11 (*a*) and (*b*)]. The light ray enters the prism along a normal and continues straight on until it hits the back face of the prism. Total internal reflection occurs here because light strikes the surface at 45 degrees which is greater than the critical angle of the glass prism (We see from Table 1.2 that this is true for both crown glass and dense flint glass). The light ray then emerges from the prism along a normal and so continues straight through the glass surface. This type of prism can be used in a periscope.

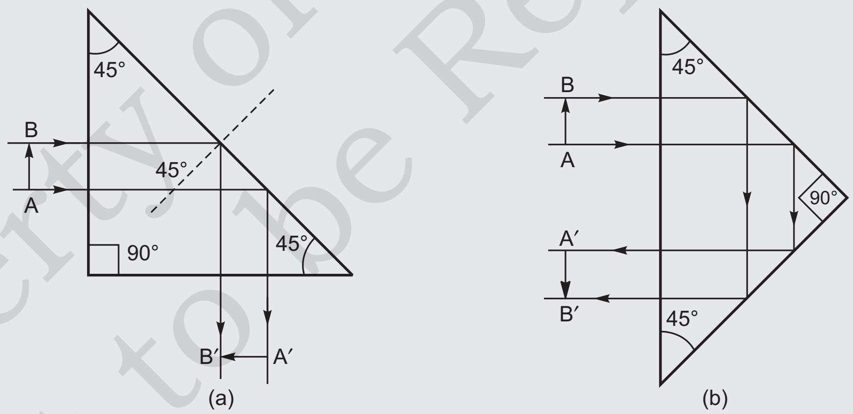


Fig. 1.11. Prisms designed to bend rays by 90° and 180° making use of total internal reflection.

1.6.4 Mirage

On hot summer days, the air near the ground becomes hotter than the air at higher levels. The refractive index of air increases with its density. Hotter air is less dense, and has smaller refractive index than the cooler air. As a result, light from a tall object such as a tree, passes through a medium whose refractive index decreases towards the ground. Thus, a ray of light from such an object successively bends away from the normal and undergoes total internal reflection, if the angle of incidence for the air near the ground exceeds the critical angle. This is shown in Fig. 1.12.

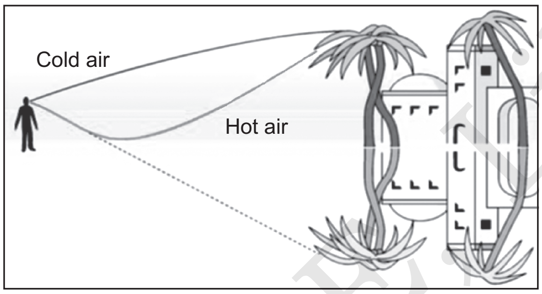


Fig. 1.12. Phenomenon of mirage

To a distant observer, the light appears to be coming from somewhere below the ground. The observer naturally assumes that light is being reflected from the ground, say, by a pool of water near the tall object. Such inverted images of distant tall objects cause an optical illusion to the observer. This phenomenon is called *mirage*.

1.7 REFRACTION OF LIGHT THROUGH A THIN LENS

Usually we see a palmist using a magnifying glass to see the lines on the palm of a person. This magnifying glass is called a lens.

A piece of a transparent medium bounded by two (at least one) spherical surfaces, is called spherical lens.

Working of a lens is based on the refraction of rays of light when they pass through the lens. Lenses do not have uniform thickness.

There are two types of spherical lense:

(*i*) **Convex or Converging Lenses:** It is thick in the middle and thin at the edges.

All types of convex lenses refract a parallel beam of light inwardly.

As these lenses converge light rays, hence are called converging lenses.

(*ii*) **Concave or Diverging Lens:** It is thin in the middle and thick at the edges.

All types of concave lenses refract a parallel beam of light outwardly.

As these lenses diverge light rays, hence called *diverging lenses*.

1.7.1 Terms Associated with Spherical Lenses

Some important terms associated with a spherical lens are stated below:

(*i*) **Aperture:** The diameter of the circular edge of the lens, is called the aperture of the lens. In Fig. 1.13, AB is the aperture of the lens.

Brightness of the image is directly proportional to the square of the aperture of the lens.

(*ii*) **Principal Axis:** The straight line passing through the two centres of curvature of the two spherical surfaces of the lens (or though one centre of curvature of one spherical surface and normal to the other plane surface), is called the principal axis of the lens. In Fig. 1.13, XY is the principal axis of the lens.

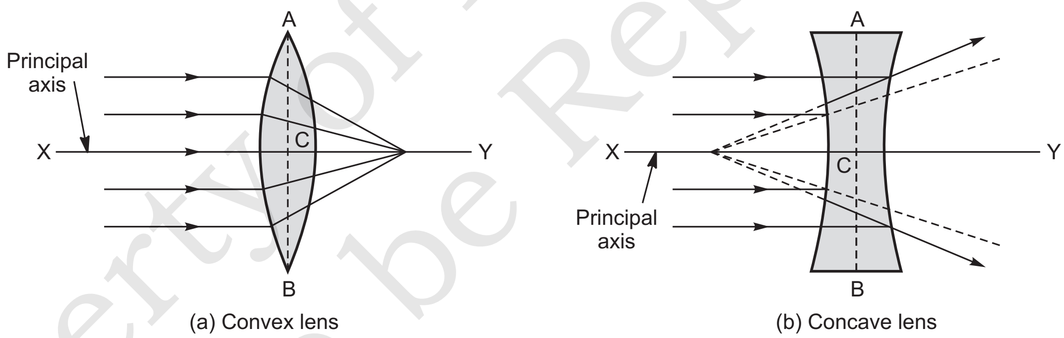


Fig. 1.13. Spherical lenses

(*iii*) **Optical Centre:** It is point on the principal axis of the lens, such that a ray of light passing through it goes undeviated.

In Fig. 1.14, C is the optical centre of the lens.

(*iv*) **First Principal Focus:** It is a point on the principal axis of the lens, such that the rays actually diverging from it (in case of a convex lens) or appear to be going towards it (in case of a concave lens), after refraction from the lens go parallel to the principal axis. Since there are two curved surfaces in a lens, hence there are two principal focus points.

In Fig. 1.14, F_1 is the first principal focus.

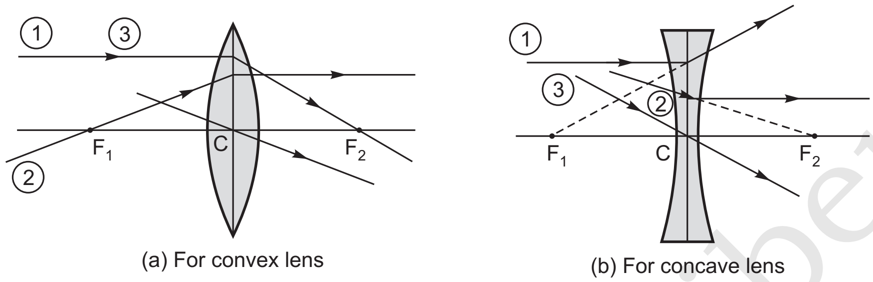


Fig. 1.14. Three special rays

(*v*) **Second Principal Focus:** It is a point on the principal axis of the lens, such that the rays incident on the lens parallel to principal axis after refraction from the lens, actually meet at this point (in case of a convex lens) or appear to come from it (in case of a concave lens).

In Fig. 1.14, F_2 is the second principal focus.

(*vi*) **Focal Length:** The distance between the optical centre of the lens and the principal focus (first or second) of the lens, is called focal length of the lens. It is represented by the symbol f.

In Fig. 1.14, $F_1C = CF_2 = f$.

Focal length of a convex lens is positive and focal length of a concave lens is negative.

(*vii*) **Focal Plane:** A plane passing through the principal focus and perpendicular to the principal axis of the lens is called focal plane.

1.8 LOCATION OF IMAGES FORMED BY THIN LENSES USING RAY DIAGRAM METHOD

1.8.1 Rules for Image Formation

When an object is kept in front of a convex lens, an image is formed. This image can be real or virtual depending on the position of the object. However, image is formed at a point where at least two rays after refraction meet or appear to meet. For finding the position and nature of the image, following three rules can be used:

Rule 1. A ray of light incident on the lens parallel to principal axis, (Ray 1), after refraction from the lens, actually passes through its focus (in case of a convex lens) or appears to come from its focus (in case of a concave lens). [Object at infinity, image at focus]

Rule 2. A ray of light incident on the lens through its principal focus (in case of a convex lens) or in direction of principal focus (in case of a concave lens) after refraction from the lens goes parallel to the principal axis. (Ray 2) [Object at focus F_1, image at infinity]

Rule 3. A ray of light incident on the lens and passing through the optical centre, passes undeviated through the lens. (Ray 3)

These special rays are very useful in drawing ray diagrams in different cases.

1.8.2 Ray Diagram

It is a diagram, in which rays are shown coming from a point on the object and falling on a lens and after refraction from the lens are shown either meeting at a point or appearing to diverge from a point, forming its real or virtual image.

If the object is big, it can be divided into many points and point to point images are obtained. Combining the point images, the image of the whole object is obtained.

Real point images produce real image and virtual point image produce virtual image of the complete object.

In Fig. 1.15, *XY* represents principal section of a convex lens. It is taken as a plane sheet due to its small thickness and small aperture.

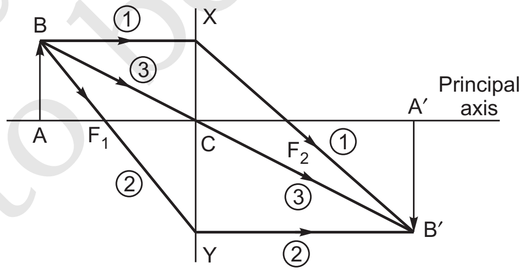


Fig. 1.15. Convex lens—refracting surface towards left

(*a*) Any two of the three special rays are taken to obtain a single point image.

(*b*) Since lenses used are supposed to be thin and have a small aperture, their surfaces can be taken as plane and their principal sections can be represented by a straight line.

AB is a real object having bottom A on the principal axis and top B upwards. Three special rays are shown coming from top B, incident on the lens. After refraction they actually meet at a point B′, which becomes real image of B. A′ lies perpendicularly below B′, on the principal axis. A′ must represent the image of bottom A of the object. A′B′ represents the real image of complete object AB.

(*c*) For small distances and sizes involved, the ray diagram can be drawn on same scale. For bigger distances and sizes, the diagram has to be drawn on a chosen scale.

1.8.3 Location of Image Formed by Convex (Converging) Lenses

Nature of the image formed by a convex lens depends on the position of the object placed in front of the lens. Different positions of the object from the optical centre of the lens produce different types of images. Object can be placed,

(*i*) at infinity (*ii*) beyond 2F
(*iii*) at 2F (*iv*) between F and 2F
(*v*) at F and (*vi*) between F and optical centre.

Different cases are as given ahead with their ray diagrams.

Case 1. *Object at Infinity*

(*i*) *A point object lying on the principal axis:* When a point object is at a large distance from the lens, we usually say that object is at infinity. Since the object is far away from the lens, hence it has not been shown in Fig. 1.16 (*a*). When object is a point object lying on the principal axis, the rays come parallel to the principal axis and after refraction from the lens, actually meet at the second principal focus F_2.

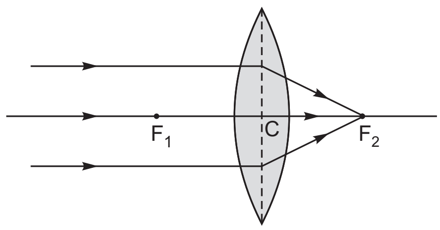


Fig. 1.16 (*a*) Convex lens point object at infinity, image at focus

The image is formed at focus F_2. It is real and point-sized. [Fig. 1.16 (*a*)]

(*ii*) *A big size object with its foot on the principal axis:* When an extended object lies at a large distance on the principal axis, we usually say that object is at infinity. As the object is at infinity, hence it is not shown in Fig. 1.16 (*b*). All the rays coming from a point on the object are parallel and incident on the lens. Ray AD and BC are coming from the same point of the object. Ray AD when passes through the lens, gets refracted along DB′ and ray BC after passing through the optical centre of the lens goes straight along CB′. Thus B′ is the image of the top point of the extended object. If we draw B′A′ perpendicular to the principal axis of the lens, we see that A′B′ is the image of the object placed at infinity.

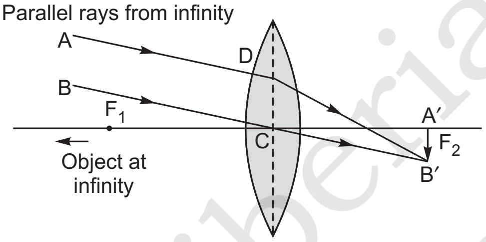


Fig. 1.16 (*b*) Convex lens: big size object at infinity, image at focus

Thus image is formed at the second principal focus F_2. It is real, inverted and diminished (smaller in size than the object).

Case 2. ***Object at distance more than twice the focal length.***

The object AB forms its image A′B′ between *f* and 2*f*.

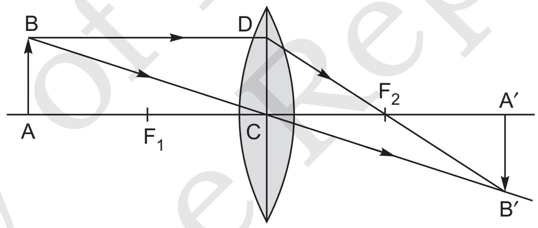


Fig. 1.16 (*c*) Convex lens : object beyond 2*f*, image between *f* and 2*f*

The image is real, inverted and diminished (smaller in size than the object) [Fig. 1.16 (*c*)].

Case 3. ***Object at a distance twice the focal length of the lens.***

The real object AB has its real image A′B′ formed at distance 2*f*.

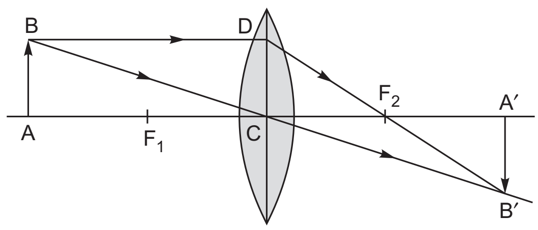


Fig. 1.16 (*d*) Convex lens: object at distance 2*f*, image at distance 2*f*

The image is real, inverted and is of the same size as the object [Fig. 1.16 (*d*)].

Case 4. *Object at a distance more than focal length and less than twice the focal length.*

The real object AB has its image A′B′ formed beyond distance $2f$.

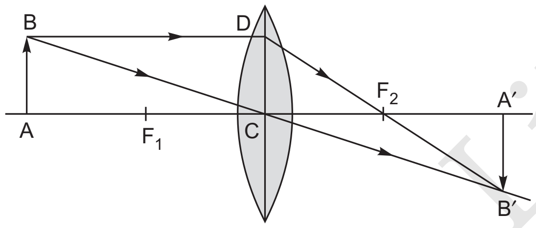


Fig. 1.16 (*e*) Convex lens: object between *f* and 2*f*

The image is real, inverted and enlarged (bigger in size than the object) [Fig.; 1.16 (*e*)]

Case 5. Objective at focus

In such a case, the image is imaginary, inverted (refracted rays go downward), at infinity and must have very large size [Fig. 1.16 (*f*)].

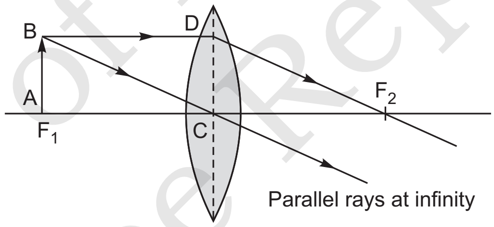


Fig. 1.16 (*f*) Convex lens: object at focus, image at infinity

Case 6. *Object between focus and optical centre*

Real object AB has its image A′B′ formed in front of the lens. The image is virtual, erect and enlarged [Fig. 1.16 (*g*)].

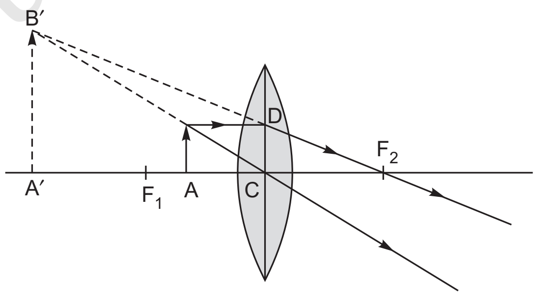


Fig. 1.16 (*g*) Convex lens: object between focus and optical centre, image in front of the lens

The results of all the cases can be given in Table 1.3.

Table 1.3 Image formed by a convex lens for different positions of the object

Case	Object Position		Image	
		Position	**Nature**	**Size**
1.	(*i*) Point object at infinity on the principal axis	at focus	real	Point
	(*ii*) Big object at infinity	at focus	real, inverted	Diminished
2.	At distance more than $2f$	between f and $2f$	real, inverted	diminished
3.	At distance $2f'$	at $2f$	real, inverted	same as object
4.	At distance between f and $2f$	beyond $2f$	real, inverted	enlarged
5.	At focus	at infinity	real, inverted	enlarged
6.	Between focus and optical centre	in front of the lens (on the left side)	virtual, erect	enlarged

1.8.4 Location of Images Formed by Concave (Diverging) Lens

Case 1. *Object at Infinity*

(*i*) A point lying on the principal axis.

Rays come parallel to the principal axis and after refraction from the lens, appear to come from the first principal focus F_1. The image is formed at focus F_1. It is virtual and point-sized [Fig. 1.17 (*a*)].

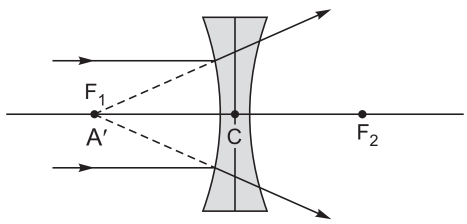


Fig. 1.17 (*a*) Concave lens: point object at infinity, image at focus

Application. Sun light diverging lens.

(*ii*) A big size object with its foot on the principal axis.

Parallel rays come inclined to the principal axis. Image of foot is formed at the focus.

The image is formed at the first principal focus, F_1. It is virtual-erect and diminished [Fig 1.17 (*b*)].

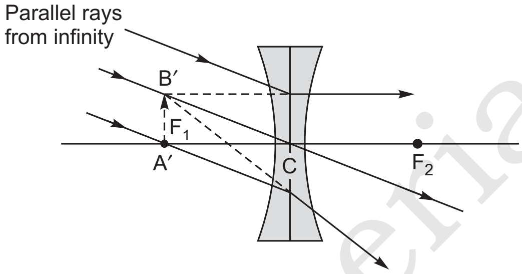


Fig. 1.17 (*b*) Concave lens: point object at infinity, image at focus

Applications.

1. Correcting myopia.
2. Galileo telescope eyepiece (normal adjustment)

Case 2. *Object at a Finite Distance*

Real object AB has its image A′B′ formed between the principal focus and optical centre C.

The image is virtual-erect and diminished [Fig. 1.17 (*c*)].

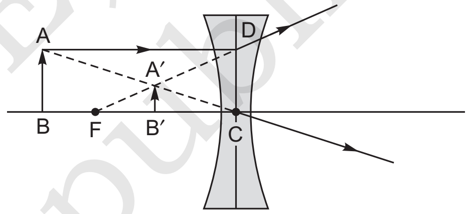


Fig. 1.17 (*c*) Concave lens: Object beyond 2F, image between F and C

The results of all the cases can be given in the Table 1.4.

Application. Galileo telescope eyepiece (near adjustment).

Table 1.4 Image formed by a concave lens for different positions of the object

Case	Object position	Image		
		Position	**Nature**	**Size**
1.	(*i*) Principal axis	at focus	virtual	point
	(*ii*) Big object at infinity	at focus	virtual, erect	diminished
2.	At finite distance	between F and C	virtual, erect	diminished

1.9 LENS FORMULA

Equation which gives us the relation between distance of the object from the optical centre of the lens (u), distance of the image from the optical centre of the lens (v) and focal length of the lens (f) is,

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

This equation is called lens formula.

While arriving at this relation, following assumptions are made:

(*i*) The lens is thin.

(*ii*) The lens has a small aperture.

(*iii*) The object lies close to the principal axis.

(*iv*) The incident rays make small angle with the lens surface or the principal axis.

1.9.1 Sign Conventions for Lenses

It is a convention which fixes the signs of different distances to be measured. The sign convention to be followed is the **New Cartesian** sign convention. It gives the following rules:

1. Object is placed on the left hand side of the lens so that incident ray goes from left to right.
2. All distances are measured from the optical centre of the lens.
3. The distances measured in the same direction as the direction of incident light, are taken as positive.
4. The distances measured in the direction opposite to the direction of incident light, are taken as negative.
5. Distance measured upward and perpendicular to the principal axis, are taken as positive.
6. Distance measured downward and perpendicular to the principal axis, are taken as negative.

Object and image lying on the axis in front of the lens, lie on the left of the lens. Their distances are taken negative.

Objects and images, lying on the axis behind the lens, lie on the right of the lens. Their distances are taken positive.

Height of objects and images lying on the axis with their top upward, are taken as positive. Height of objects and images, lying on the axis with their top downward are taken as negative.

In short

Right ↔ positive,

Left ↔ negative

Upward ↔ positive,

Downward ↔ negative

These facts are shown in Fig. 1.18. Object is on the left of the lens LM.

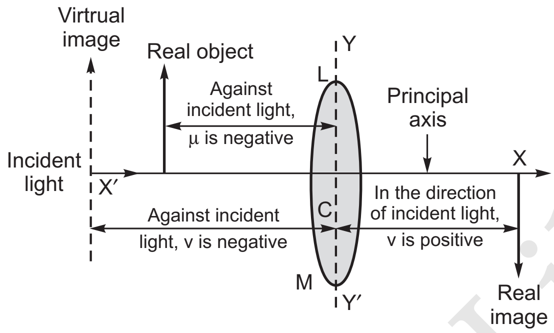


Fig. 1.18. The new cartesian sign convention for refraction by spherical lens

1.9.2 Linear Magnification

Size of the image formed by a lens depends on the position of the object from the lens.

Size of the image can be smaller than or equal to or greater than the size of the object. Size of the image relative to the object is given by linear magnification.

Linear magnification produced by a lens is equal to the ratio of the distance of image from the optical centre (v) to the distance of the object from the optical centre (u)

i.e., Magnification, $m = \frac{v}{u}$

If m is positive, the image is virtual and erect and if m is negative, the image is real and inverted.

If $m > 1$, the image is magnified, if $m < 1$, the image is diminished and if $m = 1$, the size of the image is same as that of the object.

1.10 POWER OF LENS

Power of a lens is the measure of its degree of convergence or divergence of light rays falling on it.

It is the capacity or the ability of a lens to deviate (converge or diverge) the path of rays passing through it. Power of a lens is also defined as the reciprocal of the focal length of the lens when expressed in metres.

It is represented by the symbol P.

A lens having small focal length, focuses a parallel beam of light at near point. Its converging or diverging capability is more.

Hence, it is said to have more power.

Thus, $$\text{Power } (P) \propto \frac{1}{\text{Focal length } (f) \text{ in metres}}$$

i.e., $$\boxed{P = \frac{1}{f\ (\text{metre})}}$$

The *SI* unit for power of a lens is dioptre (*D*): $1D = 1m^{-1}$. The power of a lens of focal length of 1 metre is one dioptre. Power of a lens is positive for a converging lens and negative for a diverging lens.

Power of a converging (convex) lens is positive and that of a diverging (concave) lens is negative.

When two lenses are placed in contact in such a way that their principal axis is same, their combination can be treated as a single lens.

If focal lengths of the individual lenses are f_1, f_2, the focal length (f) of the combination is given by, $\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2}$

In terms of power of the lens, we can say that the power of the combination of a number of thin lenses placed in contact is equal to the algebraic sum of the power of the individual lenses.

So, $$P = P_1 + P_2$$

1.11 DEFECTS OF VISION AND THEIR CORRECTION

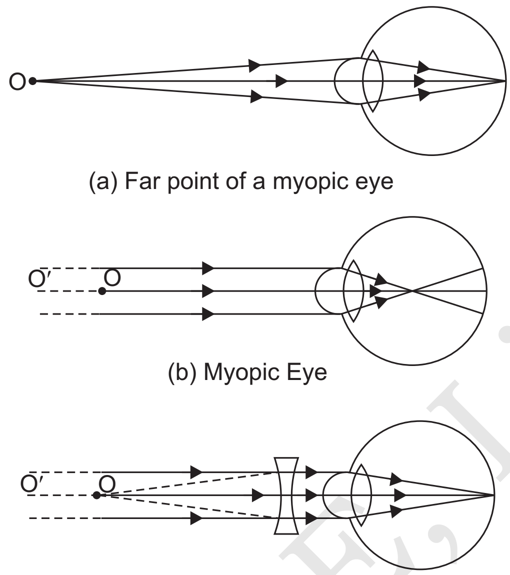
There are mainly three common refractive defects of vision. These are as follows:

Myopia or Near-sightedness: A person with myopia can see nearby objects clearly but cannot see distance objects distinctly. In other words, the far point shifts towards the eye. It is no longer at infinity. In a myopic eye, the image of a distant object is formed in front of the retina and not at the reitna itself.

Cause:

(*i*) Excessive curvature of the eye lens.

(*ii*) Enlongation of the eye-ball.



(a) Far point of a myopic eye

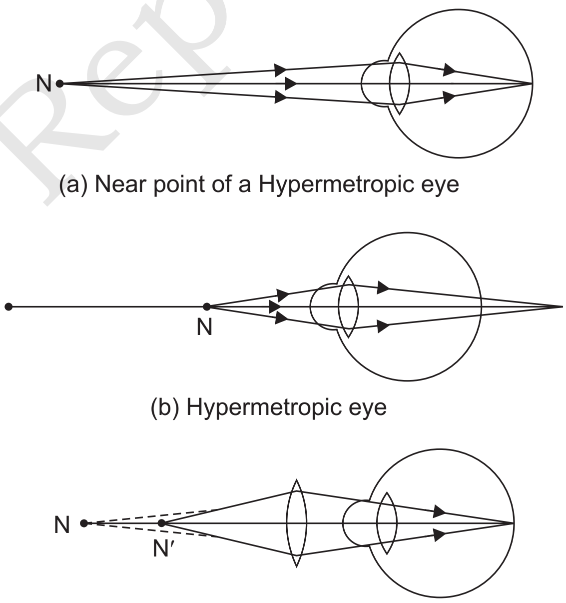
(b) Myopic Eye

(c) Correction of myopia

Fig. 1.19. Chromatic aberration

Correction: It can be corrected by using a concave lens of a suitable power.

Hypermetropia: It is also known as far-sightedness. A person with hypermetropia can see distant objects clearly but cannot see nearby objects distinctly. The nearpoint, for the person is further away from the normal near point (25 cm). The light rays from a closeby object are focused at a point behind the retina.



(a) Near point of a Hypermetropic eye

(b) Hypermetropic eye

(c) Correction for Hypermetropic eye

Fig. 1.20

Cause of Hypermetropoia:

1. The focal length of the eye-lens is too long.

2. The eye ball has become too small.

Correction: This defect can be corrected by using a convex lens of appropriate power.

Presbyopia: The power of accomodation of the eye usually decreases with ageing. For most people, the rear point gradually recedes away. They find it difficult to see nearby objects comfortable and distinctly without correction eye-glasses. This defect is called presbyopia. It arises due to the gradual weakening of the ciliary muscles and diminishing flexibility of the eye lens. Sometimes, a person may suffer from both myopia and hypermetropa. Such people often required bi-focal lenses. It consists of both concave and convex lenses.

1.12 LENS DEFECTS AND THEIR CORRECTIONS

There are two main types of defects in a lens—chromatic aberration and spherical aberration.

1.12.1 Chromatic Aberration

Chromatic aberration, also known as “colour fringing” or “purple fringing”, is a common optical problem that occurs when a lens is either unable to bring all wavelengths of colour to the same focal plane, and/or when wave-lengths of colour are focused at different positions in the focal plane. Chromatic aberration is caused by lens dispersion, with different colours of light travelling at different speeds while passing through a lens. As a result, chromatic aberration occurs when different wavelengths of colour do not converge at the same point after passing through a lens, as illustrated below.

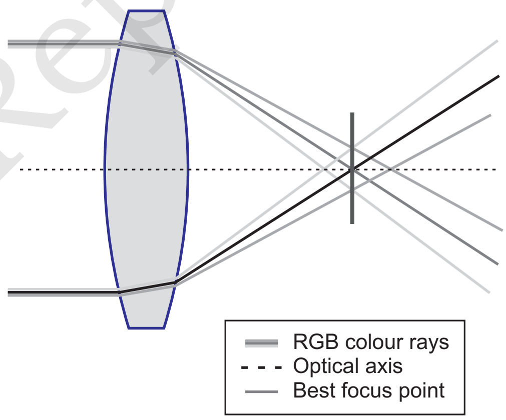


Fig. 1.21. Chromatic aberration

Correction of Chromatic Aberration

Chromatic aberration can be minimized by combining a convex lens of crown glass and a concave lens of flint glass in such a way that dispersion of light produced by the convex lens is neutralized by the concave lens. Such a combination of lenses is called an “ Achromatic Lens”. In high class cameras and optical instruments, a complicated combination of lenses is used.

1.12.2 Spherical Aberration

In spherical aberration, parallel light rays that pass through the central region of the lens focus farther away than light rays that pass through the edges of the lens. The result is many focal points, which produce a blurry image. To get a clear image, all rays need to focus at the same point.

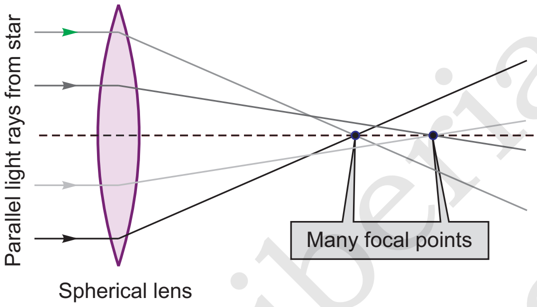


Fig. 1.22. Spherical Aberration

Correction of Spherical Aberration

This defect is removed by using a complicated lens made by combining lenses of different shapes.

1.13 DISPERSION OF LIGHT THROUGH A GLASS PRISM

Materials required:

Prism, white light and a dark room where the refraction can be clearly seen.

Procedure:

- Take the prism and keep it on the table.
- Focus a beam of light from a light source to the prism.

What do you observe? You will observe that the white light splits into 7 colours. This shows dispersion of light.

Dispersion is the splitting up of white light into seven colours on passing through a transparent medium like a glass prism.

It has been known for a long time that when a narrow beam of sunlight usually called white light, is incident on a glass prism, the emergent light is seen to be

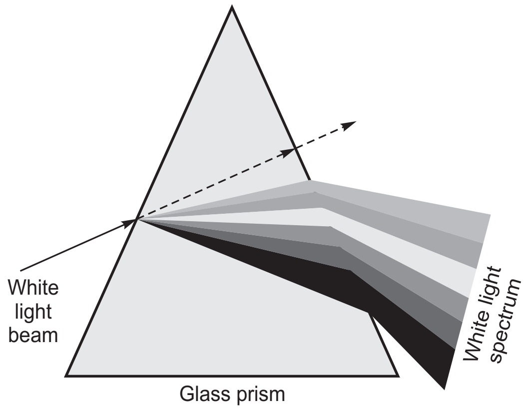


Fig. 1.23. Dispersion of sunlight or white light on passing through a glass prism. The relative deviation of different colours shown is highly exaggerated.

consisting of several colours. There is actually a continuous variation of colour, but broadly, the different component colours that appear in sequence are: violet, indigo, blue, green, yellow, orange and red (given by the acronym VIBGYOR). The red light bends the least, while the violet light bends the most (Fig. 1.23).

The phenomenon of splitting of light into its component colours is known as *dispersion*. The pattern of colour components of light is called the spectrum of light.

Example. A concave lens has focal length of 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.

Solution. A concave lens always forms image on the same side of the object.

Image-distance v = – 10 cm; Focal length f = – 15 cm;

Object–distance u = ?

Since $$\frac{1}{v} - \frac{1}{u} = \frac{1}{f} \quad \text{or} \quad \frac{1}{u} = \frac{1}{v} - \frac{1}{f}$$

$$\frac{1}{u} = \frac{1}{-10} - \frac{1}{(-15)} = -\frac{1}{10} + \frac{1}{15}$$

$$\frac{1}{u} = \frac{-3+2}{30} = \frac{1}{-30} \quad \text{or} \quad u = -30 \text{ cm}$$

Thus, the object-distance is 30 cm.

Magnification, $m = v/u$

$$m = \frac{-10 \text{ cm}}{-30 \text{ cm}} = \frac{1}{3} = +0.33$$

Example. An object is placed perpendicular to the principal axis of a convex lens of focal length 10 cm. The distance of the object from the lens is 15 cm. Find the location of the image.

Solution. Focal length, f = + 10 cm

Object-distance, u = – 15 cm

Image-distance, v = ?

Since $$\frac{1}{v} - \frac{1}{u} = \frac{1}{f} \quad \text{or} \quad \frac{1}{v} = \frac{1}{u} + \frac{1}{f}$$

$$\frac{1}{v} = \frac{1}{(-15)} + \frac{1}{10} = -\frac{1}{15} + \frac{1}{10}$$

$$\frac{1}{v} = \frac{-2+3}{30} = \frac{1}{30} \quad \text{or} \quad v = 30 \text{ cm}$$

The positive sign of v shows that the image is formed at a distance of 30 cm on the other side of the optical centre.

Example. A magician during a show makes a glass lens with $n = 1.47$ disappear in a trough of liquid. What is the refractive index of the liquid? Could the liquid be water?

Solution. The refractive index of the liquid must be equal to 1.47 in order to make the lens disappear. This means $n_1 = n_2$. This gives $1/f = 0$ or $f \to \infty$. The lens in the liquid will act like a plane sheet of glass. No, the liquid is not water. It could be glycerine.

Example. If $f = 0.5$ m for a glass lens, what is the power of the lens?

Solution. $P = 1/f = 1/0.5 = 2$ dioptre

REVIEW EXERCISE

A. MULTIPLE CHOICE QUESTIONS (MCQs)

1. Bending of a ray of light, when it enters obliquely from one medium to other is called

(*a*) reflection (*b*) refraction
(*c*) dispersion (*d*) interference.

2. The relation, $\frac{\sin i}{\sin r} = n$, is called

(*a*) Snell's law (*b*) Newton' law
(*c*) Joule's law (*d*) Boyle's law.

3. When light enters from first rarer medium to a second denser medium, then ${}^1\mu_2$ has value

(*a*) < 1 (*b*) 1
(*c*) > 1 (*d*) no definite relation

4. For light going from air to water, ${}^{a}n_{w}$ = 4/3. Then ${}^{w}n_{a}$ has value

(*a*) $\frac{16}{9}$ (*b*) $\frac{3}{2}$

(*c*) 1 (*d*) $\frac{3}{4}$.

5. In case of refraction of light from a rectangular glass slab, if i = angle of incidence and e = angle of emergence, then

(*a*) $e < i$ (*b*) $e = i$

(*c*) $e > i$ (*d*) no definite relation.

6. A lens is thick in the middle and thin at the edges. The lens is

(*a*) concave (*b*) convex

(*c*) plane (*d*) prism.

7. A lens is thin in the middle and thick at the edges. The lens is

(*a*) concave (*b*) convex

(*c*) plane (*d*) prism.

8. A lens converges rays of light. The lens is

(*a*) plane (*b*) prism

(*c*) concave (*d*) convex.

9. A lens diverges rays of light. The lens is

(*a*) plane (*b*) prism

(*c*) concave (*d*) convex.

10. A ray of light passes undeviated through a point on the principal axis. The point is

(*a*) focus (*b*) centre of curvature

(*c*) optical centre (*d*) no where.

11. For drawing a ray diagram, we take light in form of

(*a*) rays (*b*) pencil

(*c*) beam (*d*) bunch.

12. For studying refraction through a lens, we keep the lens with its refracting surface towards

(*a*) right (*b*) left

(*c*) up (*d*) down.

13. The relation between object distance u, image distance v and focal length f is called

(*a*) lens formula (*b*) mirror formula

(*c*) object formula (*d*) image formula.

14. In case of erect object having inverted image, linear magnification is
   (*a*) positive (*b*) negative
   (*c*) zero (*d*) no definite sign.

15. In case of erect object, having erect image, linear magnification is
   (*a*) positive (*b*) negative
   (*c*) zero (*d*) no definite sign.

B. FILL IN THE BLANKS

1. In refraction, a ray of light .... when it enters obliquely in some other medium.
2. The quantity, $\frac{\sin i}{\sin r} = n$ is called the .... of the medium.
3. If ${}^a n_g = 3/2$, then ${}^g n_a =$ ....
4. In case of refraction from a rectangular glass slab, angle of emergence *e* is .... angle of incidence *i*.
5. A convex lens .... rays.
6. Rays are diverged by a .... lens.
7. A ray of light passing through the optical centre of a lens goes ....
8. Object distance for an object on the left side of a lens is ....
9. Image distance for the image on the right of the lens is ....
10. Magnification is negative for an erect object and .... image.

C. VERY SHORT ANSWER TYPE QUESTIONS

1. What is meant by refraction of light?
2. Where does refraction of light occur, in the other medium or at the boundary separating the media?
3. Is speed of light in vacuum a fundamental constant?
4. What do you mean by an optical medium?
5. Where does light travel faster, in optically denser or in optically rarer medium?
6. Out of air, water and glass which is optically densest medium?
7. What does optical density of a medium signify? Is optical density of a medium same as mass density of the medium?
8. What is the minimum value of refractive index?

9. Is refractive index of a medium always constant?
10. Refractive index of medium 2 w.r.t. medium 1 is reciprocal of refractive index of medium 1 w.r.t. medium 2. Prove it.

D. SHORT ANSWER TYPE QUESTIONS

1. Identify the device used as a spherical mirror or lens in following cases, when the image formed is virtual and erect in each case.
   (*a*) Object is placed between device and its focus, image formed is enlarged and behind it.
   (*b*) Object is placed between the focus and device, image formed is enlarged and on the same side as that of the object.
2. Why does a light ray incident on a rectangular glass slab immersed in any medium emerges parallel to itself? Explain using a diagram.
3. A pencil when dipped in water in a glass tumbler appears to be bent at the interface of air and water. Will the pencil appear to be bent to the same extent, if instead of water we use liquids like, kerosene or turpentine. Support your answer with reason.
4. How is the refractive index of a medium related to the speed of light? Obtain an expression for refractive index of a medium with respect to another in terms of speed of light in these two media?
5. Refractive index of diamond with respect to glass is 1.6 and absolute refractive index of glass is 1.5. Find out the absolute refractive index of diamond.

E. LONG ANSWER TYPE QUESTIONS

1. How much time will light take to cross 2 mm thick glass pane if refractive index of glass is 3/2?
2. 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.
3. A pond of depth 20 cm is filled with water of refractive index 4/3. Calculate apparent depth of the tank when viewed normally.
4. An object of size 7.0 cm is placed at 27 cm in front of a concave mirror of focal length 18 cm. At what distance from the mirror, should a screen be placed, so that a sharp focussed image can be obtained? Find the size and nature of the image?
5. A 2.0 cm tall object is placed perpendicular to the principal axis of a convex lens of focal length 10 cm. The distance of the object from the lens is 15 cm. Find the nature, position and size of the image. Also find the magnification.