UNIT 5 LIGHT

Structure

5.1 INTRODUCTION

Much of what we know about the world around us is through light and the sense of vision. Light enables us to see and appreciate the beauty of nature and admire man-made wonders of the world. Be it rainbow in the sky, or vast diversity of hues in nature or the Taj Mahal, only light makes us to see and appreciate them all.

An age-old debate which has prescribed among scientists is related to the question, "Is light a wave or a stream of particle?" Very noteworthy and distinguished physicists have taken up each side of the argument, providing a wealth of evidence for each side. The fact is that light exhibits behaviours which are characteristics of both waves and particles.

Light is a form of energy which enables us to see objects from which light comes (or from which it is reflected). It is transferred from the source to the receiver either by the motion of the material particles or by means of wave disturbance travelling through the medium. In 1675, Sir Issac Newton submitted a paper in which he presented the fundamental postulates of his corpuscular theory of light. Phenomena of reflection, refraction, dispersion, etc. were explained successfully by this theory. Newton's corpulscular theory was followed by wave theory by Christian Huygens which explained phenomena such as interference, diffraction and polarization. Much later, the particle and the wave aspects of light were confirmed by other theories as well.

Most of the phenomenon related to light such as reflection, refraction, interference and diffraction can be understood on the basis of the wave theory of light. However, in the present unit, we shall confine ourselves to the geometrical optics such was developed before the wave theory was proposed. Geometrical optics successfully emphasis the phenomenon of reflection, refraction and image formation due to these phenomenon. The basic assumption of the geometrical optics is that light travels in a straight line. It is important to mention here that this is a simplifying assumption and is valid only when the wavelength of light is very small compared to the dimensions of the object light encounters. In fact, according to the wave theory, light do bend around objects and the bending is perceptible only when dimensions of the object are of the order of the wavelength of light.

Early studies in the field of optics were based on the concept that light consists of rays. The ray optics, therefore, uses the geometry of straight lines to account of the macroscopic phenomenon like rectilinear propagation, reflection, refraction, etc.

However, as discussed before, the microscopic phenomenon like interference, diffraction, and Doppler effect of light, could not be explained by Ray Optics. To explain these phenomenon, concept of waves was introduced. The new branch of physics based on wave concept was called wave optics.

In the present unit, you will learn propagation of light, shadows, reflection of light at plane and curved surfaces, rotation of plane mirror, refraction and total internal reflection, refraction through prism, all based on the concept of rays. At the end, you will also be introduced to diffraction.

Objectives

After studying this unit, you should be able to

- state the laws of reflection and the laws of refraction,
- draw ray diagrams for image formation by plane mirror, spherical mirrors and lenses on the basis of ray tracing rules,
- derive the mirror formula and lens formula,
- define the power of a lens,
- explain the concept of total internal reflection and the various phenomenon associated with it,
- establish a relation between refractive index, angle of minimum deviation and angle of prism for a prism, and
- discuss the working of a simple microscope, a compound microscope and a telescope.

5.2 PROPAGATION OF LIGHT

When light falls on the surface of an object, it may be

(a) absorbed,

(b) transmitted, and

(c) reflected.

Based on their ability to transmit light, substances can be broadly classified into :

(a) Transparent substances which allow light to pass through, e.g. glass, water, colourless substances, etc.

(b) Translucent substances which allow a part of the light to pass through, e.g. ground glass, oiled paper, etc.

(c) Opaque substances which do not allow light to pass through them, e.g. metals, wood, brick, etc.

Rectilinear Propagation of Light

A ray or a beam of light travels along straight lines. In our everyday life, several instances can be quoted to highlight this. Light from car headlights, torches, search lights, etc., are examples. Formation of shadows when a beam of light is intercepted by an opaque body is another example. On a bigger scale, formation of eclipses – both solar and lunar – also illustrate this principle. It must be remembered that rectilinear propagation is only an approximation, although on extremely good approximation. Later, you would learn that light actually travels in the form of waves, as evident in the phenomenon of diffraction.

Shadows

Let us consider a point source of light and an opaque obstacle in the shape of a circle. If the obstacle is held between the source and a screen, a shadow is formed on the screen. Size of the shadow obviously varies with distance between the source and the obstacle and also that between the obstacle and the screen. In the case of an extended source smaller than the object, the shadow consists of a totally dark region called "umbra" and a partially dark region called "penumbra". In the case of an extended source, larger than the object (e.g. sun), the size of umbra and penumbra change when the distances vary.

The sun (S) is a luminous body. Earth (E) and moon (M) are non-luminous bodies. What we see as moonlight is the reflection of light from the sun by the moon. Solar eclipse is caused when the moon comes in between the sun and the earth and lunar eclipse is caused when the earth comes between the sun and the moon.

Eclipses

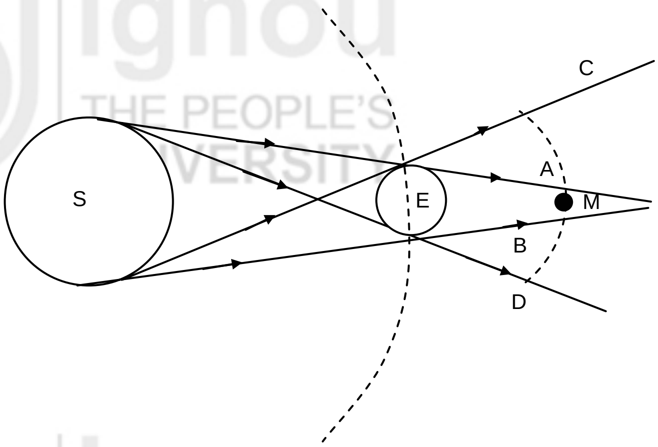


Figure 5.1

Lunar Eclipse

In Figure 5.2, the geometrical shadow formed by the earth is shown. AB represents the umbral cone and CD the penumbral cone. When the moon orbits round the earth, it enters the shadow region. When it is in the penumbral region it is partially eclipsed and when it enters to umbral cone it is totally eclipsed. Total eclipse occurs when the sun, earth and moon are in a line.

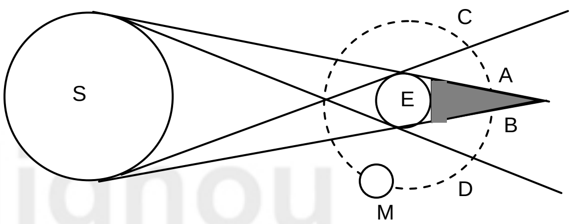
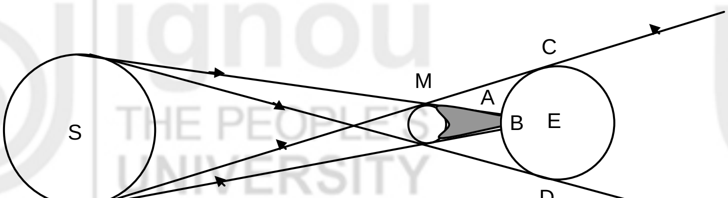


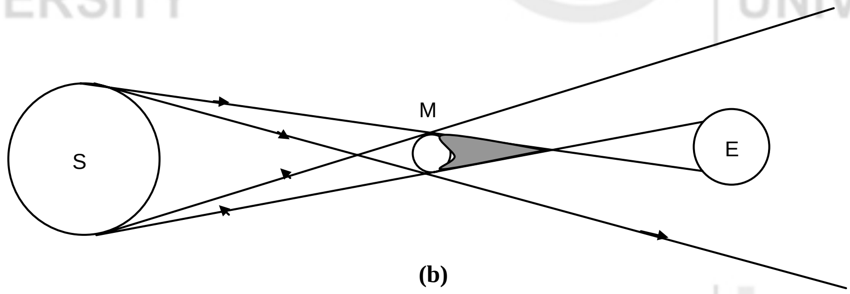
Figure 5.2

Solar Eclipse

In Figure 5.3(a), the geometrical shadow formed by the moon is shown. Places A and C are in the penumbral cone and so the persons located in this area will experience partial solar eclipse. However, place B is in the umbral zone and so any person at B will obviously experience total eclipse. One important factor to be remembered is that the earth is very much larger than the moon. The distance between the earth and the moon varies with time. Thus, if the position of the earth is such that it is beyond the umbral cone as shown in the Figure 5.3(b), observers on the earth will see either partial or annular eclipse.



(a)



(b)

Figure 5.3

5.3 REFLECTION OF LIGHT

Reflection is the phenomenon in which a ray of light meeting a surface of separation between two media returns to the same medium and in this process obeys certain laws known as "Laws of Reflection". A ray of light falling on a smooth and highly polished surface, say a mirror, gets reflected from the surface of separation.

By regular reflection, we mean that the reflected light goes in one particular direction (and not in all directions), corresponding to one particular direction of incidence.

In Figure 5.4, $M_1 M_2$ is a plane mirror. A ray of light falls on the mirror along *AB* at $\angle ABD = i$, where *BD* is normal to the mirror at *B*. it is reflected along *BC* at $\angle DBC = r$.

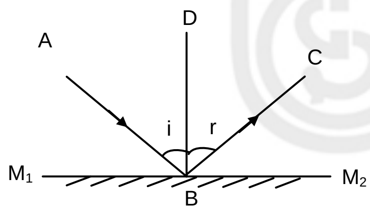


Figure 5.4

AB is the incident ray, *BC* the reflected ray and *BD* the normal at the point of incidence. Angle *i* is the angle of incidence and angle *r* the angle of reflection.

Laws of Reflection

Following are the two laws of reflection :

(a) The incident ray, normal at the point of incidence and reflected ray all lie in the same plane.

(b) The angle of incidence is equal to the angle of reflection : $\angle i = \angle r$.

Since $\angle i = \angle r$, even if we take *CB* as the incident ray, *BA* will be the reflected ray. This is known as the principle of reversibility of light.

Images

An optical image is a point where rays of light either intersect or appear to come from. Thus, image of an object is the assemblage of the image points corresponding to a large number of points, which behave like objects. Images are of two kinds. They are real and virtual. Thus, if rays of light, actually converge at a point, a real image is formed. However, if the rays of light appear to diverge from a point after reflection, the image is known as virtual image. The image which we see in a plane mirror incidentally is virtual in nature.

Reflection of Light at a Plane Surface

Let us consider a small object *O* (say, a point source of light) placed in front of a plane mirror *MM′* as shown in Figure 5.5.

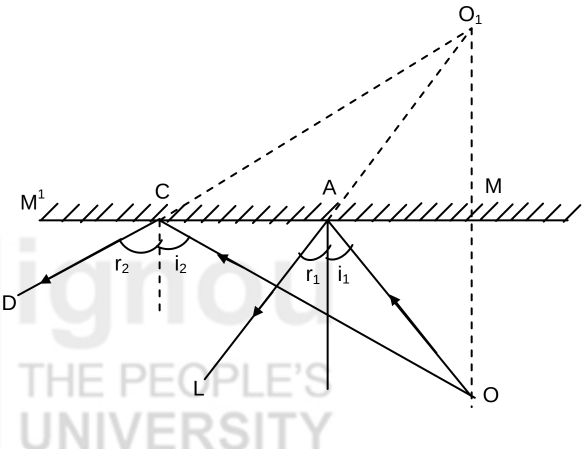


Figure 5.5

For obtaining a point image of *O*, we have to consider minimum two incident rays at different angles of incidence say $\angle i_1$ and $\angle i_2$. They get reflected at angles $\angle r_1$ and $\angle r_2$, respectively. These reflected rays diverge and so appear to come from O_1, which we call the image of *O*. The image so formed has the following characteristics :

(a) It is virtual and erect.

(b) It is laterally inverted.

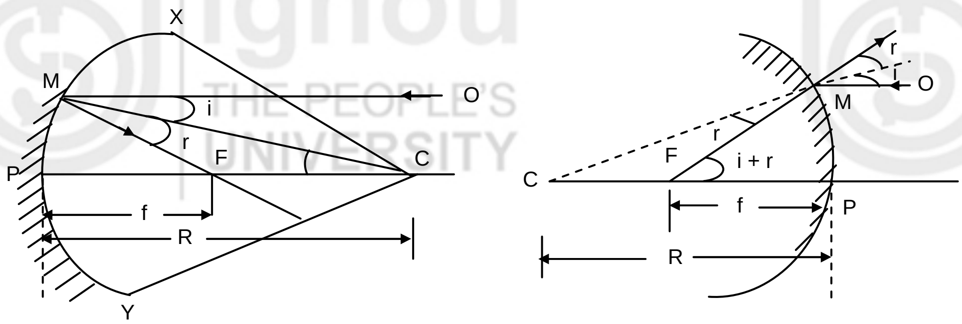
(c) Size of the object and size of the image are the same.

(d) The image is as far behind the mirror as the object is in front of it.

An extended object is just an assemblage of point objects and so the image formed is also assemblage of the point images formed.

Reflection at a Curved Surface

Curved reflecting surfaces or spherical mirrors are of two types. They are (a) concave mirror, and (b) convex mirror. Before we move on to the study of reflection at these surfaces, certain basic definitions associated with these must be understood.



(a) **(b)**

Figure 5.6

Pole of the Mirror (*P*)

Centre of the reflecting surface is called the pole of the mirror.

Centre of Curvature (*C*)

It is the centre of the sphere of which this mirror is a part.

Radius of Curvature (*R*)

It is radius of the sphere of which the mirror is a part.

Principal Axis (*PC*)

It is the line passing through the pole and the centre of curvature.

Focus (*F*)

It is the point at which a beam of light parallel to the principal axis either actually converges or appears to diverge from after reflection from the spherical surface.

Focal Length (*f*)

It is the distance between the pole and the focus.

Aperture

It is the angle subtended by the principal section of the mirror at the centre of curvature. *XCY* is the aperture.

Sign Conventions

In dealing with reflection at spherical mirrors, we shall adopt the following system of signs – called the "New Cartesian Convention" based on the conventions of Co-ordinate geometry. They are :

(a) Light is assumed to come from the left.

(b) Distances are measured from the pole (P) of the mirror.

(c) Distances measured in the direction of the incident ray are + ve and in the opposite direction – ve.

(d) Heights measured upwards and perpendicular are + ve and those measured downwards and perpendicular are – ve.

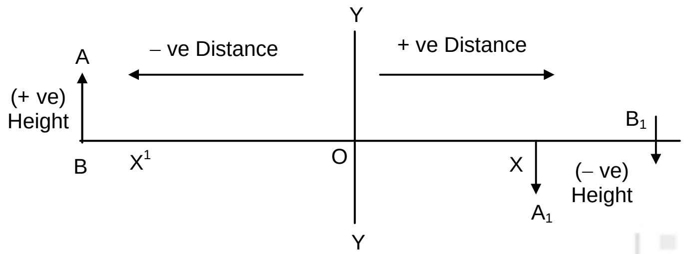


Figure 5.7

According to this convention, *f* and *R* are – ve for concave mirror and + ve for convex mirror. Magnification is negative for real and + ve for virtual image.

Relation between *f* and *R*

Concave Mirror

In Figure 5.8, *P* is pole, *C* is centre of curvature and *F* is principal focus of a concave mirror of small aperture.

Let us consider a ray of light parallel to the principal axis. This, after reflection at the spherical surface, will pass through the focus *F*. At the point of incidence *M*, $i = r$.

$$\angle OMC = i = \angle MCF \text{ (Alternate angles)}$$

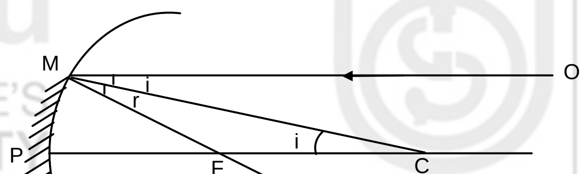


Figure 5.8

$\therefore$ In the Δ MCF, $MF = CF$.

Also, $MF = PF$, (Q Aperture is small)

Thus, $PF = CF$, i.e. F is the centre of PC

But $PC = R$ and $PF = f$.

Now $$PF = \frac{1}{2} PC$$

i.e. $$-f = -\frac{R}{2}$$

$\Rightarrow$ $$f = \frac{R}{2}$$

$\therefore$ $$R = 2f$$

In other words, radius of curvature is twice the focal length of the spherical mirror.

Convex Mirror

In Figure 5.9, P is pole, C is centre of curvature and F is the principal focus of a convex mirror of small aperture. Let us consider a ray of light parallel to the principal axis. It gets reflected along MN and on producing back, it appears to come from the principal focus F. Join CM and produce it to L. This is normal to the mirror at M.

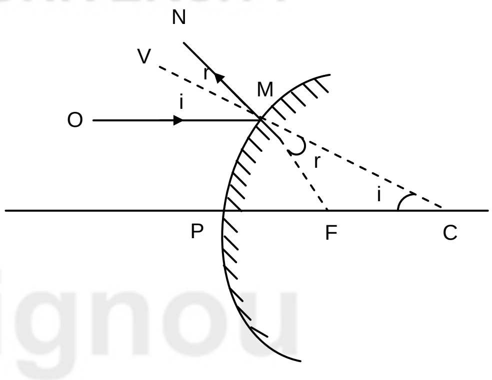


Figure 5.9

$\angle OML = i$ (Angle of incidence)

$\angle NML = r$ (Angle of reflection)

Now $\angle FMC = \angle NML = r$ (Opposite angles)

$\angle MCF = \angle LMO = i$ (Corresponding angles)

In Δ CMF, as $i = r$ (Law of reflection)

$CF = FM$

But $FP = FM$ (Q Aperture is small)

$CF = FP$

or F is the middle point of PC,

$$PF = \frac{1}{2} PC$$

$$\therefore \quad f = \frac{R}{2}$$

i.e. focal length of a convex mirror is equal to half its radius of curvature.

Note that both, f and R are positive for a convex mirror and negative for a concave mirror.

Mirror Formula for Concave Mirror

Mirror formula is a relation between focal length of the mirror and distance of object and image from the mirror.

Let P be the pole, F, the principal focus and C, the centre of curvature of a concave mirror of small aperture. Let $PF = f$, be focal length and $PC = R$ be the radius of curvature of the mirror.

Depending on the position of the object, the image formed may be real or virtual.

Real Image

When the object is held in front of the concave mirror beyond the principal focus F of the mirror, image formed is real.

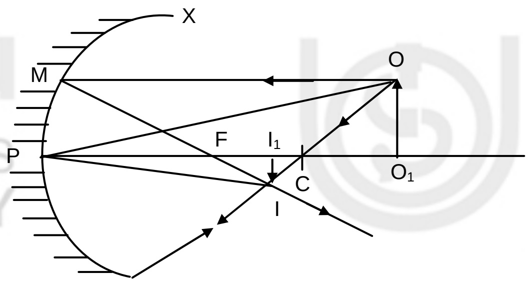


Figure 5.10

Let us consider a ray of light OM in Figure 5.10, parallel to the principal axis from an object OO_1. After reflection, it will pass through F. Similarly, a ray of light from O, passing through C, after reflection will retrace its path. The two reflected rays meet at I. Thus, I is the image of O. In the case of the extended object OO_1, I_1 will be the image of O_1 and so $I I_1$ is the image of OO_1. A ray OP is also reflected to I. We have

$$\angle OCO_1 = \angle ICI_1 \text{ (opposite angles)}$$

In Δs $OO_1 C$ and $I I_1 C$

$$\therefore \quad \frac{OO_1}{II_1} = \frac{CO_1}{CI_1} = \frac{PO_1 - PC}{PC - PI_1} = \frac{-u-(-R)}{-R-(-v)} = \frac{R-u}{v-R} = \frac{u-R}{R-v} \quad \ldots (5.1)$$

In Δs $OO_1 P$ and $I I_1 P$ are also similar because these are right-angled triangles and angles OPF and IPF are equal. Thus,

$$\therefore \quad \frac{OO_1}{II_1} = \frac{PO_1}{PI_1} = \frac{-u}{-v} = \frac{u}{v} \quad \ldots (5.2)$$

From Eqs. (5.1) and (5.2)

$$\frac{u}{v} = \frac{u-R}{R-v} = \frac{u-2f}{2f-v}$$

$$\therefore \qquad u(2f - v) = (u - 2f)v$$

or, $$2uf - uv = uv - 2fv$$

or, $$2uf + 2vf = 2uv \qquad \ldots (5.3)$$

Dividing throughout by $u\,v\,f$

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

This is often referred to as the "mirror formula".

Virtual Image

When the object is held in front of the concave mirror between the pole P and principal focus F of the mirror, the image formed is virtual, erect and magnified as shown in Figure 5.11.

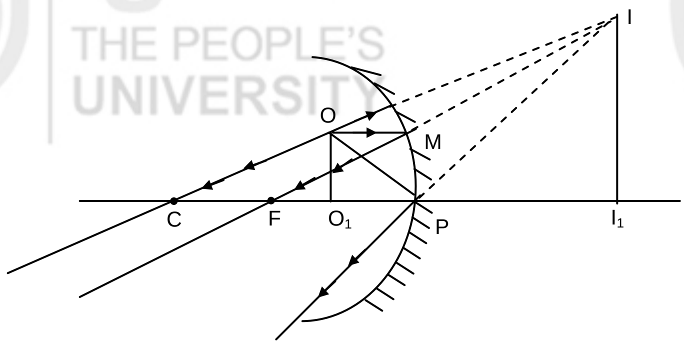


Figure 5.11

$\Delta\, COO_1$ and $\Delta\, CII_1$, are similar, we can write

$$\frac{OO_1}{II_1} = \frac{CO_1}{CI_1} = \frac{CP - PO_1}{CP + PI_1} = \frac{-R-(-u)}{-R+v} = \frac{u-R}{v-R} \qquad \ldots (5.4)$$

Now, $\Delta\, OO_1P$ and $\Delta\, II_1P$ are also similar,

$$\frac{OO_1}{II_1} = \frac{PO_1}{PI_1} = \frac{-u}{v} \qquad \ldots (5.5)$$

From Eqs. (5.4) and (5.5), we get

$$\frac{u-R}{v-R} = -\frac{u}{v}$$

$$\Rightarrow \qquad uv - Rv = -uv + Ru$$

$$\Rightarrow \qquad Ru + Rv = 2uv$$

Dividing both side by $u\,v\,R$, we get

$$\frac{1}{v} + \frac{1}{u} = \frac{2}{R} = \frac{1}{f}$$

which is the required mirror formula.

Mirror Formula for Convex Mirror

The image formed in a convex mirror is always virtual and erect, whatever be the position of the object.

Let P be the pole, F the principal focus, and C, the centre of curvature of a convex mirror of small aperture, as shown in Figure 5.12.

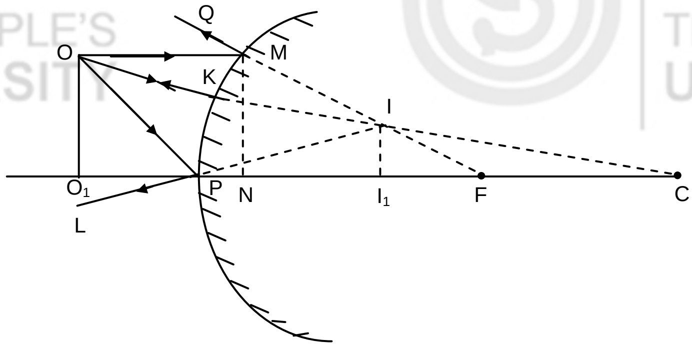


Figure 5.12

Let $PF = f$, the focal length, and $PC = R$, the radius of curvature of the mirror.

OO_1 is an object held in front of mirror perpendicular to its principal axis. The ray of light from point O of the object travelling parallel to the principal axis falls on point M on the mirror and is reflected along MQ, such that it appears to come from focus F of the convex mirror. Another ray of light incident at pole is reflected according to the laws of reflection along PL, so that $\angle OPO_1 = \angle O_1, PL$. Also, the ray of light from point O incident on the mirror towards point C along OK will be reflected back and it will also appear to come from point I. The rays QM, OK and PL appear to come from point I, so that the point I is image of the point O of the object. In the same manner, the image at every point on object OO_1 will be produced at a corresponding point of II_1, so that II_1 is the virtual image of the object OO_1 as formed by the convex mirror. Form point M, drop MN perpendicular to the principal axis.

Now, triangles $II_1\,F$ and MNF are similar.

Therefore, $$\frac{II_1}{MN} = \frac{I_1F}{NF}$$

As aperture of the convex mirror is small, $NF \;;\; PF$.

Also $$NM = OO_1$$

Therefore, $$\frac{II_1}{OO_1} = \frac{I_1F}{PF} = \frac{PF - I_1P}{PF} \qquad \text{. . . (5.6)}$$

Also, triangle $OO_1\,P$ and $II_1\,P$ are similar. Therefore,

$$\frac{II_1}{OO_1} = \frac{PI_1}{PO_1} \qquad \text{. . . (5.7)}$$

From Eqs. (5.6) and (5.7), we get

$$\frac{PF - I_1P}{PF} = \frac{PI_1}{PO_1} \qquad \text{. . . (5.8)}$$

Applying sign conventions, we have

$$PO_1 = -u$$

$$PI_1 = +v$$

$$PF = +f$$

Substituting for PO_1, PI_1 and PF in Eq. (5.8), we get

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

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

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

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

which is the required mirror formula.

Linear Magnification

The ratio of the size of the image produced by a spherical mirror to the size of the object placed, is called linear magnification (or simply magnification) produced by the spherical mirror. It is denoted by *m*.

Thus, $$m=\frac{\text{Size of image}}{\text{Size of object}}$$

If the size of object and image are denoted by h_1 and h_2 respectively, then

$$m=\frac{h_2}{h_1}=\frac{II_1}{OO_1} \qquad \text{. . . (5.9)}$$

Magnification (m) will be positive when h_2 is positive (i.e. image is erect) and (m) will be negative, when h_2 is negative (i.e. image is inverted). We assume that h_1 is always positive.

From Eq. (5.7), we get

$$\frac{II_1}{OO_1}=\frac{PI_1}{PO_1}$$

Magnification produced by concave mirror.

We know $$\frac{II_1}{OO_1}=\frac{PI_1}{PO_1}$$

Apply new Cartesian sign convention, we have

$II_1 = -h_2$ (height measured downwards)

$OO_1 = +h_1$ (height measured upward)

$PI_1 = -v$ (distance measured against incident height)

$PO_1 = -u$ (distance measured against incident height)

Therefore, the above equation becomes

$$\frac{-h_2}{h_1}=\frac{-v}{-u}$$

$\Rightarrow$ $$\frac{h_2}{h_1}=-\frac{v}{u} \qquad \text{. . . (5.10)}$$

From Eqs. (5.9) and (5.10), we get

$$m=\frac{h_2}{h_1}=-\frac{v}{u}$$

Magnification Produced by Convex Mirror

Figure 5.12 shows the formation of image II_1 of object OO_1 by a convex spherical mirror.

From Eq. (5.7), we get

$$\frac{II_1}{OO_1} = \frac{PI_1}{PO_1} \qquad \ldots (5.11)$$

Applying new Cartesian sign conventions, we have

$$II_1 = +h_2,\ OO_1 = +h_1,\ PI_1 = +v,\ PO_1 = -u$$

Therefore, Eq. (5.11) becomes

$$\frac{+h_2}{+h_1} = \frac{+v}{-u} \ \Rightarrow\ \frac{h_2}{h_1} = -\frac{v}{u} \qquad \ldots (5.12)$$

From Eqs. (5.9) and (5.12), we have

$$m = \frac{h_2}{h_1} = -\frac{v}{u}$$

Therefore, it follows that magnification produced by a spherical mirror (both concave and convex) is given by

$$m = \frac{h_2}{h_1} = -\frac{v}{u}$$

When $m > 1$, image formed is enlarged, and

$m < 1$, image formed is diminished.

Again when m is positive, image must be erect (i.e. virtual).

when m is negative, image must be inverted (i.e. real).

Other Formula for Magnification

From mirror formula,

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

Multiplying both sides by v, we get

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

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

For virtual images in both types of mirrors,

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

Again multiplying both sides of mirror formula by u, we get

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

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

But $m = -\frac{v}{u}$, so we can write,

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

Example 5.1

An object is placed at a distance of 20 cm from the pole of a concave mirror. If the focal length of the mirror is 10 cm, find the nature and position of the image.

Solution

$u = -20$ cm, $f = -10$ cm $v = ?$ $M = ?$

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

$$\therefore \quad \frac{1}{v} = \frac{1}{f} - \frac{1}{u} = -\frac{1}{10} - \frac{1}{(-20)} = \frac{-2+1}{20} = \frac{-1}{20}$$

$$\therefore \quad v = -20 \text{ cm} \qquad M = \frac{-20}{-20} = 1$$

Image is real and of the same size as the object.

Example 5.2

An object 10 cm high is placed on the axis and 10 cm from the pole of a concave mirror of focal length 15 cm. Find the nature, size and position of the image.

Solution

$f = -15$ cm; $u = -10$ cm; size of object = 10 cm; $v = ?$ $m = ?$

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

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

$$\frac{1}{v} = -\frac{1}{15} - \frac{1}{(-10)} = \frac{-2+3}{30} = \frac{1}{30}$$

$\therefore$ $v = 30$ cm (Image is virtual.)

$$m = \frac{\text{Size of Image}}{\text{Size of Object}} = \frac{v}{u} = \frac{+30}{-10} = -3$$

$$\therefore \quad -3 = \frac{\text{Size of Image}}{10}$$

$\therefore$ Image is 30 cm high, erect, virtual and $v = -30$ cm.

Example 5.3

When an object is kept at a distance of 30 cm from a convex mirror, image is formed at 10 cm from the mirror. If the object distance is doubled where will the image be?

Solution

$u_1 = -30$ cm; $v_1 = +10$ cm; $u_2 = -60$ cm; $v_2 = ?$
(Convex mirror always forms virtual image)

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

$$-\frac{1}{30} + \frac{1}{10} = -\frac{1}{60} + \frac{1}{v_2} = \frac{1}{f}$$

$$\frac{1}{v_2} = \frac{1}{60} - \frac{1}{30} + \frac{1}{10} = \frac{1-2+6}{60} = \frac{5}{60} = \frac{1}{12}$$

$$\therefore \quad v_2 = 12 \text{ cm}$$

SAQ 1

(a) Find the size, nature and position of image formed when an object of size 1 cm is placed at a distance of 15 cm from a concave mirror of focal length 10 cm.

(b) An object of 2 cm high is placed at a distance of 16 cm from a concave mirror which produces a real image 3 cm high.

(i) what is the focal length of the mirror, and

(ii) find the position of the image.

(c) An object is placed in front of a concave mirror of radius of curvature 40 cm at a distance of 10 cm. Find the position, nature and magnification of the image.

(d) A square wire of side 3.0 cm is placed 25 cm away from a concave mirror of focal length 10 cm. What is the area enclosed by the image of the wire? The centre of the wire is on the axis of the mirror, with its two sides normal to axis.

(e) An object, 4.0 cm in size is placed 25.0 cm in front of a concave mirror of focal length 15.0 cm. At what distance from the mirror should a screen be placed in order to obtain a sharp image? Find the nature and the size of the image.

(f) Draw the ray diagrams to locate the position of the image formed by a concave mirror when the object is placed at

(i) a point between the focus and centre of curvature,

(ii) the focus, and

(iii) a point between focus and the pole of the mirror.

5.4 ROTATION OF PLANE MIRROR AND SEXTANT

In this section, you will be introduced to the rotation of a plane mirror. It plays a vital role in designing optical instruments used in merchant marine.

5.4.1 Deviation by Reflection at a Single Plane Mirror Surface

The incident ray *AB* makes an angle *i* with the normal *BD* and is reflected at an angle *r*, again with the normal. But $\angle i = \angle r$. Thus the deviation of the incident ray $\delta = \pi - (i + r) = \pi - 2i$.

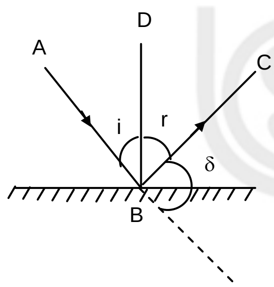


Figure 5.13

5.4.2 Deviation of the Reflected Ray by Rotating a Mirror

Consider a ray *AB* incident on a plane mirror and reflected along *BC*. The mirror is rotated in the clockwise direction through an angle θ. Since angle of incidence = angle of reflection, $i + \theta = r - \theta + 2\theta$. So, if the direction of the incident ray does not change and if the mirror is rotated through an angle θ, the reflected ray gets deviated by 2θ. This principle is used in a sextant.

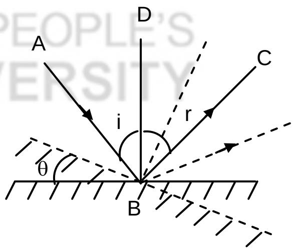


Figure 5.14

5.4.3 Sextant

This is one of the most useful instruments, used to measure on board a ship the altitude of the sun and also height of an object.

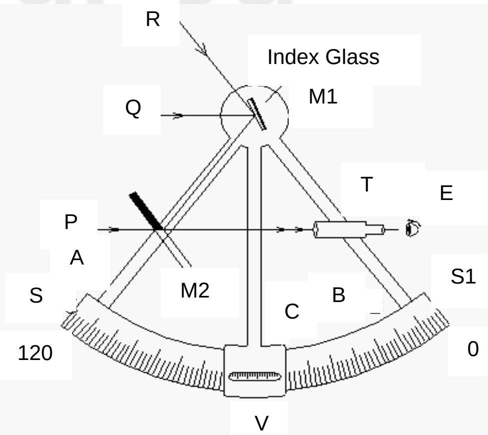


Figure 5.15

Description

It consists of a graduated circular arc SS_1 of about 60° having two radial fixed arms *A* and *B* and a third movable arm *C*, known as the Index Arm (Figure 5.15). Since SS_1 forms a sixth of a complete circle, the instrument is named sextant. The index arm has a plane mirror M_1 at the top and a vernier which moves over the scale SS_1 at the bottom. This arm is fitted with clamp and tangent screw so that it can be adjusted at any desired position. The plane mirror is perpendicular to the plane of the arm SS_1. The arm *A* carries a fixed mirror M_2 called the horizon glass, one half of which is silvered and the other half is transparent. The arm *B* carries a telescope *T* in front of M_2. The axis of the telescope passes through the line separating the two halves of the mirror M_2. Telescope *T* receives direct rays through the transparent portion of M_2 and the twice reflected rays from M_1 and M_2.

Principle

The sextant operates on the principle that when a plane mirror is rotated through an angle θ, the reflected ray gets rotated through angle 2θ.

Working

The sextant measures the angle subtended by two distant points in the same vertical or horizontal plane. To measure the angle between two points in the vertical plane, the sextant is fixed so that the telescope *T* and the horizon glass M_1 are looking at the lower point. At this stage, image of the lower point is visible directly through the transparent part of M_2. Movable arm *C* is so adjusted that the image of the lower point after reflection through M_1 and the mirror image of M_2 coincides with the direct image. Now the zero of the main scale and the zero of the vernier should coincide. If not, there is a zero error which is noted. Movable arm *C* is now rotated till the reflected image of the upper point after reflection from M_1 and M_2 coincides with the direct image of the lower point. Readings of both the main and the vernier scales are taken and the observed reading is noted. Zero error is to be subtracted. The angle between the two readings is twice the angle through which the arm *C* has rotated. To facilitate this, the scale SS_1 is marked as twice the actual degrees.

Uses

As stated earlier a sextant can be put to use in the following manner :

To Measure the Height of an Object

Let *AB* be the building with *A* as the top and *B* the bottom (Figure 5.16). These two correspond to the upper and lower points described as part of

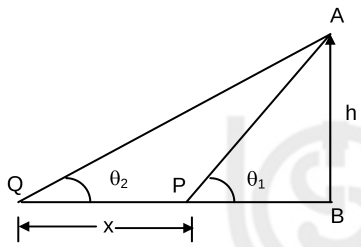


Figure 5.16

working. Thus, the angle θ_1 is measured with the sextant at a point *P*. It is then moved away through a known distance *x* to *Q* and the angle between top and the bottom is once again measured as say θ_2. Then,

$$\tan\theta_2 = \frac{h}{BQ}; \quad \tan\theta_1 = \frac{h}{BP}$$

$$\therefore \qquad BQ = h\cot\theta_2$$

$$BP = h\cot\theta_1$$

$$BQ - BP = x = h\,[\cot\theta_2 - \cot\theta_1]$$

i.e.
$$h = \frac{x}{(\cot\theta_2 - \cot\theta_1)}$$

To Measure Altitude of the Sun

It is the angle between the horizon and the direction of the sun at a place. It is difficult to get a horizon and so an artificial horizon is used in the form of a horizontal surface of mercury taken in a dish as shown in Figure 5.17.

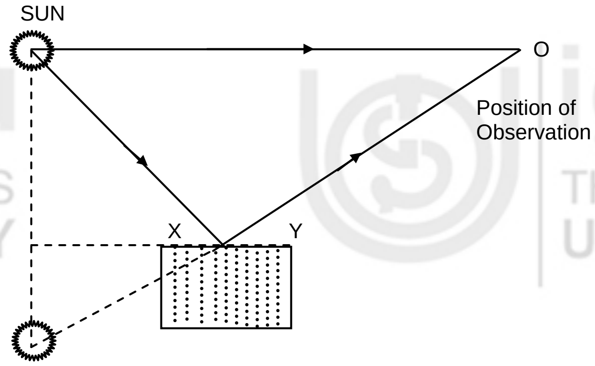


Figure 5.17

To start with, the zero error is measured as say θ_1. Now, the artificial horizon *XY* is placed in such a position that the image of the sun can be seen both directly and by reflection. The movable arm *C* is rotated till the image formed by reflection from the two mirrors M_1 and M_2 coincides with the direct image. Let this be θ_2. If α is the elevation of the sun.

$$2\alpha = \theta_2 - \theta_1 \text{ or } \alpha = \frac{\theta_2 - \theta_1}{2}.$$

5.5 REFRACTION OF LIGHT

Refraction of light is the phenomenon of change in the path of light, when it goes from one medium to another.

When a ray of light enters from one medium into a second transparent medium, such as glass, a part of it is reflected while the remaining major part is allowed to pass through the second medium. However, while doing so, the ray suffers a deviation from its original path. This is known as refraction. The ray through the first medium is the incident ray and that through the second is known as refracted ray. The refracted ray bends either towards or away from the normal at the point of incidence depending upon the optical density of the medium. Experimentally, it is found that the velocity of light in the second medium is different.

5.5.1 Laws of Refraction

These are known as Snell's Laws of Refraction. They are :

(a) The incident ray, the normal at the point of incidence and the refracted ray all lie in the same plane.

(b) For the given two media, the ratio of sine of angle of incidence to the sine of angle of refraction is a constant for a light beam of a particular wavelength for the given two media.

5.5.2 Refraction at a Surface Separating Two Media

As shown in Figure 5.18, let

AO = Incident ray,

NO = Normal at the point of incidence,

OB = Refracted ray,

CD = Surface of separation between the media M_1 and M_2,

i = Angle of incidence, and

r = Angle of refraction.

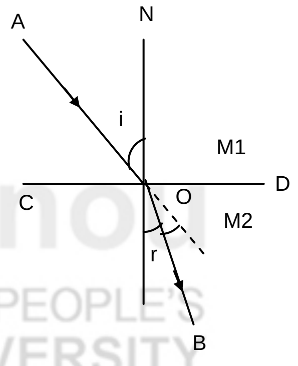


Figure 5.18

Thus, $$\frac{\sin i}{\sin r} = {}^1\mu_2 = \frac{\mu_2}{\mu_1} = \text{constant}$$

The constant is called the refractive index of M_2 with respect to M_1. Hence written as ${}^1\mu_2$. When $\mu_2 > \mu_1$, $i > r$ and so the refracted ray bends towards the normal, in a similar manner, when $\mu_2 < \mu_1$, $i <$ r and so the refracted ray goes away from the normal. Refractive index of a medium may also be defined in terms of velocity of light. Thus, the absolute refractive index of any medium is the ratio of the velocity of light in vacuum to the velocity of light in that medium, i.e.

$$\mu_{medium} = \frac{\text{Velocity of light in vacuum}}{\text{Velocity of light in the medium}}$$

If we say that μ_{glass} is 1.5, its physical significance is that, if velocity in vacuum is 3×10^8 m/s, that in the medium is 2×10^8 m/s, or the velocity of light in glass is 2/3 times the velocity of light in vacuum.

5.5.3 Refraction Through a Number of Media

Let us consider that a ray of light is entering a glass medium from air. Subsequently, this ray enters water and finally emerges into air medium as shown in Figure 5.19.

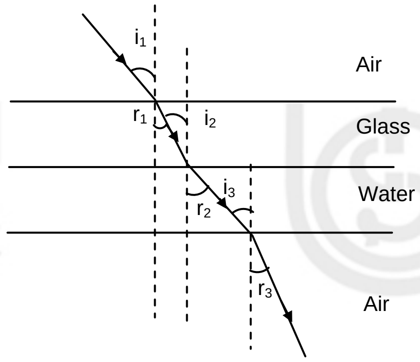


Figure 5.19

$$^{a}\mu_g = \frac{\sin i_1}{\sin r_1};\quad {}^{g}\mu_w = \frac{\sin i_2}{\sin r_2};\quad {}^{w}\mu_a = \frac{\sin i_3}{\sin r_3}$$

Since the first and the last are the same media, the ray travels undeviated.

i.e. $\left.\begin{aligned} i_1 &= r_3 \\ r_1 &= i_2 \\ r_2 &= i_3 \end{aligned}\right\}$ Alternate angles.

$$\therefore \quad {}^{a}\mu_g \times {}^{g}\mu_w \times {}^{w}\mu_a = \frac{\sin i_1}{\sin r_1} \times \frac{\sin i_2}{\sin r_2} \times \frac{\sin i_3}{\sin r_3} = 1$$

$$\therefore \quad {}^{g}\mu_w = \frac{1}{{}^{a}\mu_g \times {}^{w}\mu_a} = \frac{{}^{a}\mu_w}{{}^{a}\mu_g}, \because \ {}^{w}\mu_a = \frac{1}{{}^{a}\mu_w} = \frac{\mu_w}{\mu_g}$$

5.5.4 Total Internal Reflection

We know that a ray of light entering a rarer medium from a denser medium goes away from the normal, i.e. $r > i$. If we keep on increasing the angles of incidence, angles of refraction also increase in such a way that $\sin i / \sin r$ = Constant. However, a stage comes when the angle of refraction becomes 90°. In other words, the refracted ray grazes along the surface separating the two media. The angle of incidence for $r = 90°$ is known as critical angle (i_c). If the angle of incidence is further increased, refraction does not take place at the surface separating the two media. Instead, reflection takes place. This is known as total internal reflection. Let us consider a ray of light entering from glass into air as shown in Figure 5.20.

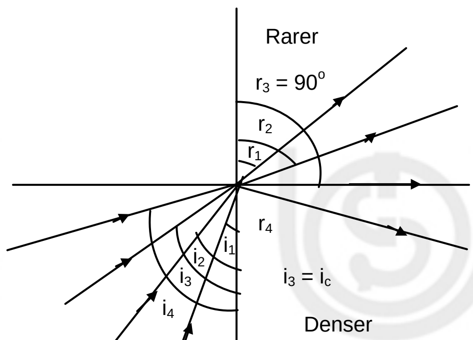


Figure 5.20

When $i = i_c$, $r = 90°$.

Thus, $$\frac{\sin i}{\sin r} = {}^a\mu_w = \frac{1}{{}^g\mu_a} = \frac{1}{\mu}$$

i.e. $$\sin i_c = \frac{1}{\mu} \quad (\because\ r = 90^o \text{ and } \sin 90 = 1)$$

If the refractive index of a medium is known, the critical angle in that medium can be calculated.

Therefore, total internal reflection may be defined as the phenomenon of reflection of light that takes place, when a ray of light travelling in a denser medium gets incident at the interface of the two media at an angle greater than the critical angle for that pair of media.

Thus, for the total internal reflection to take place, following conditions should be obeyed :

(a) Light should travel from a denser medium to a rarer medium.

(b) Angle of incidence in denser medium should be greater than the critical angle for the pair of media in contact.

Example 5.4

The refractive index of glass is 7.5. What is the speed of light in glass? Speed of light in vacuum is 3.0×10^8 ms^{-1}.

Solution

Here $\mu = 1.5$, $c = 3 \times 10^8$ ms^{-1}.

Speed of light in glass, $$v = \frac{c}{\mu} = \frac{3.0 \times 10^8}{1.5} = 2.0 \times 10^8 \text{ ms}^{-1}$$

Example 5.5

Refractive indices of water and glass are $\frac{4}{3}$ and $\frac{3}{2}$, respectively. A ray of light travelling in water is incident on the water-glass interface at 30^o. Calculate the angle of refraction.

Solution

Here, the refractive index of glass ${}^a\mu_g = \frac{4}{3}$.

The refractive index of water ${}^a\mu_w = \frac{3}{2}$.

Now, we know ${}^a\mu_w \times {}^w\mu_g = {}^a\mu_g$.

Therefore, the refractive index of glass w.r.t. water

$${}^w\mu_g = \frac{{}^a\mu_g}{{}^a\mu_w} = \frac{\frac{3}{2}}{\frac{4}{3}} = 1.125$$

In this problem, $i = 30^o$, $r = ?$

We know that $\dfrac{\sin i}{\sin r} = 1.125$

$$\sin r = \frac{\sin 30^o}{1.125} = 0.4444 \quad \text{or} \quad i = 26^o\, 23'$$

SAQ 2

(a) Calculate the critical angle for a glass-water interface if the refractive indices of glass and water are $\frac{3}{2}$ and $\frac{4}{3}$, respectively.

(b) A ray of light is incident from glass on the interface separating it from air at an angle of 40^o and is deviated through 15^o. Calculate the critical angle for the glass-air surface.

(c) Monochromatic light of wavelength 600 nm is incident from air on a glass surface. What are the wavelength, frequency, and speed of the refracted light? Take μ of glass as 1.5.

5.6 MIRAGE AND OPTICAL FIBRE

In this section, we will study mirage and optical fibre. Of these, mirage is an optical illusion which can be explained based on the phenomenen of total internal reflection. Optical fibre, on the other hand, is again a thing which uses this principle and so can be used extensively for a variety of purposes.

5.6.1 Mirage

Mirage is an optical illusion which occurs usually in deserts on hot summer rays.

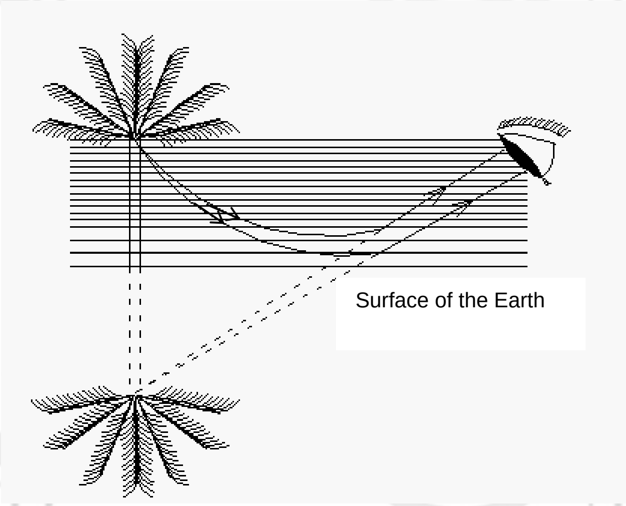


Figure 5.21

As stated earlier, it is an optical illusion in which inverted images of distant objects are seen as if reflected from a water surface. Sometimes, it even gives the impression that the object is suspended in air in the atmosphere.

In deserts, because of the intense heat, layers of air near the surface of the earth are hotter compared to the layers above them. Hence the density and the refractive index of these layers are different from those in the higher levels. Rays of light from a distant object, thus, pass through layers whose refractive indices gradually decrease. As a result, they go away from the normal, till they are incident on a layer where the angle of incidence is greater than the critical angle. Sure enough, total internal reflection takes place. These reflected rays travel upwards and undergo a series of refraction through various layers till they reach the eye of the observer, who sees the image of the object as though reflected from the surface of a calm lake.

5.6.2 Looming

In cold countries, due to mist and fog, a distant ship cannot be seen clearly. However, because of total internal reflection, the image of the ship appears to be hanging in the air for a person on the shore. As we know already, layers of air closer to the earth are denser

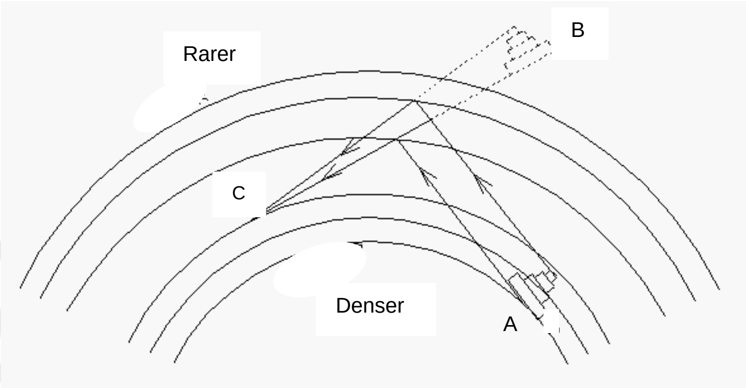


Figure 5.22

compared to the layers above. Thus, the rays from the ship pass from denser to rarer media successively and so travel away from the normal. Ultimately, they suffer total internal reflection. For a person on the shore these rays appear to come from the sky.

5.6.3 Light Pipe and Optical Fibres

Operation of a light pipe is based on total internal reflection. Unlike a normal pipe wherein water poured through one end will come out through the other because of the hole, in the case of light pipe, the hole is replaced by a transparent medium and so light entering one end of the pipe comes out through the other after multiple total internal reflections. The pipe consists of a high refractive index medium surrounded by a low index medium. It may be polished rod of glass or transparent plastic. Because of multiple reflections, an image cannot be passed through such a pipe. But the image can be broken

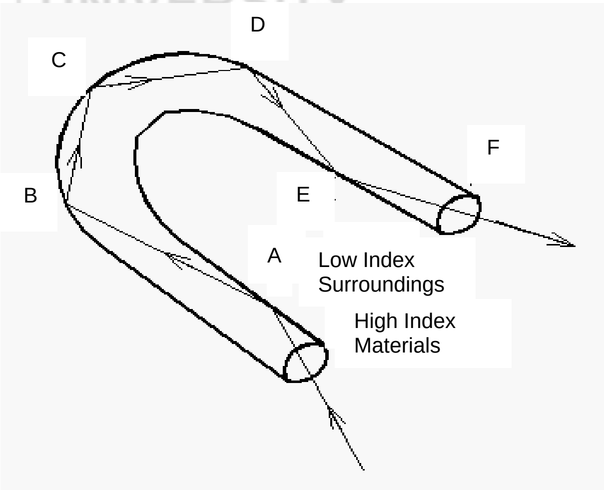


Figure 5.23

down to a large number of fine dots of various shades of light and darkness and each portion of the image is then sent through a small light pipe. A bundle of glass fibres, each behaving like a light pipe, will transmit an image if the arrangement at the point of emergence of the rays is the same as what it is at the entrance. A lens is used to cast an image on one end of the bundle and the image is then transmitted to the other end. Precaution is taken to coat each fibre with a material of low refractive index so that light through one fibre does not enter the other. Bundles in which the order of the fibres is not maintained will transmit light, though not images. Such pipes are needed to illuminate places difficult to reach. The use of this principle is so broad that a new area known as

fibre optics has been developed. In practice, glass fibres of diameter of about 2 microns are commonly used. Of late, these have been replaced by transparent plastics.

5.6.4 Use of Optical Fibres

One major use of fibre optics is in the medical field wherein this is used for internal examination of parts of the body. For example, the light pipe can be inserted into the stomach through the mouth to examine the stomach for ulcers. Light transmitted through the outer layers of the light pipe is scattered by the stomach wall and transmitted through

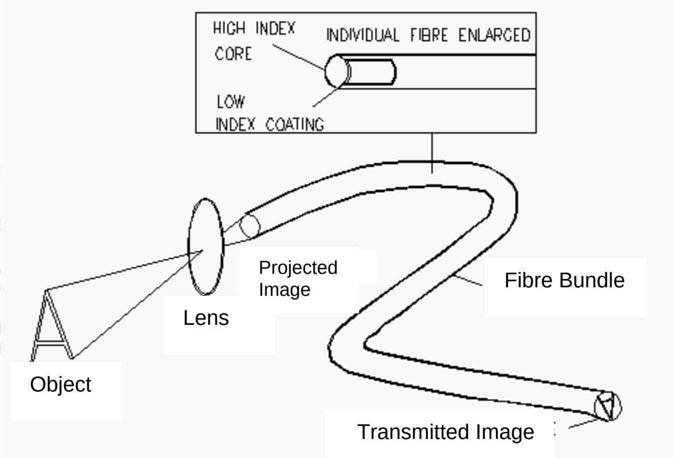


Figure 5.24

the central portion of the fibre bundle to produce an image of the stomach wall. This image can either be observed or recorded photographically. Fibres being extremely thin and numerous, excellent details can be achieved in the final image received. These light pipes are also used for transmitting high intensity laser beams for use in surgery. Use of fibre optics in the field of medicine reveals that a simple principle of physics can be put to effective use in other fields as well.

SAQ 3

To a fish under water viewing obliquely a fisherman standing on the bank of a lake, does the man look taller or shorter than what he actually is?

5.7 DISPERSION OF LIGHT

A prism is the portion of transparent refracting medium bounded by two plane surfaces meeting each other along a straight edge.

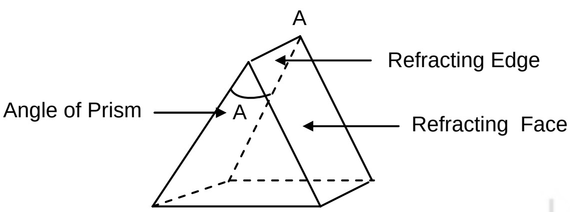


Figure 5.25

The two plane surfaces are called refracting faces and the line where the two refracting faces meet is called the refracting edge of the prism. The angle between the two refracting faces is called the angle of the prism and it is usually denoted by *A*.

Prisms and lenses, normally made of different types of glass are useful in the construction of optical instruments used on board the ship. While lenses are used as refracting media, the ability of the prisms to carryout total internal reflection of the incident rays is put to effective use in periscopes, azimuth mirror and prism binocular.

5.7.1 Refraction Through a Prism

When a ray of light enters the first surface of a prism, it undergoes refraction, i.e. the refracted ray through the prism bends closer to the normal. When it emerges through the second surface, once again it gets refracted. However, since it enters air (a rarer medium) from glass (a denser medium), the emergent ray goes away from the normal. Thus, it is obvious that the incident ray suffers a deviation 'δ' as shown in Figure 5.26. For different angles of incidence, angle of deviation also varies. The minimum deviation for the given prism, known as 'δ_m' is found out with the help of an experiment. The angle of the prism *A* is known.

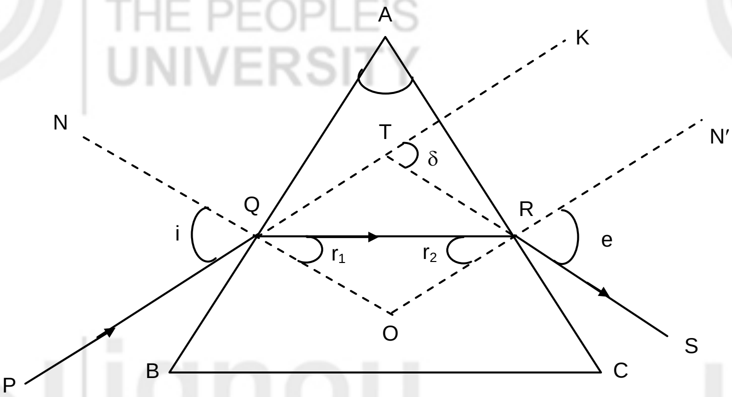


Figure 5.26

Here i = Angle of incidence,

r_1 and r_2 = Angles of refraction in the medium,

e = Angle of emergence, and

δ = Angle of deviation.

To prove $\boldsymbol{A + \delta = i + e}$

Since $\angle TQO = i$ and $\angle RQO = r_1$

We have $\angle TQR = i - r_1$

Also, $\angle TRO = e$ and $\angle QRO = r_2$

Now, we can write $\angle TRQ = e - r_2$

From Δ *TQR*, the side *QT* has been extended outwards. Therefore, the exterior and δ should be equal to sum of the interior opposite angle

$$\delta = (i - r_1) + (e - r_2)$$

$$= (i - e) - (r_1 + r_2)$$

From Δ *QRO*, we can have

$$r_1 + r_2 + \angle QOR = 180^o$$

Again $$A + \angle QOR = 180^o$$

From the above condition, we can write

$$r_1 + r_2 = A$$

So, $\delta = i + e - A$

and $A + \delta = i + e$

Thus, when a ray passes through a prism, the sum of the angle of prism and the angle of deviation is equal to the sum of the angle of incidence and the angle of emergence.

From the above expression, we find that angle of deviation depends upon angle of prism, angle of incidence and also on nature of material of prism.

From the figure, you can observe the variation of angle of deviation (δ) with the angle of incidence (i).

For one value of δ, there are two angles of incidence i_1 and i_2. However, at minimum deviation, $\delta = \delta\ m$, $e = i$, and $r_2 = r_1 = r$ (say).

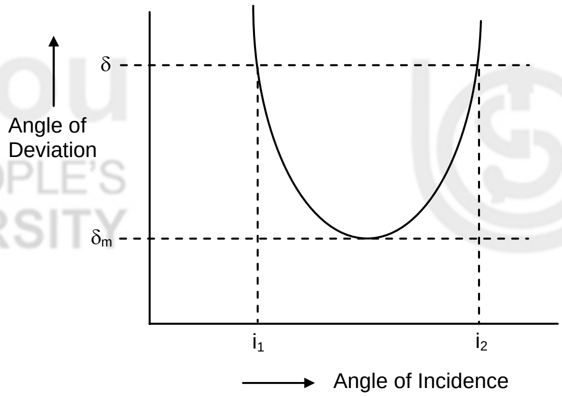


Figure 5.27

Now, $r + r = A \Rightarrow r = \frac{A}{2}$

Also, $A + \delta_m = i + i$

$\Rightarrow$ $i = \frac{A + \delta_m}{2}$

We also know that

$$\mu = \frac{\sin i}{\sin r}$$

Therefore, $$\mu = \frac{\sin\left(\frac{A + \delta_m}{2}\right)}{\sin \frac{A}{2}}$$

5.7.2 Dispersion

Dispersion of light is the phenomenon of splitting of a beam of white light into its constituent colours on passing through a prism. The band of seven colours formed on a white screen, when a beam of white light is passed through a glass prism is called spectrum of white light. The seven colours of the spectrum are red, orange, yellow, green, blue, indigo and violet. The seven colours of the spectrum can be denoted by the word VIBGYOR.

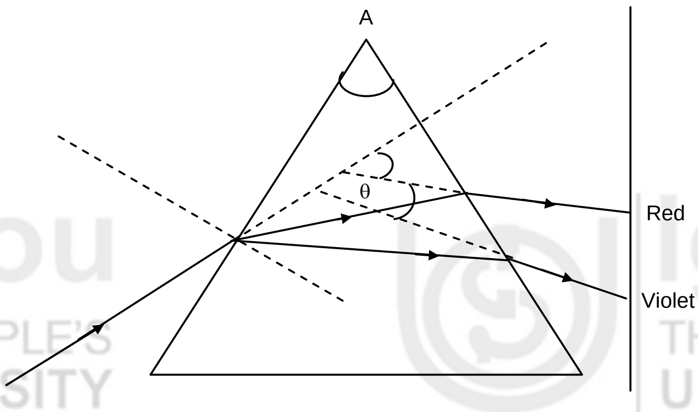


Figure 5.28

When white light passes through a prism, it is separated into rays of constituent colours. This phenomenen is known as dispersion. Dispersion is due to the fact that the refractive index is different for different colours. In other words, it varies with wavelength. In fact, μ decreases with increase in wavelength, i.e. $\mu_{blue} > \mu_{red}$. While the phenomenon is known as dispersion, the spread of colours is known as spectrum. The angle between the emergent rays is called angular dispersion ($\theta = \delta_v - \delta_r$).

5.7.3 Deviation Without Dispersion

When white light passes through a prism, both dispersion and deviation occur. Whenever there is a requirement of deviation without dispersion, we have to resort to a combination of prisms made of two different types of glass, say crown (c) and flint (f),

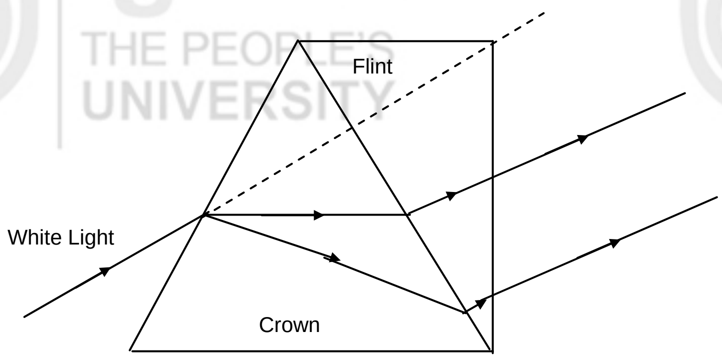


Figure 5.29

glass. In such a combination, the two prisms are so arranged that the angular dispersion due to the first prism is equal and opposite to that of the second prism, resulting in no dispersion. Such a combination is called **achromatic combination**.

5.7.4 Total Reflecting Prisms

As the name itself indicates, these are based on the principle of total internal reflection. Thus, it is possible to deviate rays of light through a desired angle with the help of these prisms. Refractive index of crown glass is 1.5 and so the critical angle for crown glass can be calculated using the expression $\mu = 1/\sin I_C$. Thus, critical angle for crown glass is 41.8°. If the angle of incidence is greater than 41.8°, the ray suffers total internal reflection. Such prisms can be used effectively in optical instruments as against mirrors.

To Turn a Ray Through 90°

ABC is a right angled prism. A ray incident normally on the face *AB* of the prism passes undeviated. When it strikes *AC*, the angle of incidence is 45°, which is more than the critical angle for the material of the prism and so gets reflected totally. Thus, it strikes the surface *BC* normally and so emerges undeviated. In effect, the incident ray has been deviated through 90°.

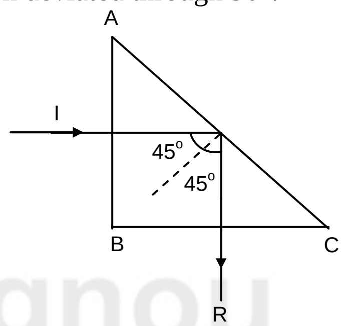


Figure 5.30

To Turn a Ray Through 180°

ABC is a right angled prism. A ray entering *AC* normally goes undeviated, strikes *AB* at an angle greater than the critical angle for the glass used, i.e. 45° and so gets deviated by 90° obeying the law of reflection. Thus, ray through the medium

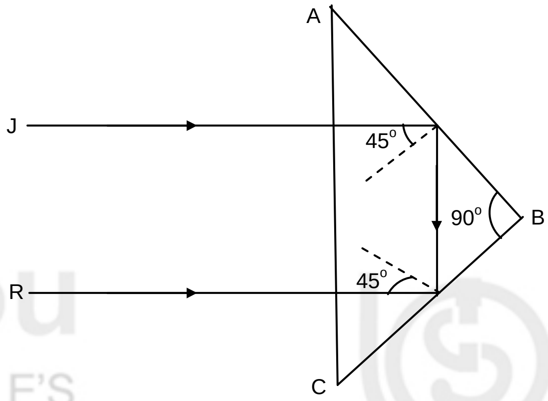


Figure 5.31

strikes the surface *BC* at 45° once again and so gets further deviated through 90°, making the total deviation 180°. In other words, the emergent ray is parallel to the incident ray but travels in the opposite direction.

Erecting Prism

The same right-angled prism when used in yet another way, serves as an erecting prism. Here the rays from an inverted object OO_1 gets refracted at the face *AB*,

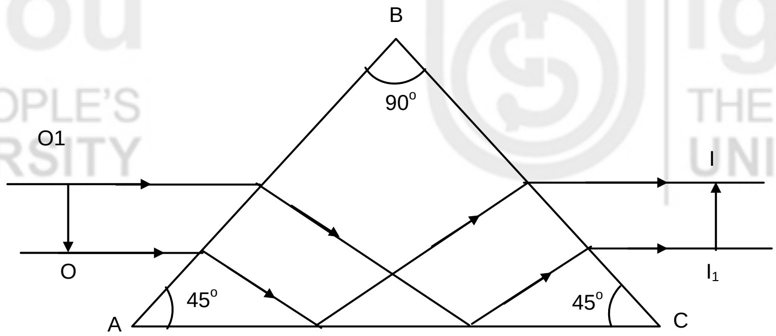


Figure 5.32

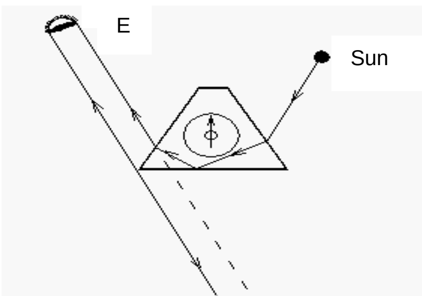
suffer total internal reflection at the surface *AC*, undergo refraction at the face *BC* and finally emerge as $I\,I_1$, an erect image of the inverted object OO_1.

5.7.5 Azimuth Mirror

This instrument is based on the principles of refraction and total internal reflection. It is used to take the bearing of both terrestrial and astronomical bodies such as the sun. Depending upon the requirement, it is used in two different positions.

Arrow Up Position

In this position (Figure 5.33), the instrument is used to obtain the bearing of the sun and other heavenly bodies. An equilateral prism is used. Rays of light from the sun suffer refraction at the first face. When these rays meet the second face, i.e.



P S1

Figure 5.33

the surface separating the glass medium from air, they are incident at an angle greater than the critical angle and so undergoes total internal reflection. These reflected rays once again suffer refraction. When they emerge through the third face, they reach the eye and final image is formed at the eye. Obviously, for the eye, the sun will appear as though it is located in the direction from which the rays enter the eye. Thus, the eye *E* would see the image of the sun at S_1, while by glancing just outside the line of the prism itself, a pointer *P* is seen by direct vision close against the graduated rim of the compass card. By bringing the image against the pointer, the bearing of the sun is read off.

Arrow Down Position

In this position (Figure 5.34), the instrument is used to measure the bearing of terrestrial objects. The diagram shows the rays. In this case, the eye *E* will

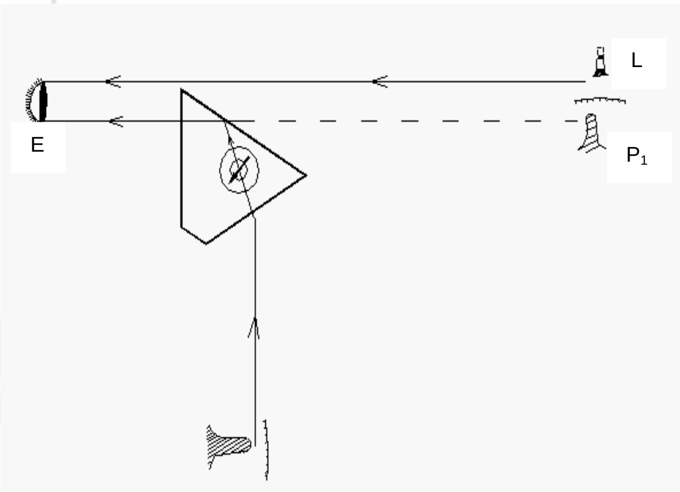
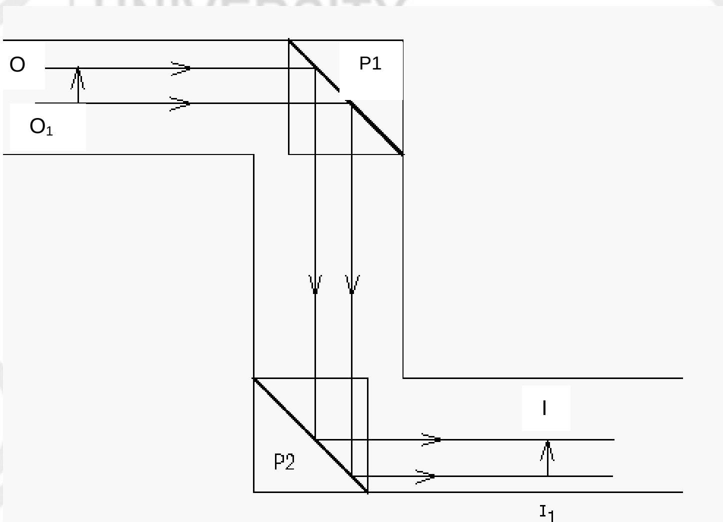


Figure 5.34

see the image of the pointer and the compass card at P_1. By raising the line of vision slightly, the observer can see the terrestrial object, say a light house *L*. The reading on the compass card gives the bearing of the light house.

5.7.6 Periscope

A periscope consists of a vertical tube with two right angled prisms placed in such a way that a ray of light entering the prisms P_1 and P_2 suffer total internal reflections and so deviate the rays through 90°. However, the deviation produced by P_2 is equal and opposite to that produced by P_1. As a result, the incident ray suffers a displacement but



P2

I_1

Figure 5.35

no deviation. In other words, the incident ray gets displaced by a length equal to the length of the tube. Periscopes are used in submarines and by soldiers in trenches enabling the viewer to remain hidden from the objects they view.

5.8 LENSES

These are refracting media bounded by either two spherical surfaces or one spherical surface and a plane surface. Depending upon this, the lenses are of different types. They are :

(a) Double convex or biconvex lens

(b) Double concave or biconcave lens

(c) Plano convex lens

(d) Plano concave lens

(e) Convexo concave lens

(f) Concavo convex lens

All convex lenses are convergent lenses, while all concave lenses are divergent lenses. Lenses are usually made of glass.

5.8.1 Basic Terms Associated with Lenses

Terminology associated with lenses are :

Principal Axis

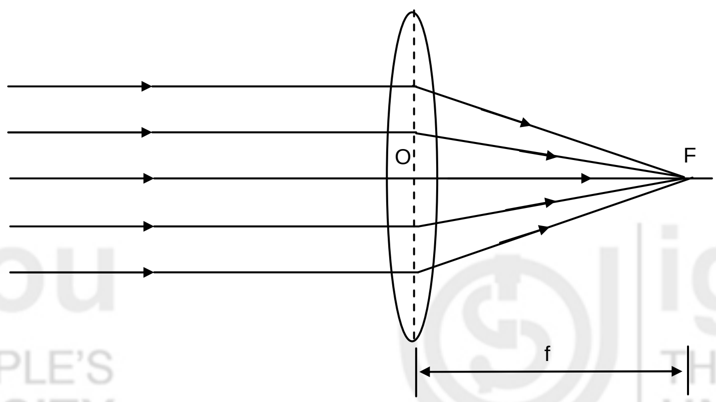
It is the line joining the centres of curvature of the two spherical surfaces, such as the line *AB* in Figure 5.36.

Optical Centre (O)

It is the point on the principal axis through which all the rays will pass when the incident and the emergent rays are parallel to each other. In the case of a thin lens however, the incident ray is considered to travel undeviated through this point. This point divides the line joining the two centres of curvature in the ratio of their radii.

Principal Focus (F)

In the case of a convex lens, it is the point at which rays parallel to the principal axis after refraction through the lens actually converge. It is also the point from where the rays emerge and travel parallel to the principal axis after refraction through the lens. Similarly, in the case of a concave lens, it is the point from where the rays of light appear to diverge when a parallel beam is incident on a lens. It is also the point from where a ray of light appears to diverge but actually goes parallel to the principal axis after refraction. There are two such foci. They are known as first principal focus and second principal focus on either side of the lens.



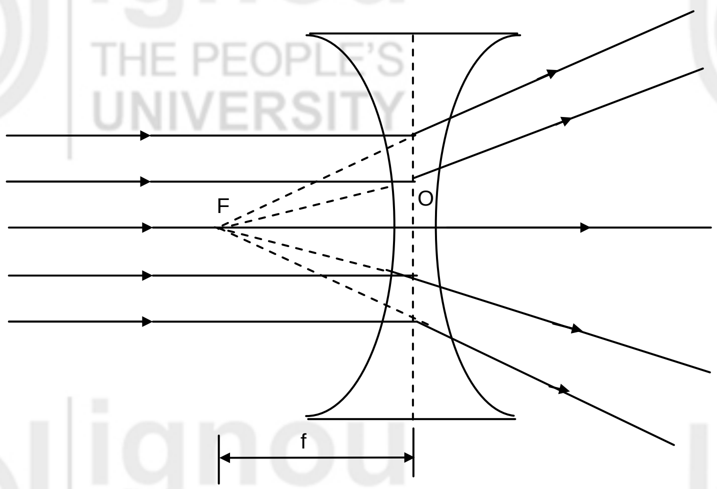


Figure 5.36

Focal Length (f)

Focal length is the distance between the optical centre and the principal focus.

Magnification (M)

Magnification is the ratio of the size of the image to the size of the object. It is also the ratio of the image distance to the object distance.

5.8.2 Sign Convention

Based on new Cartesian convention :

(a) The light is assumed to come from the left.

(b) All distances are measured from the optical centre (*O*) of the lens.

(c) All distances to the left of *O* are negative and to the right of *O* are positive. Thus, *u* is – ve, *v* is + ve for real images and – ve for virtual images and *f* is + ve for convex lens – ve for concave lens.

(d) Distances measured upward are positive and those measured downwards are negative.

5.8.3 Thin Lens Formula

Let us consider an object *AB* (Figure 5.37). Object distance is *u*. A ray of light from *A* parallel to the principal axis after refraction passes through the focus *F*. A ray of light through *O* goes undeviated. The two rays meet at *C*. *C* is the image of *A*. If we treat *AB* as number of point objects, *CD* will be the image of *AB*. It is real, inverted and is at a distance *v*.

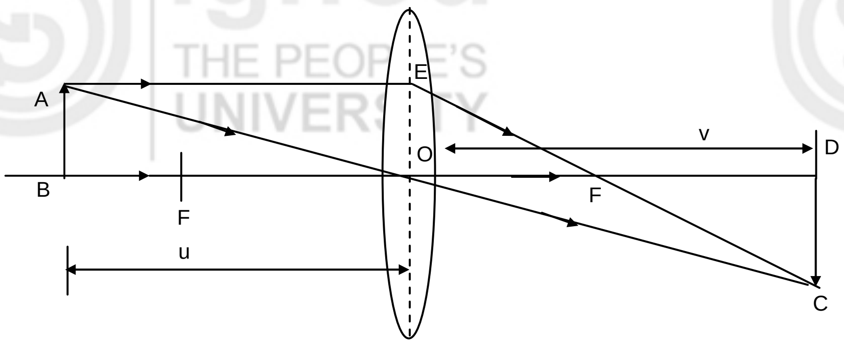


Figure 5.37

Δ *AOB* and Δ *COD* are similar

$$\therefore \quad \frac{AB}{CD} = \frac{BO}{DO} = \frac{-u}{v} \qquad \ldots (3)$$

Δ *EOF* and Δ *CFD* are also similar

Thus, $$\frac{EO}{CD} = \frac{f}{v - f} \qquad \ldots (4)$$

But $AB = EO$.

Therefore, from Eqs. (3) and (4),

$$\therefore \quad \frac{-u}{v} = \frac{f}{v - f}$$

$$-u\,v + u\,f = v\,f$$

Dividing through by $u\,v\,f$

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

i.e. $$\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$$

This is often referred to as "Lens formula".

Magnification $m = \frac{v}{u}$. Multiplying both sides of lens formula by *v*,

$$\therefore \quad \frac{v}{v} - \frac{v}{u} = \frac{v}{f}$$

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

i.e. $$m = 1 - \frac{v}{f}$$

5.8.4 Position and Nature of Image Formed by Lenses

When Object Lies at Infinity

The image will be formed at focus *F* as shown in Figure 5.38 and the image will be real, inverted and point in size.

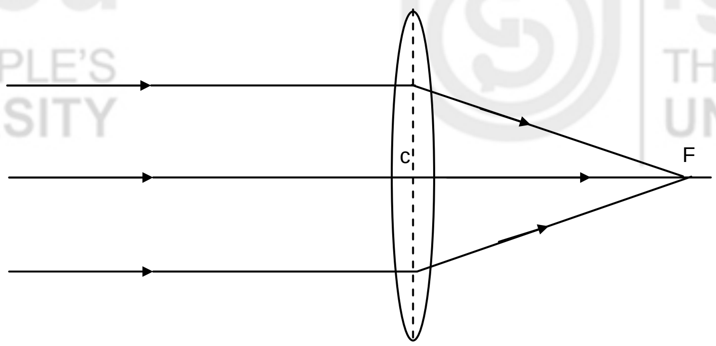


Figure 5.38

When Object Lies Beyond 2*F*

When an extended object *PQ* is placed beyond 2*F*, its image *P′Q′* will be formed by the lens as shown in Figure 5.39. The image will be formed between *F* and 2*F* and it will be real inverted and smaller in size.

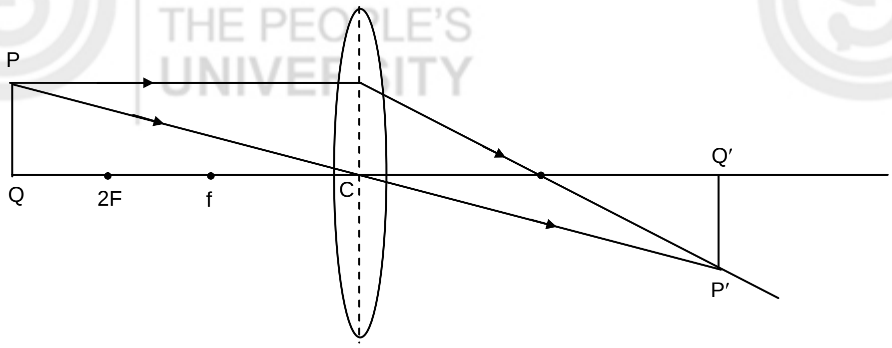


Figure 5.39

When Object Lies at 2*F*

If the object *PQ* lies at 2*F*, its image *P′Q′* will be formed as shown in Figure 5.40. The image will be formed at 2*F* and it will be real, inverted and equal in size.

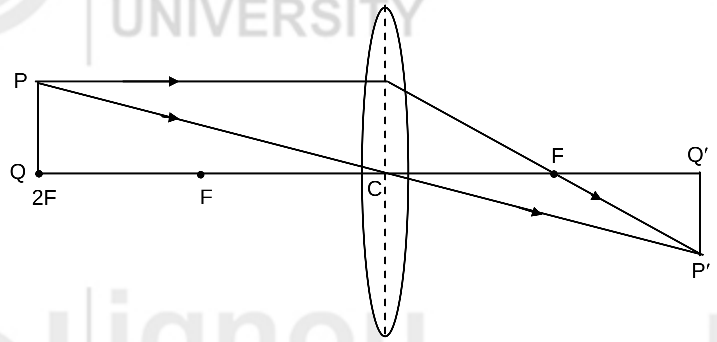


Figure 5.40

When the Object Lies between *F* and 2*F*

The image *P′ Q′* of the object *PQ* lying between *F* and 2*F* will be formed beyond 2*F*, and it will be real, inverted and larger in size as shown in Figure 5.41.

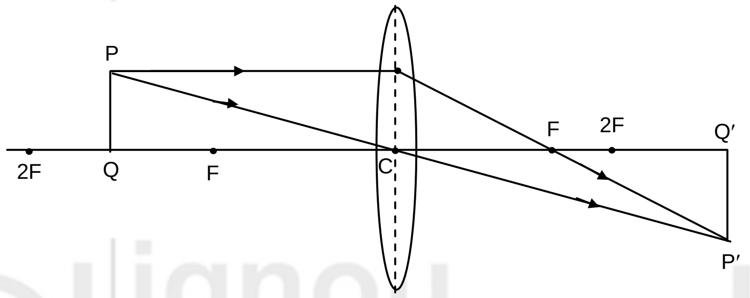


Figure 5.41

When Object Lies at *F*

When the object lies at *F*, then the rays after refraction through lens will become parallel. Hence, at infinity, highly magnified image will be formed.

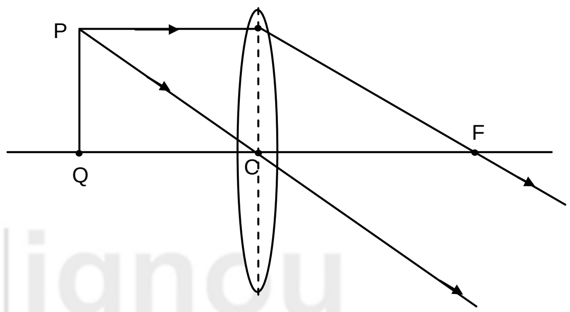


Figure 5.42

When the Object Lies between *F* and *C*

When the object *PQ* lies between *F* and *C*, its image is formed on the same side as shown in Figure 5.43. The image will be virtual, erect and magnified.

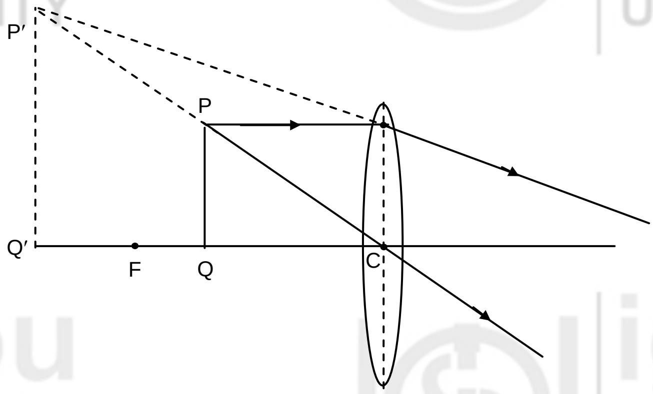


Figure 5.43

Image Formed by a Concave Lens

Let us now apply the ray tracing rules to ascertain the position and nature of images formed by concave lens.

Figure 5.44 shows an object *PQ*, placed beyond F_1 at any point on the principal axis of the lens, its image $P'Q'$ is formed on the same side as the object is. The image is always virtual, erect and smaller in size.

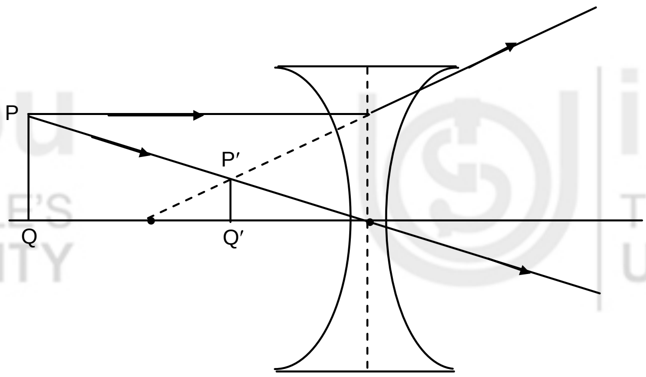


Figure 5.44

5.8.5 Power of a Lens

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

Thus $$\text{Power of lens} = \frac{1}{\text{Focal length of the lens in metres}}$$

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

where P = Power of the lens, and

f = Focal length of the lens (in metre).

The SI unit of the power of a lens is dioptre, which is denoted by *D*. One dioptre is the power of a lens whose focal length is 1 metre.

Example 5.6

A convex lens is of focal length of 20 cm. What is its power?

Solution

Here, $f = 20 \text{ cm} = \frac{20}{100} \text{ m}$ (A convex lens has positive focal length)

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

$= + 5$ dioptre (or $+ 5\,D$).

5.9 TELESCOPE AND BINOCULARS

You are familiar with telephone, television, telescope etc. “Tele” refers to long distance. Thus, telescope is meant to obtain the image of a distant object at the eye, which is close to the eyepiece of a telescope. Telescopes may be used to view either terrestrial or astronomical objects. Optical system of a telescope basically consists of

(a) An objective lens *O*, which forms an inverted image of the object being viewed.

(b) An eyepiece lens *E*, which produces an enlarged image of the first image.

Astronomical Telescope

In the case of an astronomical telescope, the objective is a convex lens combination of large focal length and large aperture. The eyepiece also is a combination convex lenses, but of short focal length and small aperture. While the objective is housed in a large brass tube, the eyepiece is housed in a small tube, capable of sliding inside the large tube. The distance between the objective and the eyepiece can be varied.

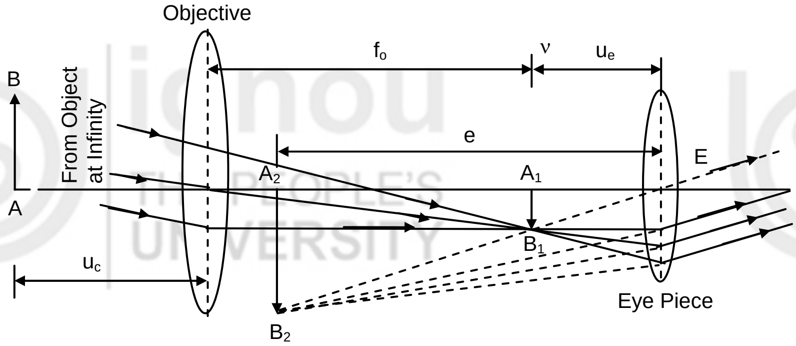


Figure 5.45

The rays coming from a distant object, i.e. an object at infinity, after refraction through the objective lens system form an inverted and diminished image $A_1 B_1$ at its focus. This forms the object for the eyepiece system of lenses. If the eyepiece is now adjusted in such a way that this object is within its focal length, the final image $A_2 B_2$ is enlarged, erect with respect to the image $A_1 B_1$ but inverted with respect to object.

Magnifying Power

It must be remembered that a telescope does not actually increase the size of the object. It only hinges the object near so that the angle subtended by the image at the eye is much larger than the angle subtended by the object at the objective or the eye. Therefore, the magnifying power is

$$M = \frac{\text{Angle subtended by the final image at the eye}}{\text{Angle subtended by the object at the eye}}$$

Thus, as seen in Figure 5.46

$$M = \frac{\beta}{\alpha} = \frac{\tan \beta}{\tan \alpha}$$ (Q α and β are very small angles)

It can be shown that $M = \dfrac{f_o}{f_e}$ in the normal adjustment position, when the final image is formed at infinity.

This means that f_o should be large and f_e small to achieve a high magnifying power.

Terrestrial Telescope

In the case of an astronomical object the image formed is inverted and it does not make a difference. But in the case of a terrestrial object, obviously an erect image is needed. This can be achieved by modifying the astronomical telescope by introducing a third lens called erecting lens (EL). As the name suggests, it just erects the image and does not magnify it as shown in Figure 5.46.

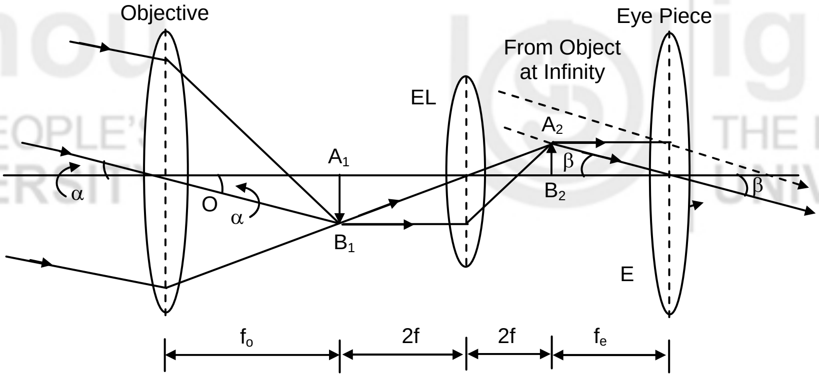


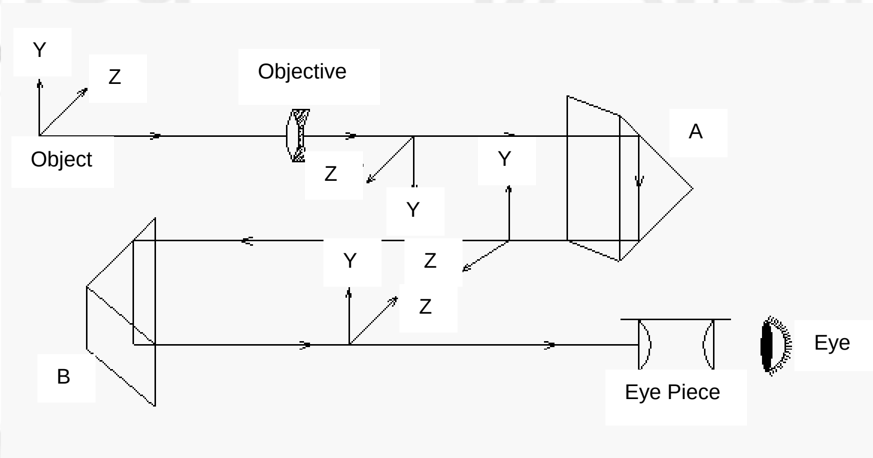
Figure 5.46

Once again it can be shown that $M = \dfrac{f_o}{f_e}$. However, the length of the telescope is increased from ($f_o + f_e$) in the case of an astronomical telescope to ($f_o + f_e + 4\,f_{EL}$) where f_{EL} is the focal length of the erecting lens.

Prism Binoculars

This consists of two astronomical telescopes, each having two totally reflecting right angled prisms. In this way, the optical distance between the objective and the eyepiece of the telescopes is made larger than the distance between the two. Hence, the field of vision is increased. Also, the effective length is made a third of the length of the telescope without compromising on the magnification and the final image which is erect.

The objective and the eyepiece lenses are convex lenses, Prism A is placed with its refracting edge horizontal and so turns the image in the vertical direction upside down. Prism B is placed with its refracting edge vertical and so it turns the image



in the horizontal direction. Thus, the final image produced is erect and magnified. Total optical path is about three times the length of the binocular and so it works as an astronomical telescope equal to 3 times its length.

Example 5.7

What must be the object distance in the case of a convex lens of focal length 20 cm if the image is twice the size of the object?

Solution

Both real and virtual images are possible. f = 20 cm, u = ?

(a) Real image $m = -2$

$$\therefore \quad \frac{v}{u} = -2$$

i.e. $$v = -2u$$

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

$$\therefore \quad -\frac{1}{2u} - \frac{1}{u} = \frac{1}{f}$$

$$\frac{-1-2}{2u} = \frac{1}{f}$$

$$-3f = 2u$$

$$-60 = 2u$$

or $$u = -30 \text{ cm}$$

(b) Virtual image $m = +2$

$$\therefore \quad \frac{v}{u} = 2 \text{ i.e. } v = 2u$$

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

$$\frac{1}{2u} - \frac{1}{u} = \frac{1}{f}$$

$$\frac{1-2}{2u} = \frac{1}{f}$$

$$-f = 2u$$

$$-20 = 2u$$

i.e. $$u = -10 \text{ cm}$$

Example 5.8

Find the position and the nature of the image if an object is placed at a distance of 6 cm from a concave lens of focal length 12 cm.

Solution

$u = -6$ cm; $f = -12$ cm; v = ?

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{f} \qquad \text{(General formula for lens)}$$

$$\frac{1}{v} - \frac{1}{-6} = \frac{1}{-12}$$

$$\therefore \quad \frac{1}{v} = -\frac{1}{12} - \frac{1}{6} = \frac{-1-2}{12} = \frac{-3}{12}$$

$$\therefore \quad v = -4 \text{ cm}$$

$$m = \frac{v}{u} = \frac{-4}{-6} = \frac{2}{3} \qquad \text{(diminished)}$$

$\therefore$ $v = -4$ cm, the image is virtual and diminished.

Example 5.9

Image is formed on a screen placed at a distance of 15 cm from a convex lens of focal length 10 cm. Find the position of the object and also the magnification.

Solution

If the image is caught on a screen, it is real image.

$v = 15$ cm ; $f = 10$ cm; $u = ?$ $m = ?$

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

$$\frac{1}{15} - \frac{1}{u} = \frac{1}{10}$$

$$\therefore \quad \frac{1}{u} = \frac{1}{15} - \frac{1}{10} = \frac{2-3}{30} = \frac{-1}{30}$$

$$\therefore \quad u = -30 \text{ cm}$$

$$m = \frac{v}{u} = \frac{15}{-30} = \frac{-1}{2}$$

SAQ 4

(a) 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.

(b) An object placed 50 cm from a lens produces a virtual image at a distance of 10 cm in front of the lens. Calculate the focal length of the lens.

(c) An object of size 3.0 cm is placed at a distance of 14 cm in front of a concave lens of focal length 28 cm. Calculate the distance of the image formed. What type of image will it be?

(d) An object is at a distance of 6 m from a convex mirror of focal length 12 cm? Where is the image formed? What is its magnification?

(e) A ray of light passes through an equilateral prism (refractive index 1.5) such that angle of incidence is equal to the angle of emergence and the latter is equal to $3/4^{th}$ of the angle of prism. Calculate the angle of deviation.

(f) Find the focal length of the convex lens used for obtaining a magnified image of an object on the screen placed at a distance of 10 m from the lens. Take the desired magnification to be 19.

(g) The power of a lens is + 2.5 *D*. What kind of lens it is and what is its focal length?

5.10 DIFFRACTION

The phenomena like reflection, refraction, dispersion, etc. which we have studied earlier, form part of ray optics. Diffraction, on the other hand, refers to bending of light round corners and can be explained by wave theory only. We shall study this phenomenon in slightly greater delail in the following sections.

5.10.1 Diffraction

Shadow formation due to an opaque obstacle placed in the path of light is something which we have studied. This is based on rectilinear propagation of light which is explained by Newton's corpuscular theory. What goes unnoticed is the spreading of light to some extent into the geometrical shadow region. This implies that light also, like sound, is capable of bending round the corners of an obstruction, though to a very very small extent. In other words, shadows formed by small obstacles are not sharp. Bending of light round the corners of an obstacle or the encroachment of light in the geometrical shadow is called diffraction.

Newton's corpuscular theory fails to explain this phenomenon, whereas wave theory by Christian Huygens is capable of explaining. According to this theory, each progressive wave produces secondary waves, the envelope of which forms the secondary wave front. For example, water waves escaping through a small hole spread out in all directions as if they have originated at the hole. Similarly, sound is found to pass round obstacles of moderate dimensions. Amount of bending, however, depends upon the size of the obstacle and the wavelength of the wave. Minute investigation reveals that light suffers some deviation from its rectilinear path. The deviation is extremely small when the wavelength of the light used is small in comparison with the dimension of the obstacle or the aperture. However, when the size of the aperture is comparable with the wavelength of the light, the deviation becomes much more pronounced. Diffraction produces bright and dark fringes known as diffraction bands or fringes.

5.10.2 Diffraction at a Straight Edge

Let *S* be a narrow slit placed perpendicular to the plane of the paper and illuminated by a monochromatic source of light (Figure 5.48). *A* is the sharp edge of an object *AB* placed parallel to the slits and WW_1, the trace of a cylindrical wavefront arriving at the straight edge at a certain instant. *XY* is a screen placed perpendicular to the plane of the paper at a distance '*d*' from the edge. *P* is a point on the screen and *SAP* is perpendicular to the screen. According to the ray optics, there will be practically uniform illumination above *P* and total darkness below *P*. However, a careful examination of the screen reveals that immediately above *P*, there are series of maxima and minima called diffraction fringes. Intensity of maxima gradually decreases as we move above *P*. At a certain distance, the fringes merge into uniform illumination. These fringes are closer as we move away from *P*. In the geometrical shadow region below *P*, illumination falls off continuously and rapidly to zero without showing any maxima or minima.

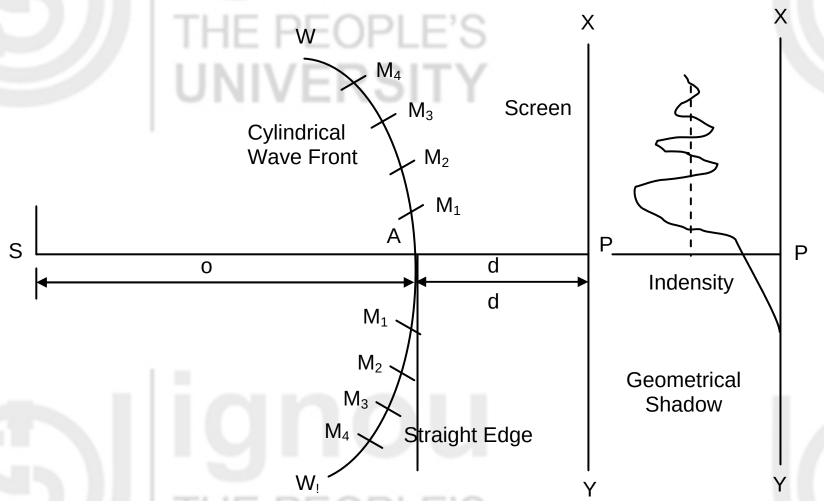


Figure 5.48

5.10.3 Diffraction at a Circular Aperture

AB represents the diameter '*d*' of a circular aperture placed perpendicular to the plane of the paper. Let λ be the wavelength of the monochromatic light incident on the aperture. The diffraction beam is focussed on a screen by a convex lens. Every point of the wave front in the plane of the circular aperture is a source of secondary wavelets which spread

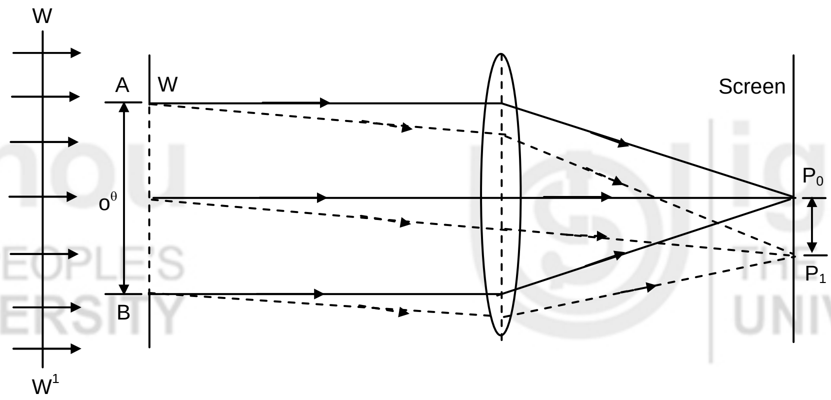


Figure 5.49

out in all directions. Wavelets coming to a focus at P_O correspond to a position of central maximum. If we consider secondary wavelets travelling in a direction inclined at an angle θ with the normal to the aperture, they meet at a point P_1 such that $P_0 P_1 = x$. The path difference between the extreme waves coming from *A* and *B* will be $AB \sin\theta = d \sin\theta$. Path difference is an integral multiple of λ for minimum and odd multiple of λ for maximum. The diffraction pattern will be one of bright circular ring of uniform illumination at P_0, surrounded by alternate dark and bright concentric rings. Intensity of dark rings is zero. However, intensity of bright rings gradually decreases from the central ring.

5.10.4 Resolving Power of Optical Instruments

When two objects are very near each other or are at a large distance from the eye, the eye may not be able to see them as two separate objects. If we want to see them as separate, optical instruments may be used depending upon other requirements. We know that the image of a point object or line is not simply a point or a line but is a diffraction pattern with a bright central maximum with alternate bright and dark fringes of rapidly decreasing intensity. Ability of our optical instrument to produce separate patterns is known as resolving power.

SAQ 5

(a) Briefly explain the phenomenon of diffraction with suitable examples.

(b) Explain the diffraction pattern in the case of diffraction at a straight edge.

(c) How are diffraction rings formed when diffraction takes place at a circular aperture?

(d) Briefly explain resolving power.

5.11 SUMMARY

Let us summarise, what you have learnt in this unit :

- Light is a form of energy which produces a sensation of sight in the eye.
- Light travels along straight lines.
- Reflection is the phenomenen in which a ray of light striking a surface separating two media is returned to the same medium.
- Laws of reflection :
  - (a) The incident ray, the normal at the point of incidence and the reflected ray, all lie in the same plane.
  - (b) The angle of incidence is equal to the angle of reflection, i.e. $i = r$.
- Real image is one which is formed by the actual intersection of the rays reflected from a surface of separation and virtual image is one in which the rays appear to diverge from a point after reflection.
- Characteristics of image formed after reflection at a smooth polished surface, i.e. plane mirror are :
  - (a) Image is behind the minor and is virtual and erect.
  - (b) Size of image is the same as that of the object.
  - (c) Object distance equals image distance.
  - (d) Image is laterally inverted.
- Sign conventions in respect of spherical mirrors :
  - (a) Light is assumed to come from the left.
  - (b) All distances are measured from the pole (P) of the mirror.
  - (c) Distances measured in the direction of the incident ray are +ve and those against are – ve.
  - (d) Heights perpendicular and upward are +ve and perpendicular and downwards are – ve.
- Radius of curvature is twice the focal length of the mirror, i.e. $R = 2f$.
- Mirror formula is $\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$.
- If a plane mirror is rotated through an angle θ, the reflected ray rotates through 2θ.
- Sextant is an optical instrument used for measuring altitude of the sun and also the height of objects. It is based on the principle stated above.
- Refraction is the phenomenon in which an incident ray gets deviated when it enters from one medium into another medium.
- Laws of refraction (Snell's laws)
  - (a) The incident ray, the normal at the point of incidence and the refracted ray, all line in one plane.
  - (b) The ratio of sine of angle of incidence to the sine of angle of refraction is a constant for the given two media

    i.e. $$\frac{\sin i}{\sin r} = {}^1\mu_2$$
- Critical angle (i_c) is the angle of incidence in the denser medium for which the angle of refraction in the rarer medium is 90°.
- Total internal reflection is the phenomenon in which angle of incidence in the denser medium is greater than the critical angle and so the ray undergoes total internal reflection.

- Mirage and looming are optical illusions. In the case of the mirage, in the deserts, inverted images of distant objects are formed giving the impression that the object has been reflected by water surface while no such water surface exists in reality. Similarly, in the case of looming, objects appear to be hanging in the sky.
- Light pipe consists of high refractive index material forming the core with a low refractive index material coating. Like a pipe in which water poured at one end comes out through the other, the light entering one end of the pipe comes out through the other end after suffering a number of total internal reflections.
- In the case of refraction through a prism,

$$\mu = \frac{\sin\left(\frac{A+\delta_m}{2}\right)}{\sin\frac{A}{2}}$$

  Refractive index for different wavelengths is different and so when white light enters a prism it is split into its constituent colours (VIBGYOR). While this phenomenon is known as dispersion, the spread of colours is known as spectrum.
- It is possible to produce deviation without dispersion using a combination of prisms, known as achromatic combination.
- Based on the principle of total internal reflection, deviation is possible through either 90° or 180°, by proper positioning of the prism in the path of light. It is also possible to erect inverted images.
- Sextant, used in the merchant navy, functions on the principle of total internal reflection and is used for measuring the altitude of the sun and also height of terrestrial objects.
- Periscope is an optical instrument used in submarines and also by soldiers in trenches hidden from the view of the enemy.
- $\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$ is known as the thin lens formula. The magnification is $m = 1 - \frac{v}{f}$.
- Telescopes are optical instruments used to view distant objects, be they terrestrial or celestial. Prism binoculars are two telescopes in one.
- Diffraction refers to the bending of light around corners. While bending of sound waves is easily understandable, diffraction in the case of light cannot be noticed by naked eye and so requires optical instruments.
- Diffraction pattern is one of a maximum intensity accompanied by alternate dark and bright fringes on either side. Nature of fringes depends upon the obstruction. Thus, in the case of diffraction at a straight edge, the pattern is alternate bright and dark fringes or bands. In the case of circular aperture, it consists of a bright circular ring accompanied by alternate dark and bright rings with the intensity of brightness decreasing steadily.

5.12 KEY WORDS

Light : Light is a form of energy which enables us to see objects from which it comes (or from which it reflects).

Magnification : The ratio of the size of the image formed (by a spherical mirror) to the size of the object is called magnification.

Refraction : The phenomenon of change in path of light as it goes from one medium to another is called refraction.

Power of a Lens	: The power of a lens is defined as the reciprocal of its focal length in metres.
Mirage	: Mirage is an optical illusion which occurs usually in desert on hot summer days. The object such as a tree appears to be inverted, as it on the bank of a pond of water.
Lens	: A lens is a portion of a transparent refracting medium bound by two spherical surfaces or one spherical surface and the other plane surface.
Dispersion of Light	: Dispersion of light is the phenomenon of splitting of a beam of white light into its constituent colours on passing through a prism.
Spherical Mirror	: A spherical mirror is a part of a spherical reflecting surface.
The Magnifying Power of a Microscope	: The magnifying power of a microscope is defined as the ratio of the angle subtended by the image at the eye and the angle subtended by the object seen directly, when both lie at the least distance of distinct vision.

5.13 ANSWERS TO SAQs

SAQ 1

(a) (i) Object distance $u = -15$ cm

$$f = -10 \text{ cm}$$

We know $$\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$$

We get $$\frac{1}{v} + \frac{1}{-15} = \frac{1}{-10}$$

$\Rightarrow$ $$v = -30 \text{ cm}$$

Thus the position of image is 30 cm to the left side of mirror or 30 cm in front of mirror.

(ii) **Nature of Image :** Real and inverted.

(iii) **Size of Image :**

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

$$= -\frac{(-30)}{-15}$$

$$= -2$$

So $$-2 = \frac{h_2}{1} \Rightarrow h_2 = -2 \text{ cm}$$

Size of image is 2 cm long.

(b) We know $$m = \frac{h_2}{h_1}$$

$$h_2 = -3 \text{ cm}, \quad h_1 = 2 \text{ cm}$$

$$m = -1.5$$

Now, $m = -\frac{v}{u}$

or $-1.5 = \frac{v}{-16} \Rightarrow v = 24$ cm

The position of image is 24 cm in front of mirror.

Calculation of Focal Length :

We know $\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$

$\Rightarrow$ $-\frac{1}{24} - \frac{1}{16} = \frac{1}{f}$

$\Rightarrow$ $f = -9.6$ cm

So focal length $f = -9.6$ cm .

(c) Here $u = -10$ cm

$R = -40$ cm

Therefore focal length $f = \frac{R}{2} = -20$ cm

We know $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$

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

$\frac{1}{v} = \frac{1}{-20} - \frac{1}{-10}$

or $v = 20$ cm

As v is positive, the virtual image is formed at a distance of 20 cm behind the mirror

$$m = -\frac{v}{u} = -\frac{20}{-10} = 2$$

(d) Here $h_1 = 3.0$ cm, $u = -25$ cm, $f = -10$ cm

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

$= \frac{1}{-10} - \frac{1}{-25}$

So, $v = -\frac{50}{3}$ cm $= -16.67$ cm

$$m = \frac{h_2}{h_1} = -\frac{v}{u}$$

Now, $\frac{h_2}{3.0} = -\frac{-\frac{50}{3}}{-25} = -\frac{2}{3}$

$\Rightarrow$ $h_2 = -2.0$ cm

The negative sign shows that image formed is real and inverted. Therefore, area enclosed by the wire = 2.0 × 2.0 = 4.0 cm^2.

(e) Here, Object size $h_1 = 4.0$ cm,

Object distance $u = -25$ cm

Focal length $f = -15$ cm

Image distance $v = ?$

Image size $h' = ?$

We know, $$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

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

$$= \frac{1}{-15} - \frac{1}{-25}$$

$$= -\frac{1}{15} + \frac{1}{25} = -\frac{2}{75}$$

$\therefore$ $v = -37.5$ cm

The screen should be placed at 37.5 cm from the mirror on the object side of the mirror. Image is real.

Also magnification,

$$m = \frac{h'}{h} = -\frac{v}{u}$$

or $$h' = -\frac{v}{u}h = -\frac{(-37.5)(+4.0)}{(-25.0)}$$

Image size, $h' = -6.0$ cm

This image is inverted and enlarged in size.

(f) (i)

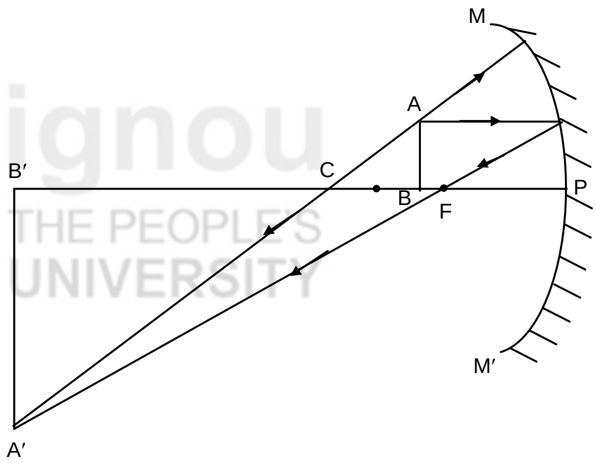


Figure 5.50

(ii)

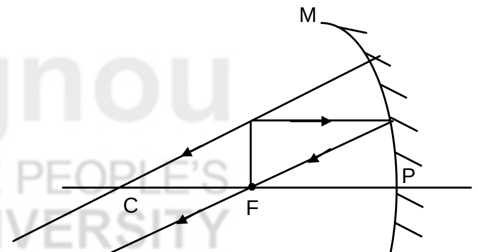


Figure 5.51

(iii)

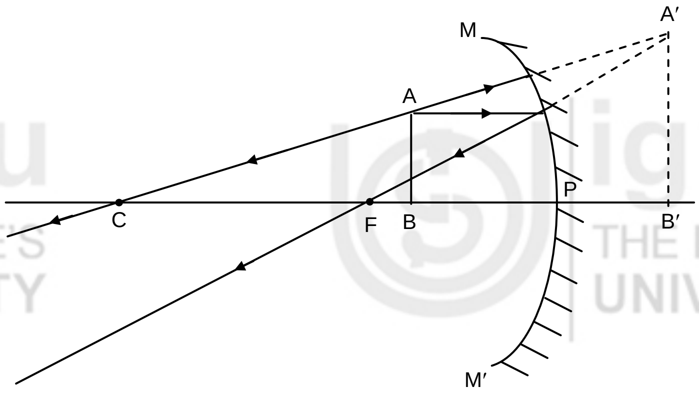


Figure 5.52

SAQ 2

(a) Refractive index of glass = 1.5

Refractive index of water = 1.33

Therefore, the refractive index of glass with respect to water is

$$\frac{1.5}{1.33} = 1.1278$$

Now, the ratio of the refractive index of the medium of incidence (glass) to the refractive index of the medium of refraction (water) is given as $\frac{1}{\sin C}$, where C is the critical angle for glass-water interface. Thus, we can write

$$\frac{1}{\sin C} = 1.1278$$

$$\Rightarrow \qquad C = 62^{\circ}\ 27'$$

(b) As per the problem, the angle of refraction = $40^{\circ} - 15^{\circ} = 25^{\circ}$

$$\frac{\mu_{glass}}{\mu_{air}} = \frac{\sin i}{\sin r} = \frac{\sin 40^{\circ}}{\sin 25^{\circ}} = 1.52$$

If C is the critical angle for glass-air interface, then

$$\frac{\mu_{glass}}{\mu_{air}} = \frac{1}{\sin C} \Rightarrow \sin C = \frac{1}{1.52} = 0.6579$$

$$\Rightarrow \qquad C = 41.1^{\circ}$$

(c) Here $\qquad \lambda = 600\ \text{nm} = 6 \times 10^{-7}\ \text{m}$

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^8}{6 \times 10^{-7}} = 5 \times 10^{14} \text{ Hz}$$

On refraction, frequency remains the same, $\nu' = \nu = 5 \times 10^4$ Hz

Wavelength changes to $\lambda' = \frac{\lambda}{\mu} = \frac{600}{1.5} = 400$ nm

Velocity changes to $v = \frac{c}{\mu} = \frac{3 \times 10^8}{1.5} = 2 \times 10^8 \text{ ms}^{-1}$

SAQ 3

As man is in air, light travels from rarer to denser medium. It bends towards the normal-appearing to come from a larger distance. Therefore, to the fish under water, man looks taller.

SAQ 4

(a) Here $u = -50$ cm, $f = -20$ cm, $v = ?$

We know, the lens formula

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

We get $$\frac{1}{v} = \frac{1}{-50} + \frac{1}{-20} = -\frac{7}{100}$$

$\Rightarrow$ $v = -14.3$ cm

So, image distance $v = -14.3$ cm.

The minus sign for image distance shows that the image is formed on the left side of the concave lens. So, the nature of image is virtual and erect.

(b) In this problem, $u = -50$ cm, $v = -10$ cm

We have to find out focal length f.

From lens formula $\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$

We get, $\Rightarrow$ $$\frac{1}{-10} - \frac{1}{-50} = \frac{1}{f}$$

$$\Rightarrow \quad \frac{1}{f} = \frac{-5+1}{50} = -\frac{4}{50}$$

$$f = -12.5 \text{ cm}$$

The minus sign for focal length shows that it is a concave lens.

(c) Here size of the object = 3.0 cm, $f = -28$ cm, $u = -14$ cm

According to the lens formula

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

or $$\frac{1}{v} = \frac{1}{f} + \frac{1}{u} = \frac{1}{-28} + \frac{1}{-14}$$

$\Rightarrow$ $v = -9.3$ cm

The negative sign of v indicates that the image is on the same side of the object and, therefore, it is virtual. Now, the magnification is given as

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

where I is the size of the image.

or $$I = \frac{v}{u} \times O = -\frac{9.3}{-14} \times 3.0 = 1.99 \text{ cm}$$

Thus, the image is diminished in size.

(d) As per the problem, we have, $u = -6$ m $= -600$ cm, $f = 12$ cm .

The mirror formula is $$\frac{1}{v} = \frac{1}{f} - \frac{1}{u} = \frac{1}{12} + \frac{1}{600} = \frac{51}{600}$$

or $$v = 11.76 \text{ cm}$$

or $$m = \frac{v}{u} = \frac{11.76}{600} = 0.0196$$

(e) Here $A = 60^o$, $\mu = 1.5$, $i_1 = i_2 = \frac{3}{4} A = 45^o$ $\delta = ?$

We know, $$A + \delta = i_1 + i_2$$

$$\Rightarrow \quad 60 + \delta = 45^o + 45^o$$

$$\delta = 90^o - 60^o = 30^o$$

(f) The convex lens forms real and inverted image. Thus $m = -19$. The image lies on the other side of the lens. Thus, $v = +10$ m.

We also know $$m = \frac{f - v}{f}$$

$$-19 f = f - 10$$

$$\Rightarrow \quad 20 f = 10$$

or $$f = 0.5 \text{ m}$$

(g) Since the power of this lens is positive, therefore, it is convex lens.

We know $$P = \frac{1}{f}$$

$$f = \frac{1}{P} = \frac{1}{2.5} \text{ m} = +40 \text{ cm}$$

So focal length is + 40 cm.

FURTHER READING

Young and Freedman, *University Physics* (10th Edition), Addison Wesley, Longman.

Nelkon and Parker, *Advanced Level Physics* (7th Edition), CBS Publishers.

Clough and Smith (Revised by R. A. Davis), *Applied Physics* (5th Edition), Brownson and Ferguson Ltd.

S. Ramamrutham, *Engineering Mechanics* (6th Edition), Dhanpat Rai Publishing Company.

U. C. Jindal, *Basics of Engineering Mechanics*, Galgotia Publications Pvt. Ltd.

PHYSICS

Physics is the scientific study of matter and energy and deals with interactions of these. The energy can take the form of motion, light, electricity, radiation, gravity. It deals with matter on scales ranging from sub-atomic particles to stars and even entire galaxies. It is generally intended for a particular technological or practical use. Herein, we study the nature of the relationship to the technology or science. Here we may not be designing something in particular, but rather using physics with the aim of developing new technologies or solving an engineering problem. Infact, it is concerned with the utilization of these scientific principles in practical devices and systems. Our aim is to train your mind to be prepared for the challenges it will present. This Block has 5 units covering areas such as mechanics, light, heat, waves and oscillations, and sound.

Unit 1 on mechanics deals with the study of forces and motions of bodies. Herein we study bodies at rest or in motion when subjected to external force(s). In this unit, we shall study various laws of motion. Newton's laws of motion, Newton's law of gravity, Kepler's law and various other concepts like angular velocity, momentum, acceleration, moment of inertia, centroids, centre of mass, etc. are also described in this unit.

Unit 2 on heat discusses the concept of heat as a form of energy. The mechanism involved in transmission of heat by conduction, convection and radiation from one body to another is also described in this unit. The terms like a specific heat, latent heat, their definitions and their real life applications are discussed in brief in this unit. We shall also study as to how expansion of liquids takes place by heating.

Unit 3 on oscillations deals with Simple Harmonic Motion (SHM). Various terms related to SHM such as the time period and frequency of periodic motion is defined. An analysis of compound pendulum and torsional pendulum, damped oscillations of the spring-mass system is also presented. The phenomenon of resonance is also explained in this unit.

Unit 4 on sound introduces you sound as a form of energy and investigates the nature, properties and behaviour of sound waves. In this unit, we shall also study about characteristics of transverse and longitudinal waves. The Newton's formula for velocity of sound, effect of different parameters such as temperature, humidity, wind velocity pressure and density on velocity of sound is discussed in brief. The Doppler's effect and its applications in various situations are presented giving examples. The working principle of siren and measurement of unknown frequency using this principle is also described.

Unit 5 on light, a form of energy, describes laws of reflection and refraction, laws/rules relating to the formation of images by plain mirror, spherical mirror, and lenses, mirror and lens formulae are suitably described in this unit. The power of a lens is defined. The concept of total internal reflection and different phenomenon associated with it are also presented. The construction and working of simple microscope, compound microscope, and telescope is presented in brief.

The material is presented in simple and lucid language giving numerous examples and SAQs. These will help you grasping the concepts involved.