Chapter 4

Refraction of Light at Plane Surfaces

(B) Light

SYLLABUS

(i) Refraction of light through a glass block and a triangular prism, qualitative treatment of simple applications such as real and apparent depth of objects in water and apparent bending of sticks in water. Application of refraction of light.

Scope of syllabus : Partial reflection and refraction due to change in medium. Laws of refraction, the effect on speed (V), wavelength (λ) and frequency (f) due to refraction of light, conditions for a light ray to pass undeviated. Values of speed of light (c) in vacuum, air, water and glass; refractive index $\mu = c/V$, $V = f\lambda$. Values of μ for common substances such as water, glass and diamond, experimental verification; refraction through glass block; lateral displacement; multiple images in thick glass plate/mirror; refraction through a glass prism; simple applications: real and apparent depths of object in water; apparent bending of a stick under water. Simple numerical problems and approximate ray diagrams required.

(ii) Total internal reflection; Critical angle; examples in triangular glass prisms; comparison with reflection from a plane mirror (qualitative only). Application of total internal reflection.

Scope of syllabus : Transmission of light from a denser medium (glass/water) to a rarer medium (air) at different angles of incidence; critical angle C, $\mu = 1/\sin C$, essential conditions for total internal reflection. Total internal reflection in a triangular glass prism; ray diagram, different cases – angles of prism (60°, 60°, 60°), (60°, 30°, 90°), (45°, 45°, 90°); use of right angle prism to obtain $\delta = 90°$ and 180° (ray diagram); comparison of total internal reflection from a prism and reflection from a plane mirror.

(A) REFRACTION, LAWS OF REFRACTION AND REFRACTIVE INDEX

In class IX, we have read the reflection of light from the plane and spherical mirrors. The return of light in the same medium after striking a surface is called *reflection of light*. The reflection of a light ray obeys *two* laws : (i) the angle of reflection is equal to the angle of incidence, and (ii) the incident ray, the normal at the point of incidence and the reflected ray, all lie in one plane. Here we shall study the refraction of light through the plane and spherical surfaces.

Light has the maximum speed in vacuum and it travels with different speeds in different media. It travels faster in air than in water or in glass. The speed of light is 3×10^8 m s^{-1} in air, $2{\cdot}25 \times 10^8$ m s^{-1} in water and 2×10^8 m s^{-1} in glass. The speed of light is constant in a transparent homogeneous medium.

While passing from one medium to the other, if light slows down, the second medium is said to be optically denser than the first medium and if light speeds up, the second medium is said to be optically rarer than the first medium.* Thus water and glass are optically denser than air (or air is optically rarer than water and glass). Similarly, glass is optically denser than water (or water is optically rarer than glass).

4.1 REFRACTION OF LIGHT

Partial reflection and refraction at the boundary of two different medium : In a transparent medium although light travels in a

* Optical density has no relation with the density of medium. Kerosene is less dense than water (as it floats on water), but it is optically denser than water. Optical density of a medium depends on the speed of light in that medium, while the density of a medium depends on its inter-molecular separation.

straight line path, but when a ray of light travelling in one transparent medium strikes obliquely at the surface of another transparent medium, a part of light comes back to the same medium obeying the laws of reflection and is called the *reflected light*. The remaining part of light passes into the other medium and travels in a straight path different from its initial direction and is called the *refracted light.*

Thus, *at the boundary separating the two media, light suffers a partial reflection and partial refraction.* Thus

> *The change in direction of the path of light, when it passes from one transparent medium to another transparent medium, is called refraction. The refraction of light is essentially a surface phenomenon.*

In Fig. 4.1 and Fig. 4.2, SS' is the surface separating the two media (say, air and glass). When light travelling in one medium falls on the surface SS', a small part of it is reflected back in the same medium obeying the laws of reflection and the rest of it is refracted through the other medium *i.e., there is a partial reflection and partial refraction at the boundary surface.* The intensity (or the amplitude) of the refracted light will obviously be less than that of the incident light because a part of the incident light has suffered reflection.

In Fig. 4.1 and 4.2, for the *incident ray* AO, the *refracted ray* is OB, the *reflected ray* is OC and the *normal* at the point of incidence O is NOM. The *angle of incidence* i is $\angle AON$ and the *angle of refraction* r is $\angle BOM$. Note that the angle r is not equal to the angle i (*i.e.,* OB is not in direction of OA).

It has been experimentally observed that

(1) *When a ray of light travels from a rarer medium to a denser medium* (say, from air to glass), *it bends towards the normal (i.e., $\angle r < \angle i$)* as shown in Fig. 4.1. The deviation* of the ray (from its initial path) is $\delta = i - r$.

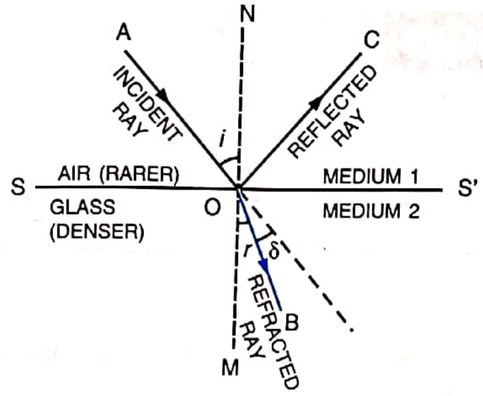

Fig. 4.1 Refraction from rarer to denser medium

(2) *When a ray of light travels from a denser medium to a rarer medium* (say, from glass to air), *it bends away from the normal* (*i.e.,* $\angle r > \angle i$) as shown in Fig. 4.2. The deviation of the ray is then $\delta = r - i$.

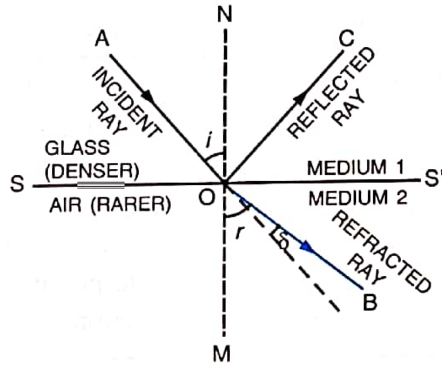

Fig. 4.2 Refraction from denser to rarer medium

(3) *The ray of light incident normally on the surface separating the two media, passes undeviated* (*i.e.,* such a ray suffers no bending at the surface). Thus if angle of incidence $\angle i = 0°$, then angle of refraction $\angle r = 0°$ as shown in Fig. 4.3. The deviation of the ray is zero (*i.e.,* $\delta = 0°$).

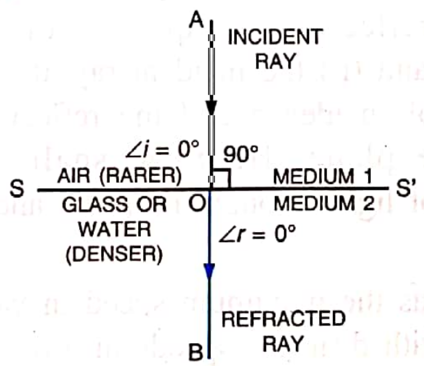

Fig. 4.3 Refraction at normal incidence

> *Note* : In discussing refraction now onward, the reflected ray from the boundary surface will not be shown although it is always there.

* *Deviation means the angle between the direction of refracted ray and the direction of incident ray. It is denoted by the letter δ.*

Cause of refraction (or cause of change in direction)

When a ray of light passes from one medium to another medium, its direction (or path) changes because of change in speed of light in going from one medium to another. In passing from one medium to other, if light slows down, it bends towards the normal and if light speeds up, it bends away from the normal. For normal incidence ($\angle i = 0°$), the speed of light changes but the direction of light does not change.

4.2 LAWS OF REFRACTION

The refraction of light obeys *two* laws of refraction which were given by the Dutch scientist Willebrod Snell, so they are known as *Snell's laws* after his name. They are :

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

(2) *The ratio of the sine of the angle of incidence i to the sine of the angle of refraction r is constant for the pair of given media. i.e., mathematically*

$$\boxed{\frac{\sin i}{\sin r} = \text{constant } {}_1\mu_2} \qquad \text{....(4.1)}$$

The constant is called the ***refractive index*** of the second medium with respect to the first medium. It is generally represented by the Greek letter ${}_1\mu_2$ (mew).

Refractive index

> *The refractive index of second medium with respect to the first medium is defined as the ratio of the sine of the angle of incidence in the first medium to the sine of the angle of refraction in the second medium.*

Unit : The refractive index has no unit as it is the ratio of two similar quantities.

4.3 SPEED OF LIGHT IN DIFFERENT MEDIA; RELATIONSHIP BETWEEN REFRACTIVE INDEX AND SPEED OF LIGHT ($\mu = c/V$)

The speed of light is maximum in vacuum and is equal to 3×10^8 m s^{-1}*. The speed of light in air is nearly same as in vacuum. It is denoted by the symbol *c*. In any other transparent media, the speed of light is less than that in air (or vacuum).

The refractive index of a medium is generally defined with respect to vacuum (or air), and it is called the *absolute refractive index* (or simply the refractive index) of the medium. It is denoted by the letter μ.

The absolute *refractive index of a medium is defined as the ratio of the speed of light in vacuum (or air) to the speed of light in that medium, i.e.,*

$$\boxed{\mu = \frac{\text{Speed of light in vacuum or air } (c)}{\text{Speed of light in that medium } (V)}} \qquad \text{...(4.2)}$$

The refractive index of a transparent medium is *always greater than 1* (it can not be less than 1), because speed of light in any medium is always less than that in vacuum (*i.e.*, $V < c$).

Examples : (1) The speed of light in air is 3×10^8 m s^{-1} and in glass it is 2×10^8 m s^{-1}, therefore the refractive index of glass is

$$\mu_{glass} = \frac{3\times10^8}{2\times10^8} = 1{\cdot}5$$

(2) The speed of light in water is $2{\cdot}25 \times 10^8$ m s^{-1}, so the refractive index of water is

$$\mu_{water} = \frac{3\times10^8}{2{\cdot}25\times10^8} = \frac{4}{3} = 1{\cdot}33$$

(3) The refractive index of diamond is 2·41, it means that light travels in air 2·41 times faster than in diamond.

The refractive index of some common transparent substances are given in the table ahead.

* Precisely the speed of light in vacuum is 299,792,458 m s^{-1}.

Refractive index (μ) of some common substances

Substance	μ	Substance	μ
Vacuum	1·00	Paraffin oil	1·44
Air	1·00 (1·0003)	Glycerine	1·47
		Turpentine oil	1·47
Ice	1·31	Ordinary glass	1·5
Water	1·33	Crown glass	1·53
Methylated spirit	1·36	Quartz	1·54
		Rock salt	1·56
Ether	1·36	Carbon disulphide	1·63
Alcohol	1·37	Flint glass	1·65
Kerosene	1·41	Ruby	1·76
Sulphuric acid	1·43	Diamond	2·41

In general, the refractive index of second medium with respect to first medium is related to the speed of light in the two media as follows :

$$\boxed{{}_1\mu_2 = \frac{\text{Speed of light in medium 1}}{\text{Speed of light in medium 2}}} \quad \text{... (4.3)}$$

where ${}_1\mu_2$ represents the refractive index of medium 2 with respect to medium 1.

If V_1 is the speed of light in medium 1 and V_2 is the speed of light in medium 2, then from eqn. (4.3),

$$\boxed{{}_1\mu_2 = \frac{V_1}{V_2} = \frac{c/V_2}{c/V_1} = \frac{\mu_2}{\mu_1}} \quad \text{... (4.4)}$$

Here μ_1 and μ_2 are the absolute refractive indices of the medium 1 and 2 respectively.

Examples : (1) Refractive index of glass with respect to water is

$${}_{\text{water}}\mu_{\text{glass}} = \frac{\text{Speed of light in water}}{\text{Speed of light in glass}}$$

$$= \frac{2{\cdot}25\times10^8}{2{\cdot}0\times10^8} = 1{\cdot}125$$

or $${}_{\text{water}}\mu_{\text{glass}} = \frac{\mu_{\text{glass}}}{\mu_{\text{water}}} = \frac{3/2}{4/3} = \frac{9}{8} = 1{\cdot}125$$

(2) Refractive index of water with respect to glass is

$${}_{\text{glass}}\mu_{\text{water}} = \frac{\text{Speed of light in glass}}{\text{Speed of light in water}}$$

$$= \frac{2\cdot0\times10^8}{2\cdot25\times10^8} = 0{\cdot}89$$

or $${}_{\text{glass}}\mu_{\text{water}} = \frac{\mu_{\text{water}}}{\mu_{\text{glass}}} = \frac{4/3}{3/2} = \frac{8}{9} = 0{\cdot}89$$

Note : If the refractive indices of medium 1 and medium 2 are same, the speed of light will be same in both the media, so a ray of light will pass from medium 1 to medium 2 without any change in its path even when the angle of incidence in medium 1 is not zero.

Conditions for a light ray to pass undeviated on refraction

A ray of light passes undeviated from medium 1 to medium 2 in either of the following two conditions :

(1) When the angle of incidence at the boundary of two media is zero (i.e., $\angle i = 0°$) as shown in Fig. 4.3.

(2) When the refractive index of medium 2 is same as that of medium 1 (Fig. 4.4), i.e., $i = r$.

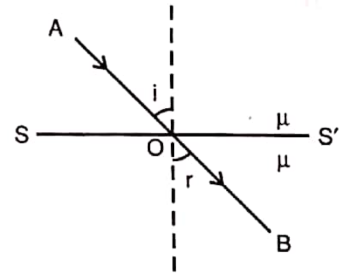

Fig. 4.4 No deviation if $\mu_1 = \mu_2 = \mu$ (say)

Effect on speed (V), wavelength (λ) and frequency (f) due to refraction of light

1. When a ray of light gets refracted from rarer to a denser medium, the speed of light decreases; while if it is refracted from denser to a rarer medium, the speed of light increases.

2. The frequency of light depends on the source of light, so it does not change on refraction.

If V is the speed of light in a medium and λ is the wavelength of light in that medium, the frequency of light is given as $f = \frac{V}{\lambda}$

or $$\boxed{V = f\lambda} \quad \text{...(4.}$$

3. When light passes from a rarer to a denser medium, the wavelength *decreases* (since speed of light *decreases*, but its frequency remains unchanged). When light passes from a denser medium to a rarer medium, the speed of light and hence its wavelength *increases*.

If a ray of light of frequency f and wavelength λ suffers refraction from air (speed of light = c) to a medium in which the speed of light is V, then the frequency of light in the medium remains unchanged (equal to f), but the wavelength of light changes to λ' such that in air $f = \frac{c}{\lambda}$ and in medium $f = \frac{V}{\lambda'}$.

$$\therefore \quad \frac{c}{\lambda} = \frac{V}{\lambda'} \quad \text{or} \quad \lambda' = \frac{V}{c}\lambda$$

But $\frac{c}{V} = \mu$ the refractive index of the medium.

$$\therefore \quad \boxed{\lambda' = \frac{\lambda}{\mu}} \quad \boxed{\mu_2 = \frac{\lambda_1}{\lambda_2}} \quad \text{..... (4.6)}$$

Obviously when light passes from a rarer to a denser medium ($\mu > 1$), its wavelength decreases ($\lambda' < \lambda$), but if light passes from a denser to a rarer medium ($\mu < 1$), its wavelength increases ($\lambda' > \lambda$).

> *Note* : Due to change in speed of light in refraction from one medium to other, the direction of ray of light changes except for $\angle i = 0°$.

Factors affecting the refractive index of a medium

The refractive index of a medium depends on the following *three* factors :

(1) Nature of the medium *i.e.* its optical density : As smaller the speed of light in a medium relative to air, higher is the refractive index of that medium. For example $V_{glass} = 2 \times 10^8$ m s^{-1}, $\mu_{glass} = 1{\cdot}5$ and $V_{water} = 2{\cdot}25 \times 10^8$ m s^{-1}, $\mu_{water} = 1{\cdot}33$.

(2) Physical condition such as temperature : With increase in temperature, the speed of light in medium increases, so the refractive index of medium decreases.

(3) The colour or wavelength of light : The speed of light of all colours is same in air (or vacuum), but in any other transparent medium, the *speed of light is different for different colours.* In a given medium, the speed of red light is maximum and that of the violet light is least, therefore *the refractive index of that medium is maximum for violet light and least for red light* (*i.e.*, $\mu_V > \mu_R$). The wavelength of red light is more than that of violet light, so *refractive index of a medium decreases with the increase in wavelength.* $\therefore \mu_V > \mu_R$

4.4 PRINCIPLE OF REVERSIBILITY OF THE PATH OF LIGHT

According to this principle, *the path of a light ray is reversible*.

In Fig. 4.5, a ray of light AO is incident at an angle i on a plane surface SS′ separating the two media 1 and 2. It is refracted along OB at an angle of refraction r. The refractive index of medium 2 with respect to medium 1 is

derivation

$${}_1\mu_2 = \frac{\mu_2}{\mu_1} = \frac{\sin i}{\sin r} = \frac{V_1}{V_2} \quad \text{..... (i)}$$

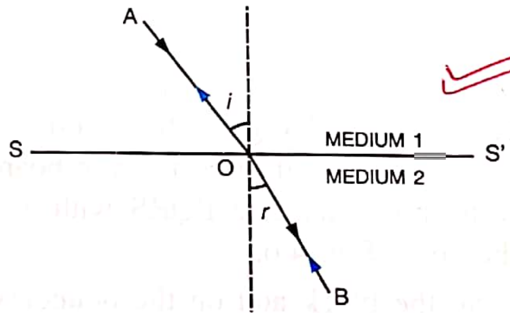

Fig. 4.5 Principle of reversibility

Now if the refraction takes place from the medium 2 to 1, the principle of reversibility requires that the ray of light incident along BO at O at an angle of incidence r in medium 2 will get refracted only along OA at an angle of refraction i in medium 1 and in no other direction than OA. The refractive index of medium 1 with respect to medium 2 is then

$${}_2\mu_1 = \frac{\mu_1}{\mu_2} = \frac{\sin r}{\sin i} = \frac{V_2}{V_1} \quad \text{..... (ii)}$$

From eqns. (i) and (ii),

$$_1\mu_2 \times {_2\mu_1} = \frac{\sin i}{\sin r} \times \frac{\sin r}{\sin i}$$

or $$\boxed{_1\mu_2 \times {_2\mu_1} = 1} \quad \text{... (4.7)}$$

or $$\boxed{_2\mu_1 = \frac{1}{_1\mu_2} \text{ or } {_1\mu_2} = \frac{1}{_2\mu_1}} \quad \text{.. (4.8)}$$

Thus, if refractive index of glass with respect to air is $_a\mu_g = \frac{3}{2}$, the refractive index of air with respect to glass will be $_g\mu_a = \frac{1}{3/2} = \frac{2}{3}$.

> *Note :* From relation $_1\mu_2 = \frac{\mu_2}{\mu_1}$, the refractive index of glass with respect to water is
>
> $$_w\mu_g = \frac{\mu_g}{\mu_w} = \frac{3/2}{4/3} = \frac{9}{8}$$
>
> and refractive index of water with respect to glass is $_g\mu_w = \frac{\mu_w}{\mu_g} = \frac{4/3}{3/2} = \frac{8}{9}$.

4.5 EXPERIMENTAL VERIFICATION OF LAWS OF REFRACTION AND DETERMINATION OF REFRACTIVE INDEX OF GLASS

Read only

Procedure :

(1) Place a rectangular glass block on a white sheet of paper fixed on a drawing board and draw its boundary line PQRS with a pencil as shown in Fig. 4.6.

(2) Remove the block and on the boundary line PQ, take a point O nearly at its middle and then draw a normal NOM on the line PQ at the point O.

(3) Draw a line AO inclined at an angle i (say, 40°) to the normal NOM.

(4) Replace the block exactly on its boundary line.

(5) Fix two pins a and b vertically on the board, about 5 cm apart, on the line AO.

(6) Now looking from the other side RS of the block by keeping the eye close to the plane of the board, fix two more pins c and d su[ch] that the base of all the four pins a, b, c a[nd] d appears to be in a straight line as se[en] through the block.

(7) Then remove the pins one by one and ma[rk] the position of each pin with a fine pen[cil] dot. Remove the block and join the points [c] and d by a line BC to meet the bounda[ry] line RS at a point B. Join the points O a[nd] B by a straight line which gives the path [of] light ray inside the glass block.

Here AO represents the incident ray, OB [the] refracted ray through the block and BC [the] emergent ray. NOM is the normal at [the] point of incidence O, ∠AON is the angle [of] incidence i and ∠BOM is the angle [of] refraction r.

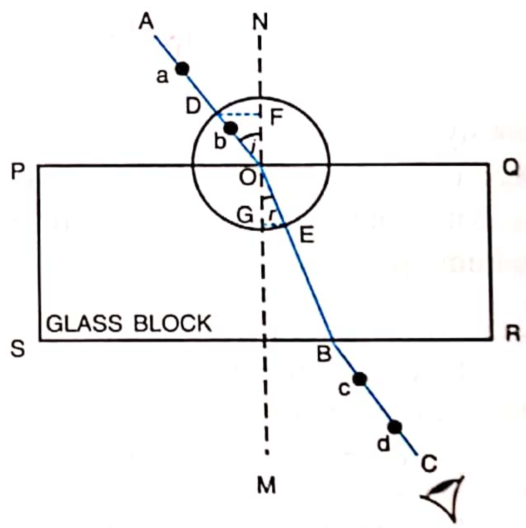

Fig. 4.6 Verfication of laws of refraction

(8) Measure the angles i and r. Read the val[ues] of sin i and sin r from the sine table [and] calculate the ratio sin i/sin r. This ratio [is] constant and it gives the refractive index [of] glass.

Alternative method : In order to verfiy [the] law of refraction without measuring the angle[s i] and r, draw a circle of suitable radius with [the] point O as centre which intersects the incident [ray] AO at D and the refracted ray OB at E. Dr[aw] normals DF and EG on NOM from the points [D] and E respectively. Measure the length of [...]

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normals DF and EG. Find DF/EG. This ratio is constant and it gives the refractive index of glass because

In right-angled ΔOFD, $\sin i = \frac{DF}{OD}$

and in right-angled ΔOGE, $\sin r = \frac{EG}{OE}$

$$\therefore \quad \mu = \frac{\sin i}{\sin r} = \frac{DF/OD}{EG/OE}$$

But OD = OE, being the radii of the same circle.

$$\therefore \quad \mu = \frac{DF}{EG}$$

(9) Repeat the steps (3) to (8) of the experiment for different values of angle of incidence i equal to 50°, 60°, 70°, 80° and in each case, find the ratio $\frac{\sin i}{\sin r}$ or $\frac{DF}{EG}$.

(10) Record your observations in a table shown below :

S.N.	i	r	$\sin i$ or DF	$\sin r$ or EG	$\frac{\sin i}{\sin r}$ or $\frac{DF}{EG} = \mu$
1.	40°				
2.	50°				
3.	60°				
4.	70°				
5.	80°				
					Average μ =

From the above observation table, we find that the ratio $\frac{\sin i}{\sin r}$ or $\frac{DF}{EG}$ comes out to be a constant for each value of angle i. *This verifies the second law of refraction.* The ratio so obtained is equal to the refractive index μ of glass, the material of the block. Thus, the refractive index μ of glass can be determined.

Further, the incident ray AO, the normal NOM at the point of incidence O and the refracted ray OB are in the plane of paper (*i.e.*, in the same plane). *This verifies the first law of refraction.*

4.6 REFRACTION OF LIGHT THROUGH A RECTANGULAR GLASS BLOCK

Fig 4.7 shows a rectangular glass block PQRS. A light ray AO falls on the surface PQ. NOM is the normal to the surface PQ at the point of incidence O. At the surface PQ, the ray AO enters from air (rarer medium) to glass (denser medium), so *it slows down and bends towards the normal* NOM. It travels inside glass in a straight path along OB. At the surface RS, the ray OB suffers another refraction. N_1BM_1 is the normal to the surface RS at the point of incidence B. The ray OB now enters from glass (denser medium) to air (rarer medium), so *it speeds up and bends away from the normal* N_1BM_1. It travels along BC in air. The ray AO is called the *incident ray*, OB the *refracted ray* and BC the *emergent ray*. The ∠AON is the *angle of incidence i*, the ∠BOM is the *angle of refraction r* and the $\angle CBM_1$ is the *angle of emergence e*. Since *refraction occurs at two parallel surfaces* PQ and RS, therefore, $\angle MOB = \angle N_1BO$ and $\angle i = \angle e$ *i.e.*, the angle of incidence i is equal to the angle of emergence e by the principle of reversibility of the path of a light ray. Thus, *the emergent ray BC is parallel to the incident ray AO.*

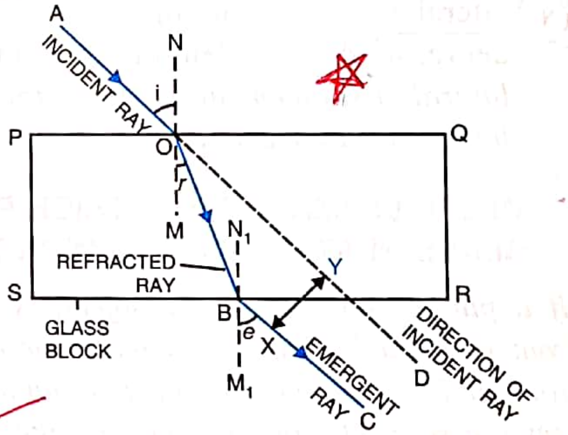

Fig. 4.7 Refraction through a rectangular glass block

Lateral displacement

In Fig. 4.7, we observe that due to refraction of light at two parallel surfaces of a *parallel sided* glass block, the angle of incidence is equal to the angle of emergence, so the incident ray AO and the emergent ray BC are parallel (*i.e.*, they are in same direction), but *they are not along the same line*. The emergent ray is *laterally displaced* from the path of incident ray. The path of incident ray AO in absence of glass block has been shown in Fig. 4.7 by the dotted line OD. The perpendicular distance XY (= x) between the path of emergent ray BC and the direction of incident ray OD is called the ***lateral displacement***.

The lateral displacement x depends on*

(i) the thickness of block (or medium),

(ii) the angle of incidence, and

(iii) the refractive index of glass, and therefore also on the wavelength of light used.

(i) **Dependence on the thickness of medium :** More the thiickness of the medium, more is the lateral displacement.

(ii) **Dependence on the angle of incidence :** More the angle of incidence, more is the lateral displacement.

(iii) **Dependence on the refractive index :** More the refractive index of the medium, more is the lateral displacement. Since refractive index increases with the decrease in wavelength of light, so the (iv) lateral displacement increases with the decrease in wavelength of light (*i.e., lateral displacement is more for violet light than for red light*).

still to be discussed

4.7 MULTIPLE IMAGES IN A THICK PLANE GLASS PLATE OR THICK MIRROR

If a pin (or an illuminated object) is placed in front of a thick plane glass plate (or a thick mirror) and is viewed obliquely, a number of images are seen. Out of these images, the second image is the brightest, while others are of decreasing brightness.

In Fig. 4.8, LMNP represents a thick plane mirror of which NP is the silvered surface. An illuminated object A is kept in front of it.

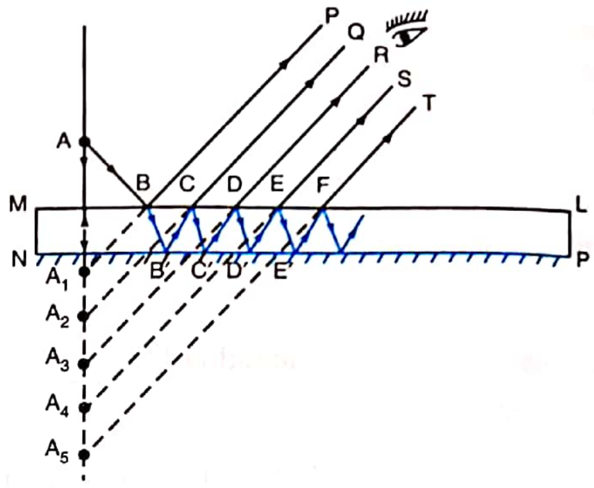

Fig. 4.8 Multiple reflections in a thick mirror

Consider two rays, one falling normally on the mirror and the other AB falling obliquely on it. When the ray of light AB falls on the surface LM of the mirror, a *small part* of light (nearly 4%) is reflected in the direction BP, forming a faint virtual image at A_1, while a *larger part* of light (nearly 96%) is refracted along BB′ inside the glass. The ray BB′ which strikes at B′, is now strongly reflected back by the silvered surface PN inside glass as B′C. This ray is then partially refracted along CQ in air and partially reflected along CC′ within the glass. The refracted ray CQ forms the virtual image A_2. The image A_2 is the *brightest image* because it is due to the light suffering a strong first reflection at the silvered surface PN.

The reflected ray CC′ further suffers multiple reflections at C′, D, D′, ... and refractions at D, E, F, ... within the thickness of glass plate giving rise to multiple virtual images A_3, A_4, A_5, ... of *gradually decreasing brightness*.

> ***Note :*** **(1)** In Fig. 4.8 due to drawing, the rays BP, CQ, ... appear to be far separated from each other, but actually they enter the eye simultaneously.
>
> **(2)** A thick glass plate also behaves like a thick plane mirror.

* Lateral displacement = $\frac{t \sin(i-r)}{\cos r}$ where t = thickness of glass block, i = angle of incidence, r = angle of refraction.