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 $\delta = i - r$.

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

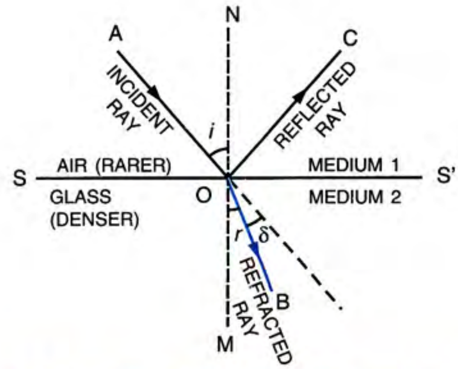

Fig. 4.1 Refraction from rarer to denser medium

(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 $\delta = r - i$.

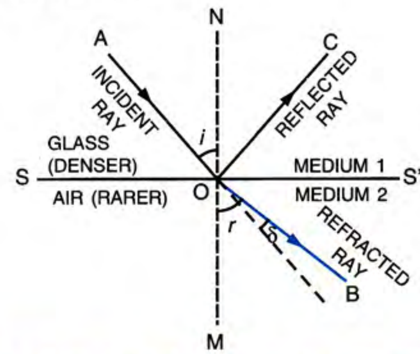

Fig. 4.2 Refraction from denser to rarer medium

(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.*, $\delta = 0°$).

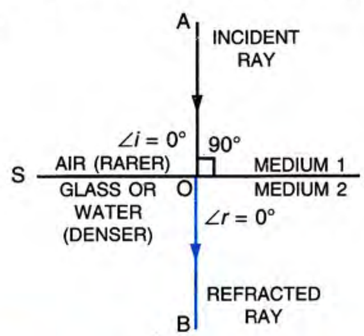

Fig. 4.3 Refraction at normal incidence

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

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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*

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

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 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.,

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

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

$$\mu_{glass} = \frac{3 \times 10^8}{2 \times 10^8} = 1{\cdot}5$$

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

$$\mu_{water} = \frac{3 \times 10^8}{2{\cdot}25 \times 10^8} = \frac{4}{3} = 1{\cdot}33$$

(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 :

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

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),

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

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

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

$$= \frac{2{\cdot}25 \times 10^8}{2{\cdot}0 \times 10^8} = 1{\cdot}125$$

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

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

$$= \frac{2{\cdot}0 \times 10^8}{2{\cdot}25 \times 10^8} = 0{\cdot}89$$

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.*, $i = r$.

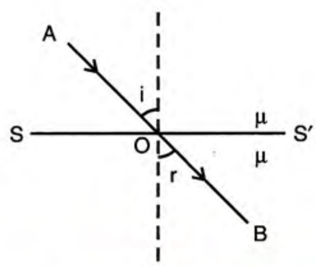

Fig. 4.4 No deviation if $\mu_1 = \mu_2 = \mu$ (say)

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

1. When a ray of light gets refracted from a rarer to a denser medium, the speed of light decreases; while if it is refracted from a 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 $$V = f\lambda \quad \text{...(4.5)}$$

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.

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

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.*

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

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

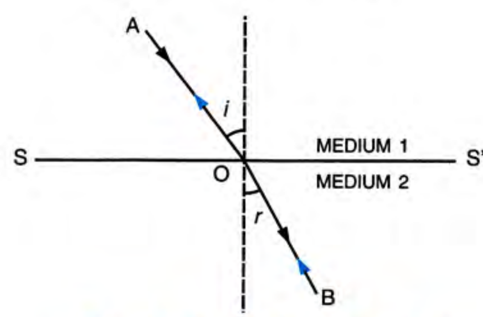

Fig. 4.5 Principle of reversibility

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

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

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

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

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 such that the base of all the four pins a, b, c and d appears to be in a straight line as seen through the block.

(7) Then remove the pins one by one and mark the position of each pin with a fine pencil dot. Remove the block and join the points c and d by a line BC to meet the boundary line RS at a point B. Join the points O and 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.*

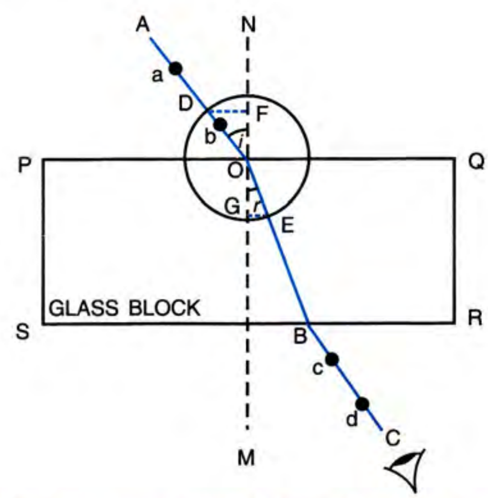

Fig. 4.6 Verfication of laws of refraction

(8) Measure the angles i and r. Read the values 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 angles 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. Draw normals DF and EG on NOM from the points D and E respectively. Measure the length of the 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 ∠*i* = ∠*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.

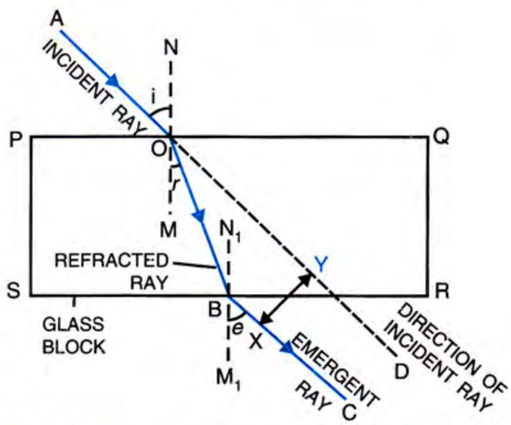

Fig. 4.7 Refraction through a rectangular glass block

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 lateral displacement increases with the decrease in wavelength of light (*i.e., lateral displacement is more for violet light than for red light*).

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.

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

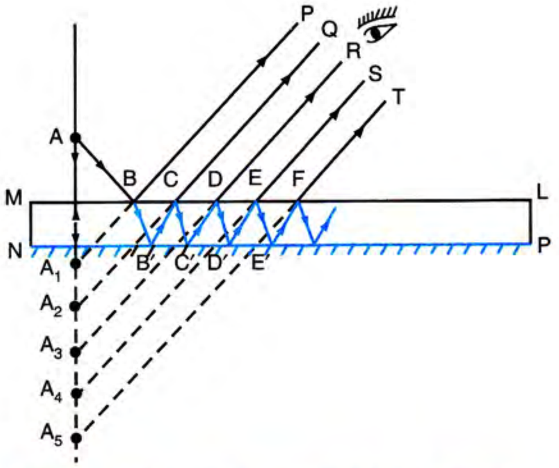

Fig. 4.8 Multiple reflections in a thick mirror

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.

EXAMPLES

1. A ray of light in passing from one transparent medium to the other medium having different optical density, bends.

(a) Name the phenomenon. Give reason for it.

(b) How do the following quantities change : speed, wavelength, frequency and amplitude if second medium is denser than the first medium.

(c) State whether the ray of light will bend or not, if both medium have same optical densities.

(a) Refraction.

The reason of bending (or refraction) is the change in speed of light in passing from one medium to other of different optical density.

(b) Speed will decrease.

Wavelength will decrease.

Frequency will remain unchanged.

Amplitude will decrease (due to partial reflection at the boundary of two media).

(c) The ray will not bend.

2. A ray of light falls normally on a glass slab. Draw diagram showing the path of the ray till it emerges out of the slab. What is the angle of incidence and angle of refraction at each surface of slab ?

The ray diagram is shown in Fig. 4.9 in which the light ray passes undeviated throught the slab.

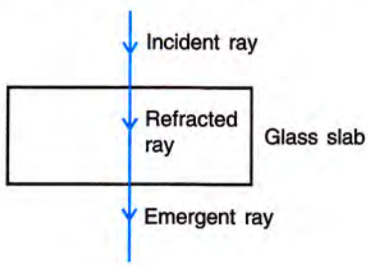

Fig. 4.9

At each surface of glass slab,

angle of incidence = **0°**

and angle of refraction = **0°**

3. 'The refractive index of water is 4/3'. Explain the meaning of this statement.

It means that the speed of light in water is 3/4th the speed of light in vacuum (or air). OR the speed of light in air (or vacuum) is 4/3 times the speed of light in water.

4. Refractive index of water is 4/3. Calculate the speed of light in water. Speed of light in vacuum is 3×10^8 m s^{-1}.

Refractive index of water

$$= \frac{\text{speed of light in vacuum}}{\text{speed of light in water}}$$

$$\therefore \quad \frac{4}{3} = \frac{3\times10^8}{\text{Speed of light in water}}$$

or Speed of light in water $= \frac{3}{4} \times (3 \times 10^8)$

$= \mathbf{2{\cdot}25 \times 10^8}$ **m s^{-1}.**

5. The refractive index of water is $\frac{4}{3}$ and of glass is $\frac{3}{2}$. What is the refractive index of glass with respect to water ?

Given : ${}_a\mu_w = \frac{4}{3}$, ${}_a\mu_g = \frac{3}{2}$

$\therefore$ Refractive index of glass with respect to water

$${}_w\mu_g = \frac{\text{refractive index of glass}}{\text{refractive index of water}}$$

or $${}_w\mu_g = \frac{{}_a\mu_g}{{}_a\mu_w} = \frac{3/2}{4/3} = \frac{9}{8} = \mathbf{1{\cdot}125}$$

6. Orange light of wavelength 6600 Å travelling in air gets refracted in water. If the speed of light in air is 3×10^8 m s^{-1} and refractive index of water is 4/3, find : (i) the frequency of light in air, (ii) the speed of light in water, and (iii) the wavelength of light in water.

Given : $\lambda_{air} = 6600$ Å $= 6600 \times 10^{-10}$ m,

$c = 3 \times 10^8$ m s^{-1}, $\mu = 4/3$

(i) From relation $c = f\lambda$ (in air)

Frequency of light in air $f_{air} = \frac{c}{\lambda_{air}}$

or $$f_{air} = \frac{3\times10^8}{6600\times10^{-10}}$$

$= \mathbf{4{\cdot}54 \times 10^{14}}$ **Hz.**

(ii) From relation $\mu = \frac{c}{V}$

Speed of light in water $V = \frac{c}{\mu} = \frac{3\times10^8}{4/3}$

$= \mathbf{2{\cdot}25 \times 10^8}$ **m s^{-1}**

(iii) Since the frequency of light remains unchanged in refraction, so $f_{water} = f_{air} = 4{\cdot}54 \times 10^{14}$ Hz

Now speed of light in water $V = f_{water} \times \lambda_{water}$

$\therefore$ Wavelength of light in water

$$\lambda_{water} = \frac{V}{f_{water}} = \frac{2{\cdot}25 \times 10^8}{4{\cdot}54 \times 10^{14}}$$
$$= \mathbf{4{\cdot}95 \times 10^{-7}\ m} \text{ or } \mathbf{4950\ \text{Å}}$$

Alternative : $\lambda_{water} = \frac{\lambda_{air}}{\mu_{water}} = \frac{6600\ \text{Å}}{4/3} = \mathbf{4950\ \text{Å}}$

7. A ray of light strikes a glass slab 5 cm thick, making an angle of incidence equal to 30°.

(a) Draw a ray diagram showing the emergent ray and the refracted ray through the glass block. The refractive index of glass is 1·5.

(b) Measure the lateral displacement of the ray. Take sin 19·5° = 1/3.

(a) Given : $\mu = 1{\cdot}5$, $i = 30°$

Let us first calculate the angle of refraction r.

From Snell's law, $\frac{\sin i}{\sin r} = \mu$

$\therefore \quad \sin r = \frac{\sin i}{\mu} = \frac{\sin 30°}{1{\cdot}5} = \frac{1/2}{1{\cdot}5} = \frac{1}{3}$

or $\quad r = 19{\cdot}5°$ (since $\sin 19{\cdot}5° = 1/3$)

The ray diagram is given in Fig 4.10. The refracted ray is drawn with angle of refraction 19·5° and emergent ray is drawn parallel to the incident ray.

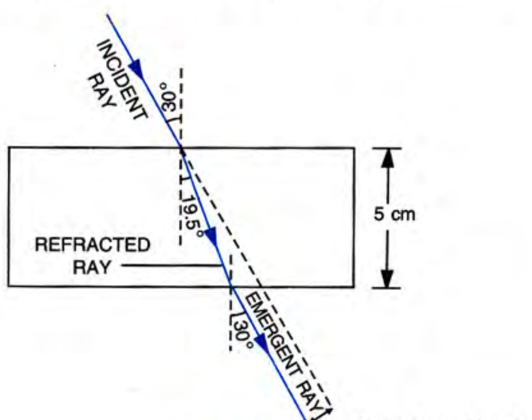

Fig. 4.10

(b) Lateral displacement = **1 cm** nearly (on proper scale).

8. The diagram below shows a glass block suspended in a liquid. A beam of light of single colour is incident from liquid on one side of the block.

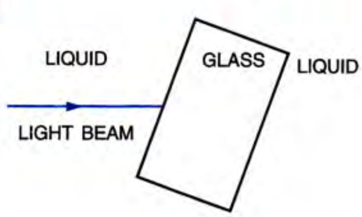

Fig. 4.11

(a) Draw diagrams to show how does the light bend when it travels from liquid to glass and then to liquid if (i) the light slows down in glass, and (ii) the light speeds up in glass.

(b) State *two* conditions under which the light ray passing from liquid to glass travels straight without bending. Will the glass be visible then ?

(a) (i) If light slows down in going from liquid to glass, it means that $\mu_{glass} > \mu_{liquid}$, so it will bend towards the normal at the point of incidence in passing from liquid to glass at the first surface, while it will bend away from the normal at the second surface in passing from glass to liquid. The ray diagram is shown in Fig. 4.12. The light beam suffers lateral displacement.

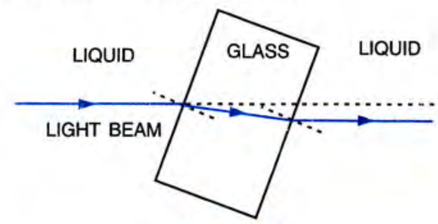

Fig. 4.12

(ii) If light speeds up in going from liquid to glass, it means that $\mu_{glass} < \mu_{liquid}$, so it will bend away from the normal at the point of incidence on the first surface in passing from liquid to glass, while it will bend towards the normal at the second surface in passing from glass to liquid. The ray diagram is shown in Fig. 4.13. The light beam suffers lateral displacement in direction opposite to that in case (i).

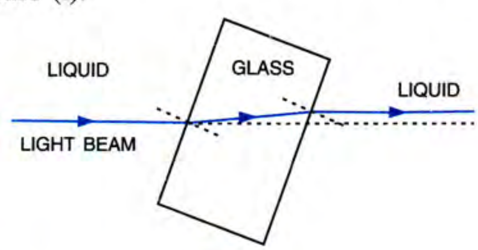

Fig. 4.13

Note : In both cases, *the emergent ray is parallel to the incident ray*.

(b) A light ray passing from liquid to glass travels straight without bending under the following *two* conditions:

(1) When the light ray falls normally on glass from liquid (*i.e.*, if $\angle i = 0°$, $\angle r = 0°$).

(2) When refractive index of liquid is same as that of glass (or speed of light in glass is same as in liquid).

In both the above conditions, the glass block **will not be visible** inside the liquid.

9. The diagram below shows two parallel rays A and B of red and violet light respectively incident from air on air-glass boundary. Complete the diagram showing the refracted rays for them in the glass.

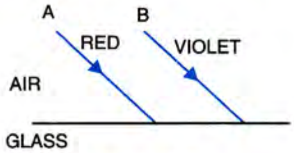

Fig. 4.14

(i) How do the speeds of the rays differ in glass ?

(ii) Are the two refracted rays in glass parallel ? Give a reason for your answer.

(iii) How does the refractive index of glass differ for the two rays ?

The completed ray diagram is shown below in Fig. 4.15.

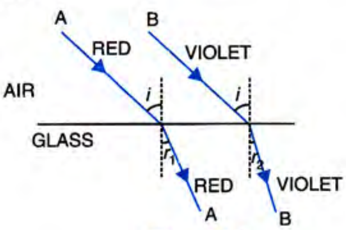

Fig. 4.15

(i) In glass, the speed of violet light is less than that of the red light.

(ii) The two refracted rays inside glass are **not parallel**. The reason is that the speed of red light in glass is less, while it is more for the violet light, so the red ray bends less, while the violet ray bends more (*i.e.*, the angle of refraction r_1 for red ray is more than the angle of refraction r_2 for the violet ray).

(iii) Since $\mu = c/V$, so the refractive index of glass is more for the violet light than for the red light (*i.e.*, $\mu_V > \mu_R$).

10. Fig. 4.16 shows a ray of light AO incident on a rectangular glass block PQRS, which is silvered at the surface RS. The ray is partly reflected and partly refracted.

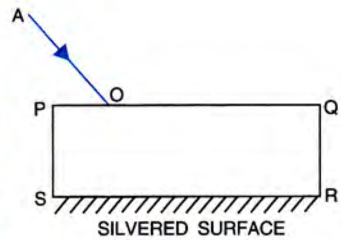

Fig. 4.16

(a) Draw the path of the reflected and refracted rays.

(b) Show at least *two* rays emerging from the surface PQ after reflection from the surface RS.

(c) How many images are formed in the above case ? Which image is the brightest ?

(a) The completed diagram is shown in Fig. 4.17 in which **OB is the reflected ray** and **OC is the refracted ray** for the incident ray AO.

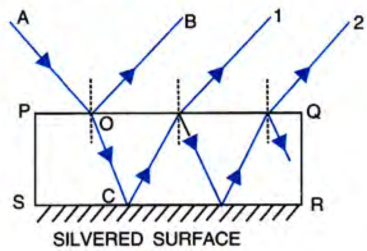

Fig. 4.17

(b) Two rays emerging from the surface PQ after reflections from the surface RS are labelled as **1 and 2.**

(c) **Multiple (or infinite) images** are formed. The **second image** formed due to first reflection at C at the silvered surface RS, is the brightest. It is seen in the direction of ray 1.

EXERCISE–4(A)

1. What do you understand by refraction of light ?
2. Draw diagrams to show the refraction of light from (i) air to glass, and (ii) glass to air. In each diagram, label the incident ray, refracted ray, the angle of incidence (*i*) and the angle of refraction (*r*).
3. A ray of light is incident normally on a plane glass slab. What will be (i) the angle of refraction, and (ii) the angle of deviation for the ray ?
   Ans. (i) 0°, (ii) 0°
4. An obliquely incident light ray bends at the surface due to change in speed, when passing from one medium to other. The ray does not bend when it is incident normally. Will the ray have different speed in other medium ? **Ans.** Yes
5. What is the cause of refraction of light when it passes from one medium to another ?
6. A light ray suffers reflection and refraction at the boundary in passing from air to water. Draw a neat labelled ray diagram to show it.
7. A ray of light passes from medium 1 to medium 2. Which of the following quantities of the refracted ray will differ from that of the incident ray : speed, intensity, frequency, and wavelength ?
   Ans. Speed, intensity and wavelength

8. State the Snell's laws of refraction of light.

9. Define the term refractive index of a medium. Can it be less than 1 ?

10. How is the refractive index of a medium related to the speed of light in it ?

11. A light ray passes from water to (i) air, and (ii) glass. In each case, state how does the speed of light change.

Ans. (i) The speed of light increases
(ii) The speed of light decreases.

12. A light ray in passing from water to a medium (a) speeds up, (b) slows down. In each case, (i) give *one* example of the medium, (ii) state whether the refractive index of medium is equal to, less than or greater than the refractive index of water.

Ans. (i) (a) air (b) glass,
(ii) (a) less than, (b) greater than

13. What do you understand by the statement 'the refractive index of glass is 1·5 for white light' ?

14. A monochromatic ray of light passes from air to glass. The wavelength of light in air is λ, the speed of light in air is c and in glass is V. If the refractive index of glass is 1·5, write down (a) the relationship between c and V, (b) the wavelength of light in glass.

Ans. (a) $c = 1{\cdot}5\ V$ (b) $\lambda/1{\cdot}5$

15. In an experiment of finding the refractive index of glass, if blue light is replaced by the red light, how will the refractive index of glass change ? Give reason in support of your answer.

16. (a) For which colour of white light, is the refractive index of a transparent medium (i) the least, (ii) the most ?

(b) Which colour of light travels fastest in any medium except air ?

Ans. (a) (i) Red (ii) Violet, (b) Red

17. Name *two* factors on which the refractive index of a medium depends ? State how does it depend on the factors stated by you.

18. How does the refractive index of a medium depend on the wavelength of light used ?

Ans. Refractive index of a medium decreases with increase in wavelength of light.

19. How does the refractive index of a medium depend on its temperature ?

Ans. Refractive index decreases with increase in temperature of medium.

20. In Fig. 4.18, a ray of light A incident from air suffers partial reflection and refraction at the boundary of water.

(a) Complete the diagram showing (i) the reflected ray B and (ii) the refracted ray C.

(b) How are the angles of incidence i and refraction r related ?

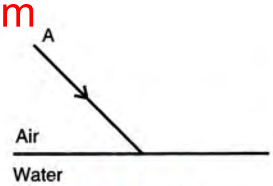

Fig. 4.18

Ans. (b) $\sin i/\sin r = \mu_w$

21. The diagram alongside shows the refraction of a ray of light from air to a liquid.

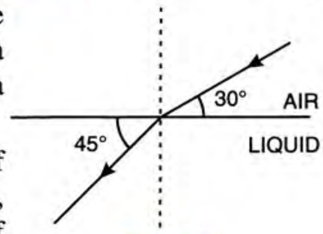

Fig. 4.19

(a) Write the values of (i) angle ofincidence, and (ii) angle of refraction.

(b) Use Snell's law to find the refractive index of liquid with respect to air.

Ans. (a) (i) 60°, (ii) 45°, (b) $\sqrt{\frac{3}{2}}$ or 1·22

22. The refractive index of water with respect to air is ${}_a\mu_w$ and of glass with respect to air is ${}_a\mu_g$. Express the refractive index of glass with respect to water.

Ans. ${}_w\mu_g = \dfrac{{}_a\mu_g}{{}_a\mu_w}$

23. What is lateral displacement ? Draw a ray diagram showing the lateral displacement of a ray of light when it passes through a parallel sided glass slab.

24. A ray of light strikes the surface of a rectangular glass slab such that the angle of incidence in air is (i) 0°, (ii) 45°. In each case, draw diagram to show the path taken by the ray as it passes through the glass slab and emerges from it.

25. In the adjacent diagram, AO is a ray of light incident on a rectangular glass slab.

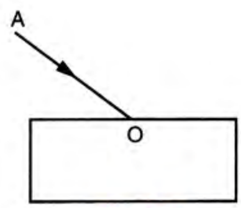

Fig 4.20

(a) Complete the path of the ray till it emerges out of the slab.

(b) In the diagram, mark the angle of incidence (i) and the angle of refraction (r) at the first interface. How is the refractive index of glass related to the angles i and r ?

(c) Mark angle of emergence by the letter e. How are the angles i and e related ?

(d) Which *two* rays are parallel to each other ? Name them.

(e) Indicate in the diagram the lateral displacement between the emergent ray and the incident ray. State *one* factor that affects the lateral displacement.

26. A ray of green light enters a liquid from air, as shown in Fig. 4.21. The angle 1 is 45° and angle 2 is 30°.

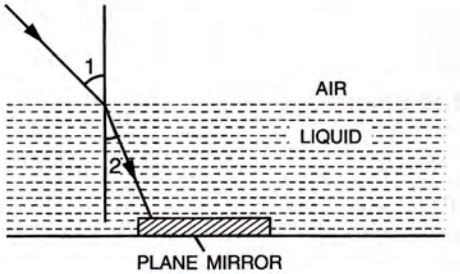

Fig. 4.21

(a) Find the refractive index of liquid.

(b) Show in the diagram the path of the ray after it strikes the mirror and re-enters in air. Mark in the diagram the angles wherever necessary.

(c) Redraw the digaram if plane mirror becomes normal to the refracted ray inside the liquid. State the principle used.

Ans. (a) $\sqrt{2}$ or 1·41

27. Light of a single colour is passed through a liquid having a piece of glass suspended in it. On changing the temperature of liquid, at a particular temperature the glass piece is not seen.

(i) When is the glass piece not seen ?

(ii) Why is the light of a single colour used ?

Ans. (i) The glass piece is not seen when the refractive index of liquid becomes equal to the refractive index of glass.

(ii) Light of a single colour is used because the refractive index of a medium (glass or liquid) is different for the light of different colours.

28. When an illuminated object is held in front of a thick plane glass mirror, several images are seen, out of which the second image is brightest. Give reason.

29. Fill in the blanks to complete the following sentences :

(a) When light travels from a rarer to a denser medium, its speed ....

(b) When light travels from a denser to a rarer medium, its speed ....

(c) The refractive index of glass with respect to air is 3/2. The refractive index of air with respect to glass will be..................

Ans. (a) decreases, (b) increases, (c) 2/3.

MULTIPLE CHOICE TYPE

1. When a ray of light from air enters a denser medium, it :

(a) bends away from the normal

(b) bends towards the normal

(c) goes undeviated

(d) is reflected back.

Ans. (b) bends towards the normal.

2. A light ray does not bend at the boundary in passing from one medium to the other medium if the angle of incidence is :

(a) 0° (b) 45° (c) 60° (d) 90°. **Ans.** (a) 0°

3. The highest refractive index is of :

(a) Glass (b) Water

(c) Diamond (d) Ruby. **Ans.** (c) Diamond

NUMERICALS

1. The speed of light in air is 3×10^8 m s^{-1}. Calculate the speed of light in glass. The refractive index of glass is 1·5. **Ans.** 2×10^8 m s^{-1}

2. The speed of light in diamond is 125,000 km s^{-1}. What is its refractive index ? (Speed of light in air $= 3 \times 10^8$ m s^{-1}). **Ans.** 2·4

3. The refractive index of water with respect to air is 4/3. What is the refractive index of air with respect to water ? **Ans.** 0·75

4. A ray of light of wavelength 5400 Å suffers refraction from air to glass. Taking ${}_a\mu_g = 3/2$, find the wavelength of light in glass. **Ans.** 3600 Å

(B) REFRACTION OF LIGHT THROUGH A PRISM

4.8 PRISM

A prism is a transparent medium bounded by five plane surfaces with a triangular cross section. Two opposite surfaces of prism are identical parallel triangles, while the other three surfaces are rectangular and inclined on each other.

> *A prism is a transparent refracting medium bounded by five plane surfaces with a triangular cross section.*

Fig. 4.22 shows a prism in which the opposite surfaces ABC and DEF are triangular. The *principal section* of prism is the triangle ABC. The ∠BAC is the *angle of prism*, which is denoted by the letter *A*. The two rectangular surfaces ABED and ACFD shown shaded are the *refracting surfaces*. The line AD is the *refracting edge* and the rectangular surface BCFE is the *base* of the prism, which is usually grounded or made rough.

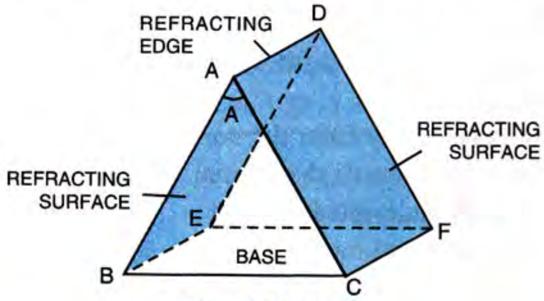

Fig. 4.22 Prism

> ***Note :*** In ray diagrams, a prism is shown only by its principal section ABC.

4.9 REFRACTION OF LIGHT THROUGH A GLASS PRISM

Fig. 4.23 shows the principal section ABC of a glass prism. The angle of prism is ∠BAC = *A*. A monochromatic ray of light (*i.e., a light ray of single colour*) OP strikes the face AB of the prism at an angle of incidence i_1. It suffers refraction from air (rarer medium) to glass (denser medium) at the face AB, so it bends towards the normal PN making an angle of refraction r_1 and travels along PQ inside the prism. Thus PQ is the *refracted ray*. The refracted ray PQ strikes the face AC of the prism at an angle of incidence r_2. It suffers refraction from glass (denser medium) to air (rarer medium) at the face AC, so it bends away from the normal NQ and emerges out of the prism as QR at an angle of emergence i_2. Thus QR is the *emergent ray*.

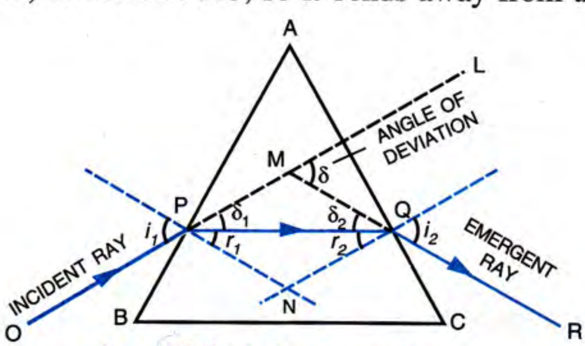

Fig. 4.23 Deviation by a prism

> ***Note :*** Due to the principle of reversibility of path of a light ray, if a ray directed along RQ is considered as the incident ray, it will follow the path QPO. It means that for the incident ray RQ, the emergent ray will be PO.

Thus in a prism, the ray of light suffers refraction at two *inclined* faces AB and AC of the prism. *In each refraction, the ray bends towards the base of the prism.* At the first face AB of the prism the ray OP, instead of going along OPM, has bent at P along PQ, so suffers a deviation by an ∠MPQ equal to δ_1. At the second face AC, the ray PQ has bent at Q along QR which appears to be coming along MQR, so suffers a deviation by an ∠MQP equal to δ_2.

In the absence of the prism, the incident ray OP would have travelled along OPML. The emergent ray QR appears to be coming along MQR. Thus the prism has produced a deviation by an ∠LMQ, which is the angle between the direction of incident ray (OP produced forward) and the emergent ray (QR produced backward). It is called the *angle of deviation* and is denoted by the greek alphabet δ (delta).

In Fig. 4.23, ∠ LMQ = ∠ MPQ + ∠ MQP

∴ Angle of deviation δ = ∠ MPQ + ∠ MQP

$$= \delta_1 + \delta_2 \quad \text{......(i)}$$

Since ∠ MPN = i_1 (angle of incidence), and ∠ MQN = i_2 (angle of emergence).*

Therefore ∠ MPQ = $\delta_1 = (i_1 - r_1)$

and ∠ MQP = $\delta_2 = (i_2 - r_2)$

∴ From eqn. (i), $\delta = (i_1 - r_1) + (i_2 - r_2)$

or $$\boxed{\delta = (i_1 + i_2) - (r_1 + r_2)} \quad \text{..(4.9)}$$

Also for the quadilateral APNQ in Fig 4.23,

∠APN = ∠AQN = 90°

* *Sometimes angle of emergence is denoted by the letter e in place of i_2, then angle of incidence is written i in place of i_1.*

$\therefore \; \angle PNQ + \angle PAQ = 180°$

But $\quad \angle PAQ = A,$

$\therefore \quad \angle PNQ = 180° - A \quad$ ......(ii)

But in triangle PNQ,

$\angle PNQ = 180° - (r_1 + r_2) \quad$ ......(iii)

$\therefore$ From eqns. (ii) and (iii),

$[180° - (r_1 + r_2)] = 180° - A$

or $\quad \boxed{r_1 + r_2 = A} \quad$ ......(4.10)

Hence from eqns. (4.9) and (4.10),

$\delta = (i_1 + i_2) - A$

or $\quad \boxed{i_1 + i_2 = A + \delta} \quad$ ......(4.11)*

> ***Note :*** In a prism, the refraction of light occurs at two inclined faces, so the emergent ray is not parallel to the incident ray, but it is deviated towards the base of prism. On the other hand, in a parallel sided glass slab, the refraction of light occurs at two parallel faces, so the emergent ray is parallel to the incident ray with a lateral shift.

Factors affecting the angle of deviation

The angle of deviation δ (*i.e.*, the deviation produced by a prism) depends on the following *four* factors :

(1) *the angle of incidence (i),*

(2) *the material of prism (i.e., on refractive index* μ*),*

(3) *the angle of prism (A), and*

(4) *the colour* or *wavelength* (λ) *of light used.*

(1) Dependence of angle of deviation on the angle of incidence; i-δ graph

It is experimentally observed that as the angle of incidence increases, the angle of deviation first decreases, reaches to a minimum value for a certain angle of incidence and then on further increasing the angle of incidence, the angle of deviation begins to increase.

* *If angle of incidence is i and angle of emergence is e, then eqn. (4.11) takes the form* $i + e = A + \delta$.

> ***Note :*** To get the graph showing the variation of angle of deviation with the angle of incidence experimentally, the direction of incident ray is kept unchanged and the prism is rotated. On rotation of *prism, the direction of normal at the face of prism changes, so the angle which the incident ray makes with the normal (i.e., the angle of incidence) changes.*

The angle of deviation δ is noted for each angle of incidence i and then a graph is drawn for δ *vs* i. Fig. 4.24 shows the variation in angle of deviation (δ) with the angle of incidence (i). It is called the i-δ curve in which the minimum value of angle of deviation is marked as δ_{min}.

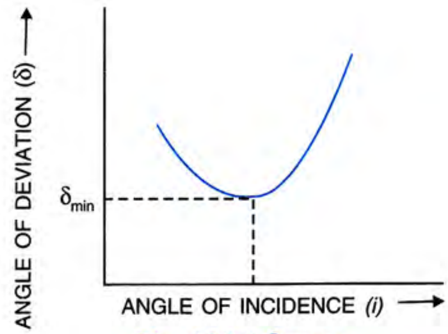

Fig. 4.24 i-δ curve

It is found that *the angle of deviation becomes minimum* (δ_{min}) *when the angle of incidence is equal to the angle of emergence i.e., when* $i_1 = i_2$ or when $r_1 = r_2$. In Fig. 4.23, if Δ ABC is equilateral (or equiangular), for $r_1 = r_2$, the ray PQ will be parallel to the base BC.

The position of prism with respect to the incident ray at which the incident ray suffers minimum deviation is called the *position of minimum deviation. Thus in the position of minimum deviation, the refracted ray inside the prism is parallel to its base, if the prism is equilateral (or the principal section of prism forms an isosceles triangle).* In other words,

In the position of minimum deviation, *i.e.*, when $\delta = \delta_{min}$, $i_1 = i_2 = i$ (say).

Then from eqn. (4.11),

$\boxed{\delta_{min} = 2i - A} \quad$ ...(4.12)

For a given prism and given colour of light, δ_{min} is *unique* since only *one* horizontal line can be drawn parallel to i-axis at the lowest point of i-δ curve, *i.e.*, only for one value of angle of incidence i, the refracted ray inside the prism is parallel to its base.

Deviation at different angles of incidence : Fig. 4.25 shows the deviation of a light ray by an equilateral prism of glass ($\mu = 1{\cdot}5$) at different angles of incidence. The values of different angles can be calculated using the eqns. (4.1), (4.10) and (4.11) with $A = 60°$. In Fig. 4.25(a), angle of incidence $i_1 = 70°$, angle of emergence $i_2 = 33°$ and angle of deviation $\delta = 43°$. In Fig. 4.25(b), $i_1 = 48°$, $i_2 = 48°$ and $\delta = 36°$, while in Fig. 4.25(c), $i_1 = 30°$, $i_2 = 77°$ and $\delta = 47°$.

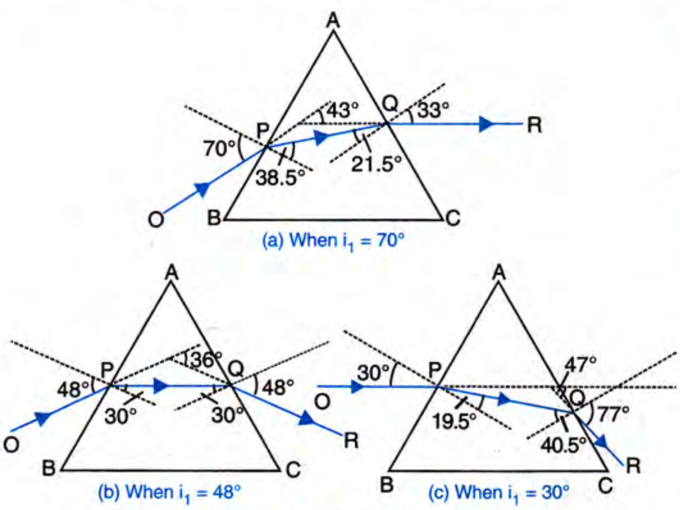

Fig. 4.25 Deviation by a equilateral prism at different angles of incidence

From the ray diagrams shown in Fig. 4.25, *it can easily be inferred that δ has the minimum value in Fig. 4.25(b) when the angle of incidence i_1 is 48° and the refracted ray* PQ *is parallel to the base* BC *of prism. In this condition, the angle of emergence i_2 is also 48° (equal to the angle of incidence i_1). In Fig. 4.25(b), the angle of minimum deviation is*

$$\delta_{min} = 2i - A = 2 \times 48° - 60° = 36°.$$

(2) Dependence of angle of deviation on the material of prism (or refractive index)

It is found that *for a given angle of incidence, the prism with a higher refractive index produces a greater deviation than the prism which has a lower refractive index. A flint glass prism produces more deviation than a crown glass prism of same refracting angle since $\mu_{flint} > \mu_{crown}$.*

(3) Dependence of angle of deviation on the angle of prism*

It is found that *the angle of deviation* (δ) *increases with the increase in the angle of prism (A).*

(4) Dependence of angle of deviation on the colour (or wavelength) of light

The refractive index of a given transparent medium is different for the light of different colours. It decreases with the increase in the wavelength of light. Thus the refractive index of the material of a prism is maximum for the violet light and minimum for the red light. Consequently, *a given prism deviates the violet light most and the red light least (i.e.,$\delta_{violet} > \delta_{red}$* since $\mu_{violet} > \mu_{red}$).

* *For small angle of prism A, angle of deviation $\delta = (\mu - 1)A$.*

EXAMPLES

1. Fig. 4.26 alongside shows an equilateral prism ABC and the ray QR emerging out from the prism after suffering minimum deviation. Complete the diagram to show the refracted ray PQ inside the prism and the incident ray OP on the prism. State in words how have you completed the diagram.

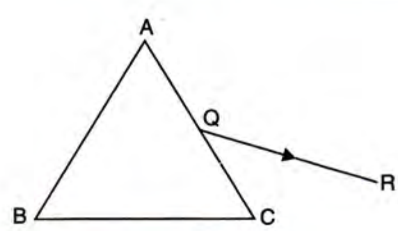

Fig. 4.26

The completed diagram is shown below in Fig. 4.27.

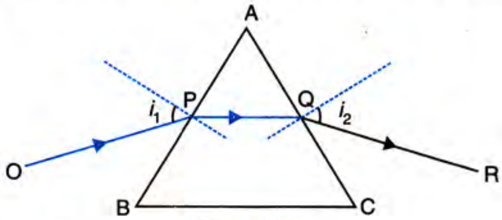

Fig. 4.27

Way of drawing :

(1) The refracted ray PQ is drawn parallel to the base BC of the prism since the emergent ray QR has suffered minimum deviation.

(2) After drawing normals on face AB of prism at P and on face AC of prism at Q, the incident ray OP is drawn such that the angle of incidence i_1 is equal to the angle of emergence i_2.

2. In Fig. 4.28, a monochromatic point source of light S is viewed by an observer O through a prism P. Complete the diagram to show the image formed by the prism and as seen by the observer O. Label the image by the letter I.

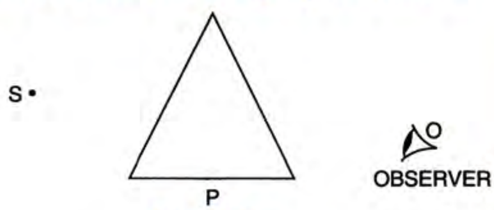

Fig. 4.28

The completed ray diagram is shown in Fig. 4.29. Two rays SA and SL from the source of light S, are incident on the prism. They are refracted along AB and LM respectively from the first face of the prism. The rays AB and LM again get refracted from the second face of the prism and emerge out of the prism along BC and MN respectively such that they appear to come from a point I. Thus I is the image of the point source S. In other words, the observer O sees the source S raised to the position I.

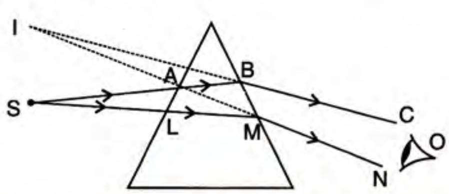

Fig. 4.29

3. Fig. 4.30 shows two identical prisms P and Q placed with their faces parallel to each other. A light ray of yellow colour AB is incident at the face of the prism P. Complete the diagram to show the path of the ray till it emerges out of the prism Q.

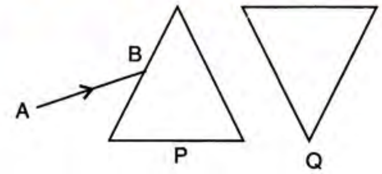

Fig. 4.30

The completed diagram is shown in Fig. 4.31 in which the ray CD emerging out of the prism Q is parallel to the ray AB incident on the prism P.

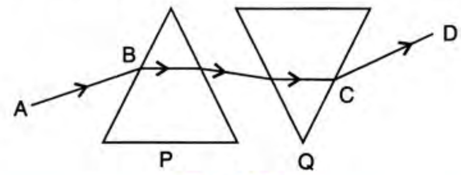

Fig. 4.31

4. Fig. 4.32 below shows a light ray of green colour incident normally on the prisms A, B and C. In each case, draw the path of the ray of light as it enters and emerges out of the prism. Mark the angle wherever necessary.

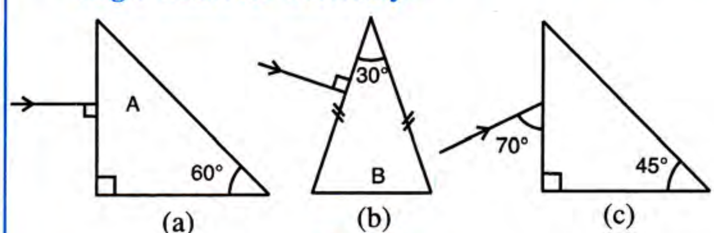

Fig. 4.32

The completed diagrams are given in Fig. 4.33.

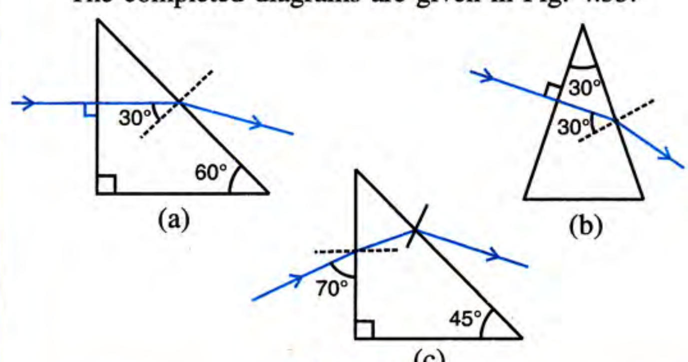

Fig. 4.33

Note : (i) The light ray incident normally on a surface gets refracted without deviation.

(ii) The light ray in passing from air to prism obliquely bends towards the normal at the point of incidence.

(iii) The light ray in passing from prism to air obliquely bends away from the normal at its point of incidence.

EXERCISE–4(B)

1. What is a prism ?
With the help of a diagram of principal section of a prism, indicate its refracting surfaces, refracting angle and base.

2. The diagrams (a) and (b) in Fig. 4.34 below show the refraction of a ray of light of single colour through a prism and a parallel sided glass slab respectively.

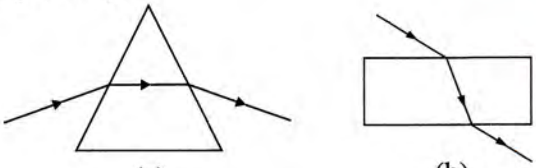

Fig. 4.34

(i) In each diagram, label the incident, refracted, emergent rays and the angle of deviation.

(ii) In what way the direction of emergent ray in the two cases differ with respect to the incident ray ? Explain your answer.

3. Define the term angle of deviation.

4. Complete the following sentence :
Angle of deviation is the angle which the .... ray makes with the direction of .... ray.
Ans. emergent, incident

5. What do you understand by the deviation produced by a prism ? Why is it caused ? State *three* factors on which the angle of deviation depends.

6. (a) How does the angle of deviation produced by a prism change with increase in the angle of incidence. Draw a curve showing the variation in the angle of deviation with the angle of incidence at a prism surface.
(b) Using the curve in part (a) above, how do you infer that for a given prism, the angle of minimum deviation δ_{min} is unique for the given light.

7. State whether the following statement is 'true' or 'false' :
The deviation produced by a prism is independent of the angle of incidence and is same for all colours of light. **Ans.** False

8. How does the deviation produced by a prism depend on (i) the refraction index of its material, and (ii) the wavelength of incident light.

9. How does the angle of minimum deviation produced by a prism change with increase in (i) the wavelength of incident light, and (ii) the refracting angle of prism ? **Ans.** (i) decreases (ii) increases.

10. Write a relation for the angle of deviation (δ) for a ray of light passing through an equilateral prism in terms of the angle of incidence (i_1), angle of emergence (i_2) and angle of prism (A).
Ans. $\delta = (i_1 + i_2) - A$

11. A ray of light incident at an angle of incidence i_1 passes through an equilateral glass prism such that the refracted ray inside prism is parallel to its base and emerges at an angle of emergence i_2. (i) How is the angle of emergence 'i_2' related to the angle of incidence 'i_1' ? (ii) What can you say about the angle of deviation in such a situation ?
Ans. (i) $i_2 = i_1$ (ii) angle of deviation is minimum.

12. How is the angle of emergence related to the angle of incidence when prism is in the position of minimum deviation ? Illustrate your answer with the help of a labelled diagram using an equilateral prism.

13. A light ray of yellow colour is incident on an equilateral glass prism at an angle of incidence equal to 48° and suffers minimum deviation by an angle of 36°. (i) What will be the angle of emergence ? (ii) If the angle of incidence is changed to (a) 30°, (b) 60°, state in each case whether the angle of deviation will be equal to, less than or more than 36° ?
Ans. (i) 48° (ii) (a) more than 36° (b) more than 36°

14. Name the colour of white light which is deviated (i) the most, and (ii) the least, on passing through a prism.
Ans. (i) violet (ii) red

15. Which of the two prisms, A made of crown glass and B made of flint glass, deviates a ray of light more ? **Ans.** B made of flint glass

16. How does the angle of deviation depend on the refracting angle of the prism ?

17. An object is viewed through a glass prism with its vertex pointing upwards. Draw a ray diagram to show the formation of its image seen by the observer.

18. A ray of light is normally incident on one face of an equilateral glass prism. Answer the following :
   (a) What is the angle of incidence on the first face of the prism ?
   (b) What is the angle of refraction from the first face of the prism ?
   (c) What will be the angle of incidence at the second face of the prism ?
   (d) Will the light ray suffer minimum deviation by the prism ?

Ans. (a) 0° (ii) 0° (iii) 60° (iv) No

19. Fig. 4.35 below shows two identical prisms A and B placed with their faces parallel to each other. A ray of light of single colour PQ is incident at the face of the prism A. Complete the diagram to show the path of the ray till it emerges out of the prism B.

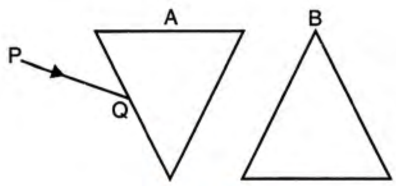

Fig. 4.35

[**Hint :** The emergent ray out of the prism B will be parallel to the incident ray PQ]

MULTIPLE CHOICE TYPE

1. In refraction of light through a prism, the light ray :
   (a) suffers refraction only at one face of the prism
   (b) emerges out from the prism in a direction parallel to the incident ray
   (c) bends at both the surfaces of prism towards its base
   (d) bends at both the surfaces of prism opposite to its base.

Ans. (c) bends at both the surfaces of prism towards its base.

2. A ray of light suffers refraction through an equilateral prism. The deviation produced by the prism does not depend on the :
   (a) angle of incidence (b) colour of light
   (c) material of prism (d) size of prism.

Ans. (d) size of prism.

NUMERICALS

1. A ray of light incident at an angle of incidence 48° on a prism of refracting angle 60° suffers minimum deviation. Calculate the angle of minimum deviation.
   [**Hint :** $\delta_{min} = 2i - A$] **Ans.** 36°

2. What should be the angle of incidence for a ray of light which suffers minimum deviation of 36° through an equilateral prism ?
   [**Hint :** $A = 60°$, $i = (A + \delta_{min})/2$] **Ans.** 48°

(C) SIMPLE APPLICATIONS OF REFRACTION OF LIGHT

4.10 REAL AND APPARENT DEPTH

An object placed in a denser medium when viewed from a rarer medium, appears to be at a depth lesser than its real depth. This is because of refraction of light.

In Fig. 4.36, consider a point object O kept at the bottom of a transparent medium (such as water or glass) separated from air by the surface PQ. A ray of light OA, starting from the object O, is incident on the surface PQ normally, so it passes undeviated along the path AA′. Another ray OB, starting from the object O, strikes the boundary surface PQ at B and suffers refraction. Since the ray travels from a denser medium (water or glass) to a rarer medium (air), so it bends away from the normal N′BN drawn at the point of incidence B on the surface PQ and travels along BC in air.

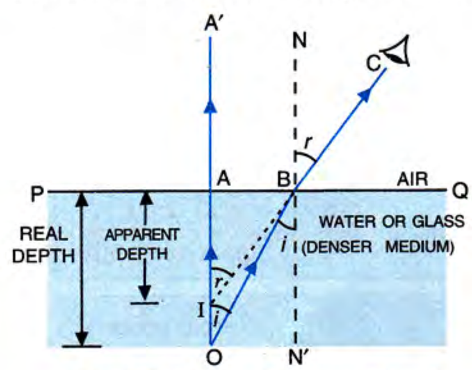

Fig. 4.36 Real and apparent depth

> ***Note :*** The point B is very close to the point A, and both the rays OA′ and BC enter the eye simultaneously. In Fig. 4.36, they have been shown separately for the sake of clarity of the ray diagram.

When viewed by the eye, the ray BC appears to be coming from a point I which is the *virtual image* of O, obtained on producing A′A and CB backward. Thus any object (*e.g.* a coin) placed at O, when seen from above (air), will appear to be at I which is at a lesser depth (= AI) than its actual depth (= AO).

In Fig. 4.36, for the incident ray OB, angle of incidence $i = \angle OBN'$ and angle of refraction $r = \angle CBN$. Since AO and BN′ are parallel and OB is a transversal line, so

$$\angle AOB = \angle OBN' = i$$

Similarly, IA′ and BN are parallel and IC is the transversal line, so

$$\angle BIA' = \angle CBN = r$$

Now in right-angled triangle BAO,

$$\sin i = \frac{BA}{OB}$$

and in right-angled triangle IAB,

$$\sin r = \frac{BA}{IB}$$

But from the definition of refractive index, the refractive index of air with respect to the medium

$${}_m\mu_a = \frac{\sin i}{\sin r} = \frac{BA/OB}{BA/IB} = \frac{IB}{OB}$$

∴ Refractive index of medium with respect to air

$${}_a\mu_m = \frac{1}{{}_m\mu_a} = \frac{OB}{IB}$$

Since the point B is very close to the point A, *i.e.*, the object is viewed from a point vertically above the object O, ∴ IB = IA and OB = OA.

Hence $$\boxed{{}_a\mu_m = \frac{OA}{IA} = \frac{\text{real depth}}{\text{apparent depth}}} \qquad ...(4.13)$$

or $$\boxed{\text{Apparent depth} = \frac{\text{real depth}}{{}_a\mu_m}} \qquad ....(4.14)$$

Thus,

Shift OI = real depth – apparent depth

or $$\boxed{\text{Shift} = \text{real depth} \times \left(1 - \frac{1}{{}_a\mu_m}\right)} \qquad ..(4.15)$$

The shift by which the object appears to be raised, depends on :

(1) *the refractive index of the medium,*

(2) *the thickness of the denser medium, and*

(3) *the colour* (or wavelength) *of incident light**.

(1) Dependence of shift on the refractive index : Higher the refraction index of the medium, more is the shift.

(2) Dependence of shift on the thickness of medium : Thicker the medium, more is the shift.

(3) Dependence on wavelength (or colour) of light : The shift decreases with the increase in the wavelength of light used. Since $\mu_V > \mu_R$, therefore the shift is more for the violet light than for the red light in a given medium.

Examples

(i) For glass, ${}_a\mu_g = \frac{3}{2}$, therefore the thickness of glass slab appears only two-third of its real thickness when it is viewed from air by keeping the eye vertical above the slab.

(ii) For water, ${}_a\mu_w = \frac{4}{3}$, therefore the depth of a water pond appears three-fourth of its real depth on seeing it from air in a nearly vertical direction (*i.e.*, it appears shallow). This is why a fish when seen from air appears to be nearer the surface of water than at its actual depth.

> ***Note :*** The apparent depth of an object lying in a denser medium is always less than its real depth when viewed from any direction in the rarer medium. But the above eqns. (4.13), (4.14) and (4.15) are valid only when the object is seen from vertically above.

* *The refractive index of a medium increases with the decrease in wavelength of incident light* ($\mu_V > \mu_R$).

4.11 APPARENT BENDING OF A STICK UNDER WATER

Fig. 4.37 shows a straight stick (or pencil) XOP placed obliquely in water. The portion OP of the stick (or pencil) under water when seen from air appears to be shortened and raised up as OP′. This is due to refraction of light from water to air. The rays of light coming from tip P of the stick (or pencil) when pass from water to air, bend away from the normal and appear to be coming from a point P′ which is the *virtual image* of the point P. The same is true for every point of the stick (or pencil) inside water from P to O.

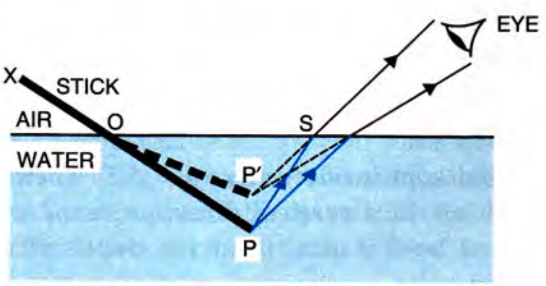

Fig. 4.37 Bending of stick due to refraction

Thus, the part PO of the stick (or pencil) appears to be P′O, *i.e., the immersed part of the stick appears to be raised and therefore bent at the point* O *on the surface of water and the stick (or pencil)* XOP *appears as* XOP′.

> ***Note :*** *An object placed in a rarer medium when viewed from a denser medium appears to be at a greater distance than its real distance. In Fig. 4.38, an object* O *placed in air when viewed from water appears to be at* I *which is higher than the object* O.

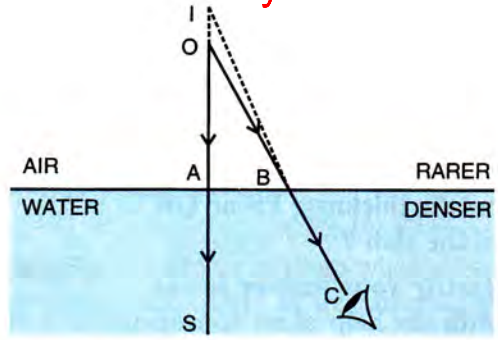

Fig. 4.38 An object in rarer medium viewed from a denser medium

4.12 SOME CONSEQUENCES OF THE REFRACTION OF LIGHT

In our daily life we come across many phenomena which are caused by the refraction of light. Some of these are given below :

(i) *A star appears twinkling in the sky due to change in refractive index of air with temperature.*

(ii) *The sun is seen a few minutes before it rises above the horizon in the morning while in the evening few minutes longer after it sets.*

(iii) *A coin kept in a vessel and not visible when seen from just below the edge of the vessel, can be viewed from the same position when water is poured into the vessel.*

(iv) *A print appears to be raised when a glass slab is placed over it.*

(v) *A piece of paper stuck at the bottom of a glass slab appears to be raised when seen from above.*

(vi) *A tank appears shallow than its actual depth.*

(vii) *A person's legs appear to be short when standing in a tank.*

EXAMPLES

1. As seen from above, the apparent depth of a liquid in a vessel is 15 cm, when its real depth is 20 cm. Find the refractive index of the liquid.

Given, real depth = 20 cm, apparent depth = 15 cm.

$$\text{Refractive index of the liquid} = \frac{\text{real depth}}{\text{apparent depth}} = \frac{20}{15} = \mathbf{1 \cdot 33}$$

2. A point source of light O of single colour is seen through a rectangular glass slab PQRS. The paths of two rays, in and outside the slab, are shown in Fig. 4.39.

(i) In the diagram, label the position I of the source O where it will appear when seen through the surface RS.

(ii) **Does the source O appear to be nearer or farther with respect to the surface PQ ?**

(iii) **How does the shift depend on the thickness PS or QR of the slab ?**

(iv) **Justify your answer in (ii) with the help of an appropriate ray diagram.**

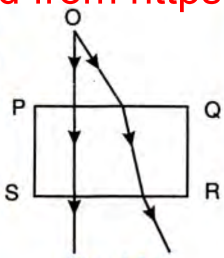

Fig. 4.39

(v) **For the same rectangular glass slab, which colour from the visible spectra (violet to red) will produce the maximum shift ?**

(i) In Fig. 4.40, I is the position of source O when seen through the surface RS.

(ii) The source O appears to be at I, **nearer** with respect to the surface PQ when viewed through the surface RS.

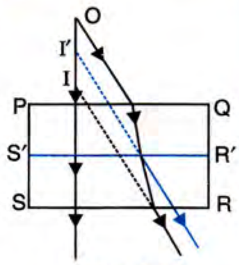

Fig. 4.40

(iii) The shift OI **decreases with the decrease in thickness** PS or QR of the slab.

(iv) The ray diagram is shown in Fig. 4.40 in which for the thickness PS, the image is at I, while for the thickness PS′ (< PS), another emergent ray (parallel to the given previous emergent ray) is drawn and the image is at I′. Now the shift is OI′ which is less than the shift OI for the thickness PS of the slab.

(v) The same rectangular glass slab will produce **maximum shift for the violet light** incident on it for which the refractive index of glass is most.

3. **A glass slab is placed over a piece of paper on which VIBGYOR is printed with each letter into its corresponding colours.**

(i) **Will the image of all the letters be in the same place ?**

(ii) **The letter of which colour will appear to be raised (a) maximum, and (b) minimum ? Explain your answer.**

(i) **No**. The image of all the letters will **not** be in the same place.

(ii) (a) The letter of **violet** colour (*i.e.*, V) appears to be raised maximum. (b) The letter of **red** colour (*i.e.*, R) appears to be raised minimum.

Reason : Apparent depth = $\frac{\text{real depth}}{\text{refractive index}}$ and refractive index of glass is most for the violet light while least for the red light, therefore the apparent depth is least for the violet letter and most for the red letter.

43. **A coin kept inside water (μ = 4/3) when viewed from air in a vertical direction, appears to be raised by 2·0 mm. Find the depth of coin in water.**

Given : $\mu = \frac{4}{3}$, shift = 2·0 mm

Let real depth be x mm. Then

Apparent depth $= \frac{x}{\mu} = \frac{x}{4/3} = \frac{3}{4}x$

Shift = real depth − apparent depth

$= x - \frac{3}{4}x = \frac{1}{4}x$

i.e., $\frac{1}{4}x = 2{\cdot}0$ mm $\therefore\ x = 8{\cdot}0$ mm

Thus depth of coin is water = **8·0 mm**

EXERCISE–4(C)

1. How is the refractive index of a medium related to the real and apparent depths of an object in that medium ?

2. Prove that

Refractive index $= \frac{\text{real depth}}{\text{apparent depth}}$.

3. A tank of water is viewed normally from above.

(a) State how does the depth of tank appear to change.

(b) Draw a labelled ray diagram to explain your answer.

4. Water in a pond appears to be only three-quarter of its actual depth. (a) What property of light is responsible for this observation ? Illustrate your answer with the help of a ray diagram. (b) How is the refractive index of water calculated from its real and apparent depths ?

5. Draw a ray diagram to show the appearance of a stick partially immersed in water. Explain your answer.

6. A fish is looking at a 1·0 m high plant at the edge of a pond. Will the plant appear to the fish shorter

or taller than its actual height ? Draw a ray diagram to support your answer. **Ans.** Taller

7. A student puts his pencil into an empty trough and observes the pencil from the position as indicated in Fig. 4.41.

Fig. 4.41

(i) What change will be observed in the appearance of the pencil when water is poured into the trough ?

(ii) Name the phenomenon which accounts for the above stated observation.

(iii) Complete the diagram showing how the student's eye sees the pencil through water.

8. An object placed in one medium when seen from the other medium, appears to be vertically shifted. Name *two* factors on which the magnitude of shift depends and state how does it depend on them.

MULTIPLE CHOICE TYPE

1. A small air bubble in a glass block when seen from above appears to be raised because of :

(a) refraction of light

(b) reflection of light

(c) reflection and refraction of light

(d) none of the above.

Ans. (a) refraction of light

2. An object in a denser medium when viewed from a rarer medium appears to be raised. The shift is maximum for :

(a) red light (b) violet light

(c) yellow light (d) green light.

Ans. (b) violet light

NUMERICALS

1. A water pond appears to be 2·7 m deep. If the refractive index of water is 4/3, find the actual depth of the pond. **Ans.** 3·6 m

2. A coin is placed at the bottom of a beaker containing water (refractive index = 4/3) to a depth of 12 cm. By what height the coin appears to be raised when seen from vertically above ? **Ans.** 3 cm

3. A postage stamp kept below a rectangular glass slab of refractive index 1·5 when viewed from vertically above it, appears to be raised by 7·0 mm. Calculate the thickness of the glass slab. **Ans.** 2·1 cm

(D) CRITICAL ANGLE AND TOTAL INTERNAL REFLECTION

4.13 TRANSMISSION OF LIGHT FROM A DENSER MEDIUM (GLASS OR WATER) TO A RARER MEDIUM (AIR) AT DIFFERENT ANGLES OF INCIDENCE

Consider the refraction of light from a denser medium to a rarer medium. When a light ray travelling in a denser medium falls on the surface separating it from a rarer medium, it is partly reflected back into the denser medium and partly refracted in the rarer medium. The refracted ray bends away from the normal on the surface at the point of incidence obeying the laws of refraction. Now we shall consider this process of reflection and refraction at different angles of incidence.

Case (i) when the angle of incidence is small ($i < C$) : In Fig 4.42, a light ray AO travelling in glass is incident at the glass-air interface at a small angle of incidence *i*. It is partly reflected and partly refracted. We get a weak reflected ray OC and a strong refracted ray OB. Since the incident ray bends away from the normal when it suffers refraction from glass to

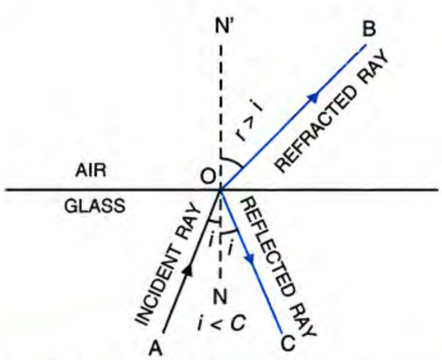

Fig. 4.42 Refraction from glass to air when $i < C$

air, therefore the angle of refraction r is greater than the angle of incidence i.

Now if the angle of incidence i is gradually increased, the angle of refraction r also increases, but the intensity of refracted ray keeps on decreasing. Finally the angle of refraction r reaches its maximum value equal to 90° at a certain angle of incidence $i = C$. Here C is called the *critical angle**.

Case (ii) when the angle of incidence is equal to the critical angle ($i = C$) : At angle of incidence equal to the critical angle ($i = C$), the angle of refraction becomes 90° as shown in Fig. 4.43. The refracted ray is along the glass-air interface and is very weak.

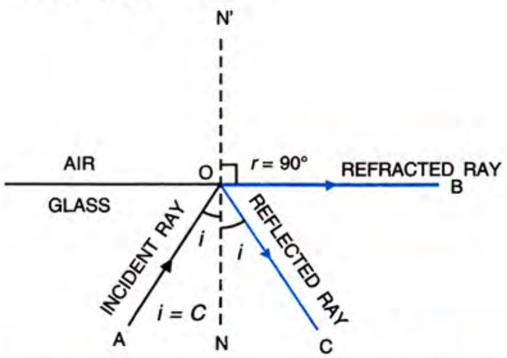

Fig. 4.43 Refraction from glass to air when i = C

In Fig. 4.43, for the incident ray AO at $i = C$, the refracted ray is OB and the reflected ray is OC.

Case (iii) when the angle of incidence is greater than the critical angle ($i > C$) : Fig. 4.44 shows that for the incident ray AO at an angle of incidence i greater than the critical angle C, *no refracted ray is obtained* and the incident ray is totally reflected as OC.

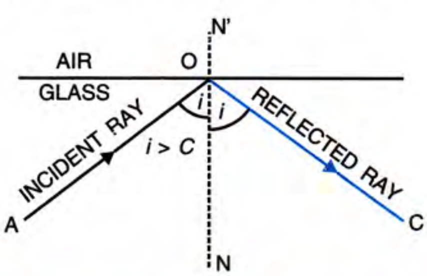

Fig. 4.43 Total reflection when i > C (no refraction)

* *Symbol i_c is also used to denote the critical angle.*

4.14 CRITICAL ANGLE

We have read that when a ray of light passes from a denser medium to a rarer medium, at a certain angle of incidence $i = C$, the angle of refraction becomes 90°, *i.e.*, at $i = C$, $r = 90°$. The angle C is called the *critical angle*. Thus,

Critical angle is the angle of incidence in the denser medium corresponding to which the angle of refraction in the rarer medium is 90°.

4.15 RELATIONSHIP BETWEEN THE CRITICAL ANGLE AND THE REFRACTIVE INDEX ($\mu = 1/\sin C$)

In Fig. 4.43, AO is an incident ray from glass to air at an angle of incidence $i = C$ (critical angle) for which the angle of refraction r is 90°. Therefore, the refractive index of air with respect to glass is

$$ {}_g\mu_a = \frac{\sin C}{\sin 90°} $$

But $\sin 90° = 1 \quad \therefore \quad {}_g\mu_a = \sin C$

But refractive index of glass with respect to air is

$$ {}_a\mu_g = \frac{1}{{}_g\mu_a} $$

$$ \therefore \quad \boxed{{}_a\mu_g = \frac{1}{\sin C} = \text{cosec } C} \qquad ...(4.16) $$

Thus, knowing the refractive index of the denser medium with respect to the rarer medium, we can calculate the critical angle C for that pair of media.

Examples :

(1) For glass, refractive index ${}_a\mu_g = \frac{3}{2}$

$\therefore \quad \sin C = \frac{1}{{}_a\mu_g} = \frac{2}{3}$

But $\sin 42° = \frac{2}{3}$, $\therefore \quad C = 42°$

(2) For water, refractive index ${}_a\mu_w = \frac{4}{3}$

$\therefore \quad \sin C = \frac{1}{{}_a\mu_w} = \frac{3}{4}$

But $\sin 49° = \frac{3}{4}$, $\therefore \quad C = 49°$

The table below gives the critical angle for some substances with respect to air.

Critical angle for some substances with respect to air

Substance	μ	*Critical angle C*
Water	1·33	48° 45' ≈ 49°
Turpentine	1.47	42° 54' ≈ 43°
Glass	1·5	41° 48' ≈ 42°
Flint glass	1·57	39° 28' ≈ 39°
Diamond	2·41	24° 30' ≈ 25°

Factors affecting the critical angle

The critical angle for a given pair of media depends on their refractive indices. But the refractive index of a medium is affected by the following *two* factors :

(1) the colour (or wavelength) of light, and

(2) the temperature.

Therefore the critical angle depends on the above *two* factors.

(1) Dependence on the colour of light : The refractive index of a transparent medium decreases with the increase of wavelength of light (it is most for the violet light and least for the red light), therefore the critical angle for a pair of media is least for the violet light and most for the red light *i.e. the critical angle increases with the increase in wavelength of light.*

(2) Dependence on temperature : On increasing the temperature of medium, its refractive index decreases, so the critical angle for that pair of media increases. Thus *critical angle increases with an increase in temperature.*

4.16 TOTAL INTERNAL REFLECTION

When light travels from a *rarer* to a *denser* medium, at all angles of incidence a part of it is reflected and the rest of it is refracted at the boundary surface. Thus both the reflection and refraction occur simultaneously. On the other hand, *when light travels from a denser to a rarer medium, under certain condition (when the angle of incidence is greater than the critical angle), no part of light is refracted, but the entire light is reflected back in the same medium.* In Fig. 4.45, the light ray AO *gets entirely reflected* as OC obeying the laws of reflection and it does not suffer refraction. This phenomenon is called *total internal reflection.*

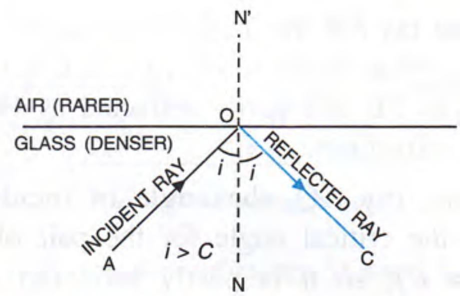

Fig. 4.45 Total internal reflection when $i > C$

Thus,

When a ray of light travelling in a denser medium, is incident at the surface of a rarer medium at the angle of incidence greater than the critical angle for the pair of media, the ray is totally reflected back into the denser medium. This phenomenon is called total internal reflection.

Essential conditions for the total internal reflection

There are following *two* necessary conditions for the total internal reflection :

(1) *The light must travel from a **denser** to a **rarer** medium.*

(2) *The angle of incidence must be **greater than** the critical angle for the pair of media.*

Note : In the process of total internal reflection, 100% energy (or intensity) is reflected back. No other device such as plane mirror, etc. produces 100% reflection (due to absorption and refraction of some part of light). Due to this property, the phenomenon of total internal reflection is used in the construction of periscope, binocular and certain types of camera in which a total reflecting prism replaces a plane mirror for the reflection of light.

Refraction and total internal reflection of light rays at different angles of incidence

Fig 4.46 shows the refraction of light rays from a point source A kept in a denser medium to a rarer medium at different increasing angles of incidence.

For the ray AO, the angle of incidence is zero, it is refracted as OA'.

For the ray AP, the angle of incidence i is less than the critical angle C (*i.e.*, $i < C$), it is partly reflected as PB and partly refracted as PC at an angle of refraction $r > i$.

For the ray AQ, the angle of incidence is equal to the critical angle for the pair of media (*i.e.*, $i = C$), so it is partly reflected as QB′ and partly refracted as QC′ at the angle of refraction r equal to 90°.

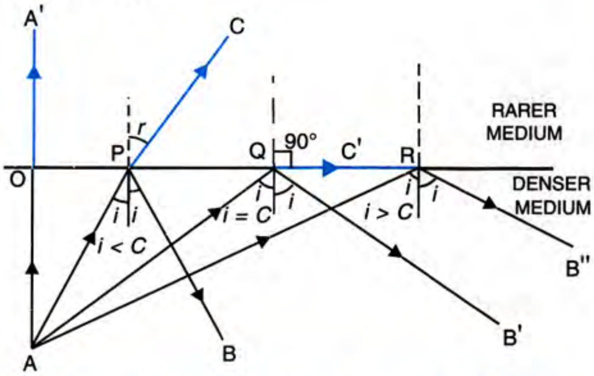

Fig 4.46 Refraction and total internal reflection

For the ray AR, the angle of incidence is greater than the critical angle (*i.e.*, $i > C$), so it is totally reflected as RB″ at an angle of reflection $r = i$, and *no refraction occurs*.

> ***Note :*** The above phenomenon of refraction and total internal reflection can easily be demonstrated with the help of a laser pen source. The main precaution is taken that the laser source is not seen directly as it may damage the eyes.

4.17 TOTAL INTERNAL REFLECTION IN A PRISM

Now we shall consider total internal reflection in *three* different prisms : (1) 45°, 90°, 45° prism (*i.e.*, right angled isosceles prism or total reflecting prism), (2) prism of each angle 60° (*i.e.*, equilateral prism), and (3) 30°, 90°, 60° prism (*i.e.*, a right-angled prism).

(1) Total internal reflection through a 45°, 90°, 45° prism (or right-angled isosceles prism)

Total reflecting prism : *A prism having an angle of 90° between its two refracting surfaces and the other two angles each equal to 45°, is called a total reflecting prism* because *the light incident normally on any of its faces, suffers total internal reflection inside the prism.* Due to this behaviour, a total reflecting prism is used for the following *three* purposes :

(a) *to deviate a ray of light through 90°,*
(b) *to deviate a ray of light through 180°,* and
(c) *to erect the inverted image without producing deviation in its path.*

(a) To deviate a ray of light through 90°

In Fig. 4.47, ABC is a total reflecting prism. A beam of light is incident *normally* at the face AB. It passes undeviated into the prism and strikes at the face AC at an angle of incidence equal to 45°. For glass-air interface, the critical angle is about 42°, therefore the beam of light *suffers total internal reflection* at face AC because the angle of incidence is greater than the critical angle. The reflected beam inside the prism then strikes the face BC, where it is incident normally and therefore passes undeviated. As a result, the incident beam gets deviated through 90° emerging out through the prism. Fig. 4.47 shows the path of two rays PQ and P′Q′ through the prism and then out of it.

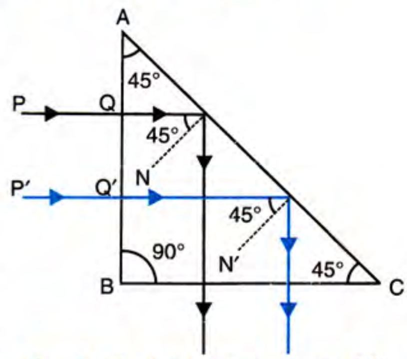

Fig. 4.47 Deviation through 90°

> ***Note :*** By the principle of reversibility of path of light, if light is incident *normally* on the face BC of the prism, it will emerge out from the face AB after suffering total internal reflection at the face AC.

Use : This action of prism is used in a *periscope* where a total reflecting prism is preferred over a plane mirror.

(b) To deviate a ray of light through 180°

In Fig. 4.48, the beam of light from the object PQ falls *normally* on the face AC (*i.e.*, hypotenuse) of the prism, so it enters undeviated inside the prism and strikes the glass-air interface AB of the prism. Since the beam of light is travelling from glass to air at an angle of incidence equal to 45° which is greater than the critical angle (= 42° for glass-air), therefore the beam of light *suffers total internal reflection*. The reflected beam inside the prism strikes the face BC at an angle of incidence equal to 45°, so it again suffers *total internal reflection*. The beam of light inside the prism now falls normally on the face AC and therefore passes undeviated out of the prism, forming the image P′Q′ of the object PQ. The beam thus gets deviated by 90° at each reflection and the total deviation due to two reflections becomes 180°.

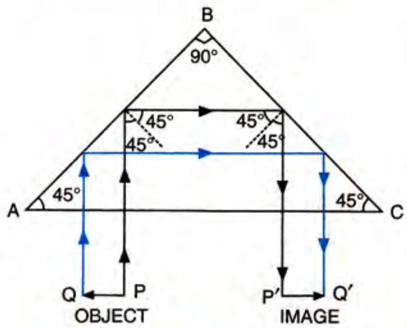

Fig. 4.48 Deviation through 180°

Use : This action of prism is used in a *binocular* and *camera to invert the image without the loss of intensity*.

(c) To erect the inverted image without deviation

In Fig 4.49, the beam of light from the object PQ is incident *parallel* to the face AC (*i.e.*, hypotenuse) of the prism and strikes the face AB of the prism. It suffers refraction from air to glass and strikes the face AC of the prism travelling from glass to air at an angle of incidence greater than the critical angle (= 42°), therefore it suffers *total internal reflection*. The beam inside the prism now strikes the face BC at an angle of incidence less than the critical angle hence it suffers refraction from glass to air and bends away from the normal. *The beam emerges parallel to the face* AC. As a result of refraction, on emergence the rays are inverted and for the inverted object PQ, the erect image P′Q′ is obtained. A prism when used in this manner is called the *erecting prism*.

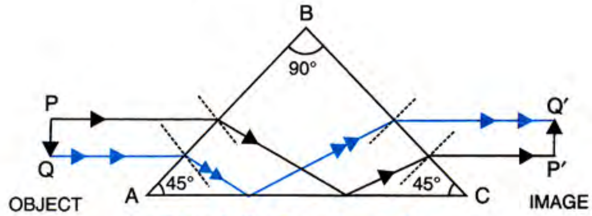

Fig. 4.49 Erecting prism

Use : This action of prism is used in *a slide projector*.

(2) Total internal reflection through a prism where each angle is 60° (*i.e.*, equilateral prism)

A prism of each angle 60° can be used to deviate a light ray through 60° by total internal reflection. Fig. 4.50 shows a prism ABC of each angle 60°. A light ray PQ incident *normally* on the face AB of the prism passes undeviated as QR into the prism and it strikes the face AC at an angle of incidence 60° at the point R. Now the light ray QR suffers total internal reflection at the glass-air interface, since the angle of incidence (= 60°) is greater than the critical angle which is 42°, such that ∠QRS is 120°. The ray RS obtained after total internal reflection falls

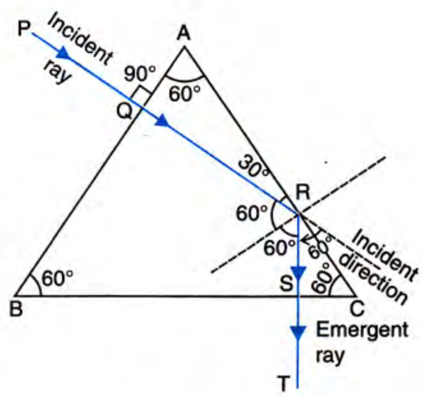

Fig. 4.50 Deviation through 60° by an equilateral prism

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normally on the face BC of the prism and so it passes out undeviated through the face BC. Thus ST is the emergent ray. From Fig. 4.50, it is clear that the incident ray PQ has turned through an angle of 60° towards the base from its initial direction and it emerges out as ST.

(3) Total internal reflection and refraction of light through a 30°, 90°, 60° prism (or right angled prism)

A 30°, 90°, 60° prism can be used to deviate a light ray through an angle less than 60° by total internal reflection. Fig. 4.51 shows a prism ABC of angles 30°, 90° and 60°. A light ray PQ incident *normally* on the face BC of the prism (opposite to the 30° refracting angle) passes undeviated as QR into the prism and it strikes the face AC at an angle of incidence 60° at the point R. Now the light ray QR suffers *total internal reflection* at the glass-air interface since the angle of incidence (= 60°) is greater than the critical angle which is 42°. The ray RS obtained after total internal reflection is incident at the face AB of the prism at an angle of 30°. This angle of incidence at glass-air interface is less than the critical angle, so the ray RS is refracted from glass to air as ST with an angle of refraction greater than 30°. Thus the emergent ray ST has turned through an angle δ (which is less than 60°) from the direction of incident ray PQ.

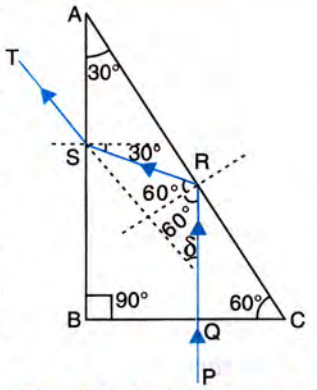

Fig. 4.51 Deviation through less than 60° by a 30°, 90°, 60° prism

Non occurance of total internal reflection through a 30°, 90°, 60° prism : *If a light ray* PQ *is incident normally on the face* AB *or a part of face* AC *of the prism* ABC, *it does not suffer total internal reflection inside the prism and gets refracted as* RS *obeying the laws of refraction as shown in Fig. 4.52 (a) and (b).* In each case, the angle of incidence at the other face inside the prism is 30° which is less than the critical angle (*i.e.*, 42°).

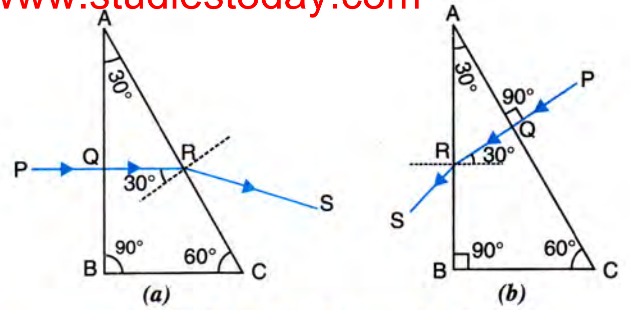

Fig. 4.52 No total internal reflection through a 30°, 90°, 60° prism

Exception : *A ray of light incident normally on hypotenuse of prism below the foot of perpendicular on it from its opposite corner, suffers total internal reflection and gets deviated by an angle greater than 60°.* In Fig. 4.53, a light ray PQ is incident *normally* on the face AC (hypotenuse) of the prism in the portion DC such that the point D is the foot of perpendicular from B on AC. It passes undeviated as QR inside the prism and strikes the face BC of the prism at an angle of incidence 60° which is greater than the critical angle (= 42°). The ray suffers *total internal reflection* inside the prism as RS. The reflected ray RS then strikes the face AB at an angle of incidence 30°, so it suffers refraction from glass to air and emerges out of the prism as ST, bending away from the normal at the face AB. Thus the incident ray PQ gets deviated through an angle greater than 60°.

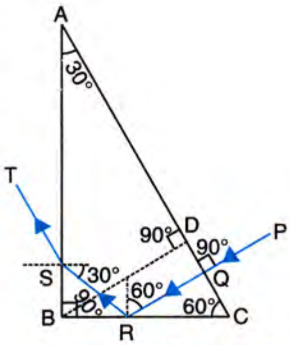

Fig. 4.53 Total internal reflection through a 30°, 90°, 60° prism

4.18 USE OF A TOTAL INTERNAL REFLECTING PRISM IN PLACE OF A PLANE MIRROR

A total reflecting prism is used in place of a plane mirror to deviate the light ray by 90° in a periscope and by 180° in a binocular as well as in a camera. The reason is that due to total internal reflection in the prism, the entire incident light (100%) is reflected back into the denser medium, whereas in ordinary reflection from a plane mirror, some light is refracted and absorbed, so the reflection is not 100%. Thus the image obtained by the use of a total reflecting prism, is much brighter than that obtained by using a plane mirror. Further the brightness of image formed by a total reflecting prism always remains unchanged, while due to deterioration of silvering of the plane mirror after a long use, the image formed by it becomes faint.

Distinction between the total internal reflection and reflection from a plane mirror

Total internal reflection	Reflection from a plane mirror
1. It takes place only when light passes from a denser medium to a rarer medium at an angle of incidence greater than the critical angle for that pair of media.	1. It takes place when light is incident on a plane mirror from any medium at any angle of incidence.
2. The entire light is reflected.	2. Only a part of light is reflected while rest is refracted and absorbed.
3. There is no loss of energy. The energy of reflected ray is same as that of the incident ray.	3. There is a loss of energy. The energy of reflected ray is always less than that of the incident ray.
4. The image is much brighter. and the brightness remains unchanged even after the long use of the total reflecting device.	4. The image is less bright and the brightness gradually decreases as the silvering on mirror becomes old and rough.

4.19 SOME CONSEQUENCES OF TOTAL INTERNAL REFLECTION

In our daily life, we observe many consequences of total internal reflection. Some of these are given below :

(1) On a hot sunny day, a driver may see a pool of water (or wet road) in front of him at some distance. It is the phenomenon of *mirage* which is often observed in desert.

(2) An empty test tube placed in water in a beaker with mouth outside the water surface, shines like a mirror when seen at certain angles.

(3) A crack in a glass vessel often shines like a mirror.

(4) A piece of diamond sparkles when viewed from certain directions.

(5) An optical fibre is used to transmit a light signal over a long distance without the loss of energy. However, some energy gets lost due to absorption of light in its material.

EXAMPLES

1. Fig. 4.54 shows the section of a semi-circular glass slab having its centre at O. Three rays of light A, B and C of the same colour are incident on the slab and strike on the edge XY at the point O. The light ray B suffers refraction along OB′.

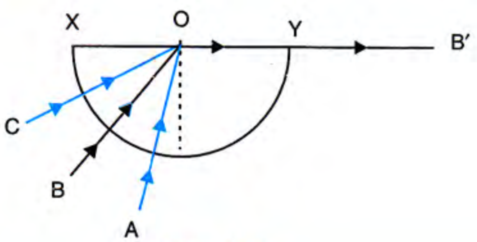

Fig. 4.54

(a) On the diagram, mark the critical angle by *C*.

(b) The rays enter the slab undeviated. Give reason.

(c) Draw the path of rays A and C after they strike the edge XY.

(d) Name the phenomenon which the rays A and C exhibit.

(a) In Fig. 4.55, the critical angle has been marked as *C* which is the angle of incidence for the ray B.

(b) Each of the ray A, B and C is incident normally on the slab along its radius, so it enters the slab undeviated.

(c) Fig. 4.55 shows the path of the rays A and C after they strike the edge XY as OA′ and OC′ respectively.

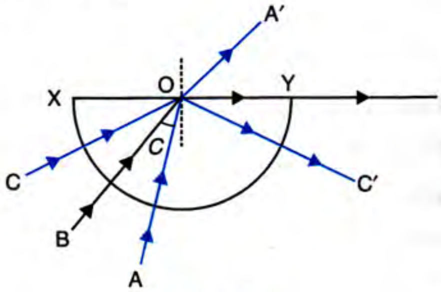

Fig. 4.55

(d) The ray A suffers refraction from glass to air while the ray C suffers total internal reflection.

> *Note :* The partially reflected ray for A and B has not been shown in Fig. 4.55.

2. Show with the aid of a ray diagram, how a right angled isosceles prism can be used to invert the rays. (a) How should the rays fall on the prism ? (b) Which phenomenon is responsible for this action of prism ? (c) What is the nature of the image in relation to the object ?

The use of a right-angled isosceles prism to invert the rays is shown in Fig. 4.56.

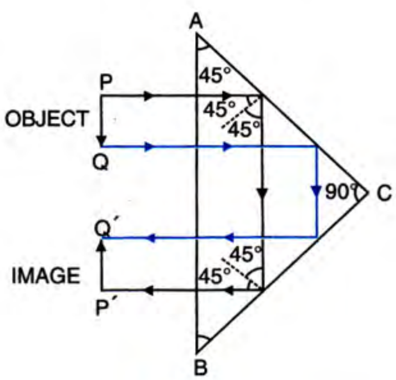

Fig. 4.56

(a) The light rays must fall normally on the hypotenuse of the prism.

(b) It is based on the phenomenon of total internal reflection.

(c) In Fig. 4.56, for the inverted object PQ, the image P'Q' is upright.

3. (a) Fig. 4.57 shows two isosceles right angled prisms A and B and the light rays incident on the prism A. Complete the diagram to show the rays emerging out of the prism B.

(b) State the principle used for completing the ray diagram in part (a) above.

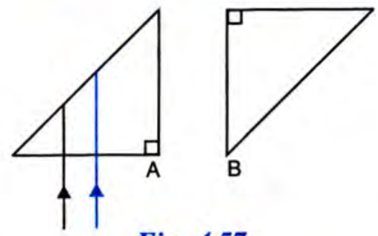

Fig. 4.57

(a) The completed ray diagram is given below in Fig. 4.58.

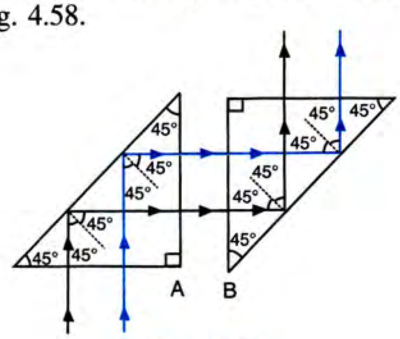

Fig. 4.58

(b) The following *two* principles have been used :

(i) The ray of light falling normally on the glass-air surface or air-glass surface, passes undeviated through it (*i.e.*, $i = 0°$, $r = 0°$).

(ii) The ray of light travelling from glass, when strikes the glass-air surface at an angle of incidence equal to 45° which is greater than the critical angle (= 42° for glass-air), suffers total internal reflection.

4. The critical angle for material of which the equiangular prism ABC shown in Fig. 4.59 is made, is 60°. A ray of light incident on the side AB of the prism is refracted along DE such that the angle it makes with the side AC is 150° and ∠EDB = 90°. Draw the path of the incident ray on the side AB (which travels along DE) and also the path which the ray DE travels from the point E onwards.

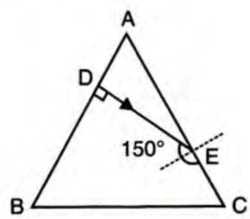

Fig. 4.59

The completed diagram is shown in Fig. 4.60. Since the refracted ray DE is normal to the surface AB of the prism (*i.e.* $\angle r = 0°$), so the incident ray at the point D should also be normal to the surface AB so that $\angle i = 0°$. At the point E, the angle of incidence for the ray DE is 150° – 90° = 60° which is equal to the critical angle, so the ray DE is refracted at 90°, *i.e.,* it is refracted along EC.

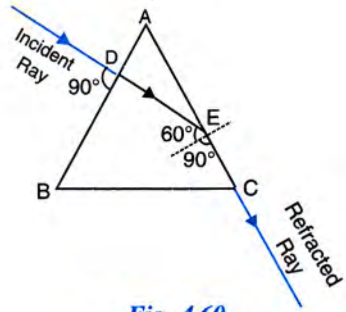

Fig. 4.60

> ***Note :*** Partial reflection of the ray DE has not been shown.

EXERCISE–4(D)

1. Explain the term critical angle with the aid of a labelled diagram.

2. How is the critical angle related to the refractive index of a medium ?

3. State the approximate value of the critical angle for (a) glass-air surface (b) water-air surface.
Ans. (a) 42° (b) 49°

4. What is meant by the statement 'the critical angle for diamond is 24°' ?

5. A light ray is incident from a denser medium on the boundary separating it from a rarer medium at an angle of incidence equal to the critical angle. What is the angle of refraction for the ray ?
Ans. 90°

6. Name *two* factors which affect the critical angle for a given pair of media. State how do the factors affect it.

7. The critical angle for glass-air is 45° for the light of yellow colour. State whether it will be less than, equal to, or more than 45° for (i) red light, and (ii) blue light ?
Ans. (i) more than 45° (ii) less than 45°

8. (a) What is total internal reflection ?
(b) State *two* conditions necessary for the total internal reflection to occur.
(c) Draw diagrams to illustrate the total internal reflection.

9. Fill in the blanks to complete the following sentences :
(a) Total internal reflection occurs only when a ray of light passes from a .... medium to a .... medium.
(b) Critical angle is the angle of .... in denser medium for which the angle of .... in rarer medium is ....
Ans. (a) denser, rarer, (b) incidence, refraction, 90°

10. State whether the following statement is true or false ? If the angle of incidence is greater than the critical angle, light is not refracted at all, when it falls on the surface from a denser medium to a rarer medium.
Ans. True

11. The refractive index of air with respect to glass is expressed as ${}_g\mu_a = \frac{\sin i}{\sin r}$.
(a) Write down a similar expression for ${}_a\mu_g$ in terms of the angles i and r.
(b) If angle r = 90°, what is the corresponding angle i called ?
(c) What is the physical significance of the angle i in part (b) ?
Ans. (a) ${}_a\mu_g = \frac{\sin r}{\sin i}$, (b) critical angle,
(c) If angle of incidence exceeds the value of i obtained in part (b), total internal reflection occurs.

12. Fig. 4.61 shows a point source P inside a water container. *Three* rays A, B and C starting from the source P are shown up to the water surface. (a) Show in the diagram the path of these rays after striking the water surface. The critical angle for

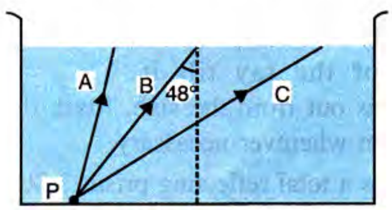

Fig. 4.61

water-air surface is 48°. (b) Name the phenomenon which the rays A, B and C exhibit.

13. In Fig. 4.62, PQ and PR are the *two* light rays emerging from an object P. The ray PQ is refracted as QS.

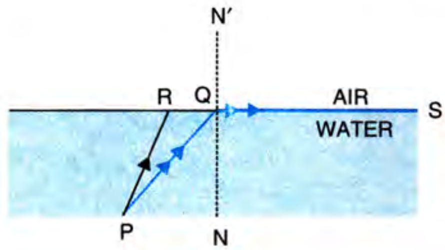

Fig. 4.62

(a) State the special name given to the angle of incidence ∠PQN of the ray PQ.

(b) What is the angle of refraction for the refracted ray QS ?

(c) Name the phenomenon that occurs if the angle of incidence ∠PQN is increased.

(d) The ray PR suffers partial reflection and refraction on the water-air surface. Give reason.

(e) Draw in the diagram the refracted ray for the incident ray PR and hence show the position of image of the object P by the letter P′ when seen vertically from above.

Ans. (a) Critical angle (b) 90° (c) Total internal reflection (d) For the ray PR, angle of incidence is less than ∠PQN (*i.e.*, the critical angle).

14. The refractive index of glass is 1·5. From a point P inside a glass slab, draw rays PA, PB and PC incident on the glass-air surface at an angle of incidence 30°, 42° and 60° respectively.

(a) In the diagram show the approximate direction of these rays as they emerge out of the slab.

(b) What is the angle of refraction for the ray PB ? (Take $\sin 42° = \frac{2}{3}$) **Ans.** (b) 90°

15. A ray of light enters a glass slab ABDC as shown in Fig. 4.63 and strikes at the centre O of the circular part AC of the slab. The critical angle of glass is 42°. Complete the path of the ray till it emerges out from the slab. Mark the angles in the diagram wherever necessary.

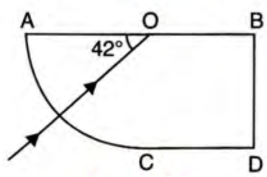

Fig. 4.63

16. What is a total reflecting prism ? State *three* actions that it can produce. Draw a diagram to show *one* such action of the total reflecting prism.

17. Show with the help of a diagram how a total reflecting prism can be used to turn a ray of light through 90°. Name *one* instrument in which such a prism is used.

18. A ray of light OP passes through a right angled prism as shown in the adjacent diagram (Fig. 4.64).

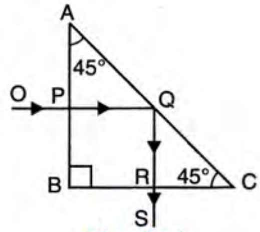

Fig. 4.64

(a) State the angles of incidence at the faces AC and BC.

(b) Name the phenomenon which the ray suffers at the face AC.

Ans. (a) Angle of incidence at the face AC = 45° and angle of incidence at the face BC = 0°

(b) The ray suffers total internal reflection at the face AC.

19. In Fig. 4.65, a ray of light PQ is incident normally on the hypotenuse of an isoceles right angled prism ABC. (a) Complete the path of the ray PQ till it emerges from the prism. Mark in the diagram the angle wherever necessary. (b) What is the angle of deviation of the ray PQ ? (c) Name a device in which this action is used. **Ans.** (b) 180°, (c) Binocular

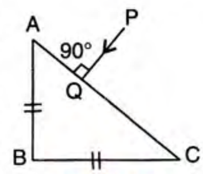

Fig. 4.65

20. In Fig. 4.66, a ray of light PQ is incident normally on the face AB of an equilateral glass prism. Complete the ray diagram showing its emergence into air after passing through the prism. Take critical angle for glass = 42°.

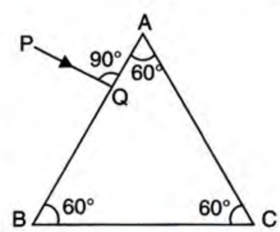

Fig. 4.66

(a) Write the angles of incidence at the faces AB and AC of the prism.

(b) Name the phenomenon which the ray of light suffers at the face AB, AC and BC of the prism.

Ans. (a) At the face AB, i = 0° and at the face AC, i = 60°

(b) At the face AB – refraction,

at the face AC – total internal reflection,

at the face BC – refraction.

21. Draw a neat labelled ray diagram to show the total internal reflection of a ray of light normally incident on one face of a 30°, 90°, 60° prism.

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22. Two isosceles right-angled glass prisms P and Q are placed near each other as shown in Fig. 4.67. Complete the path of the light ray entering the prism P till it emerges out of the prism Q.

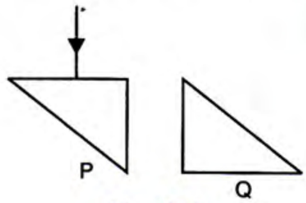

Fig. 4.67

23. What device other than a plane mirror can be used to turn a ray of light through 180° ? Draw a diagram in support of your answer. Name an instrument in which this device is used.

24. Mention *one* difference between the reflection of light from a plane mirror and total internal reflection of light from a prism.

25. State *one* advantage of using a total reflecting prism as a reflector in place of a plane mirror.

MULTIPLE CHOICE TYPE

1. The critical angle for glass-air interface is :

(a) 24° (b) 48° (c) 42° (d) 45°.

Ans. (c) 42°

2. A total reflecting right angled isosceles prism can be used to deviate a ray of light through :

(a) 30° (b) 60° (c) 75° (d) 90°.

Ans. (d) 90°

3. A total reflecting equilateral prism can be used to deviate a ray of light through :

(a) 30° (b) 60° (c) 75° (d) 90°.

Ans. (d) 60°