Chapter: Refraction at plane surface

$$v_{air/vaccum} = 3.0 \times 10^8 m/s$$
$$v_{water} = 2.24 \times 10^8 m/s$$
$$v_{glass} = 2.0 \times 10^8 m/s$$

Medium or Optical Medium:-

A material through which light can pass is called an optical medium or medium.

e.g. air, water, glass etc. are optical media.

Types of Medium:

1) Rarer Medium:

A medium in which speed of light is more than another is called rarer medium.

e.g. (a) In air & water

Here, air = rarer & Water = denser

b) In Water & glass:

Here Water = rarer & glass = denser

c) In air, glass: Here air = rarer & glass = Denser

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2) Denser Medium:

A medium in which speed of light is less than other is called Denser Medium.

e.g. In air & water

Here air = rarer and Water= Denser

NOTE: The same material may be rarer and denser with respect to the different materials. e.g. water is rarer w.r.t. glass but it is denser w.r.t. air. Thus, we can say **Rarer and Denser media are relative term.**

Refraction of light:

The bending of light when it passes from one medium to another is called refraction of light. Due to the change of medium, **speed and wavelength** of light are changed but its **frequency** remains constant.

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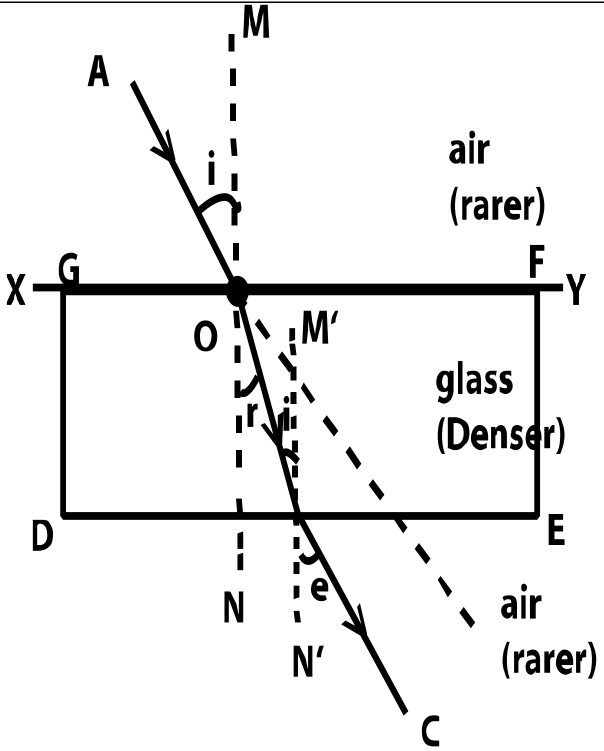
Here, DEFG = rectangular glass slab XY = media separator AD = Incident ray OB = refracted ray BC = emergent ray $\angle AOM$ $=$ angle of Incidence $\angle NOB$ $=$ angle of refraction $\angle N'BC$ $=$ angle of emergence MN and M'N' are two Normal's. O = Point of incidence	 Fig (1) Refraction of Light

It has been experimentally observed that

a) When a ray of light travels from Rarer medium to Denser medium (e.g. ray from air to glass), it bends toward the normal and in this condition: $i>r$

b) When a ray of light travels from Denser medium to Rarer medium. (e.g. ray from glass to air), it bends away from the Normal and hence $i<r$.

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c) When a ray of light incident normally, in passes undeviated i.e. no bending occurs and hence i=0 and r = 0.

Refraction is associated with change in speed of light as medium changes and that occurs even if the rays fall normally and proceed without bending.

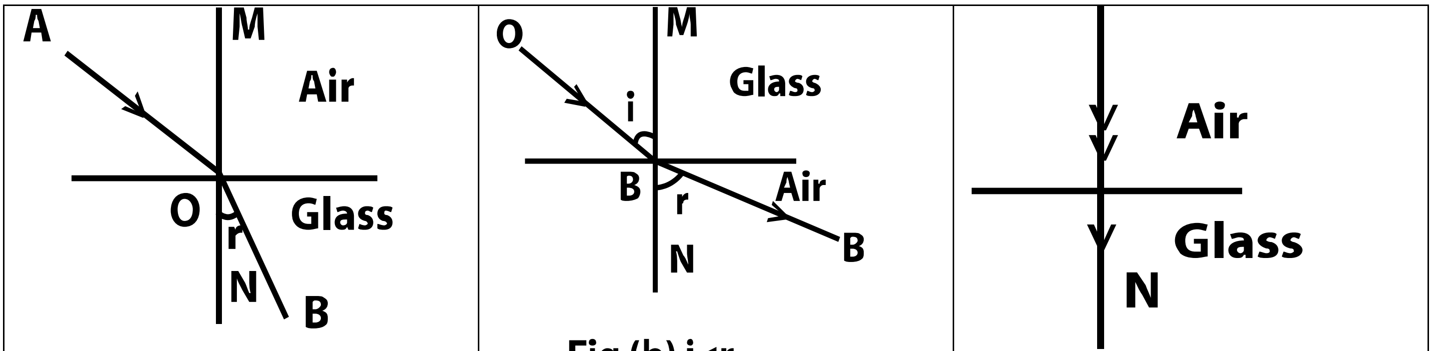

Fig (a) i>r

Fig (b) i<r

Fig (c) i=r=0°

Fig (I) Refraction of Light

Cause of Refraction of Light:-

The light has different speeds in different media. Thus, when light travels from one medium to another medium, it bends toward or away from the Normal. This occurs due to the change in speed of light. This change in speed of light causes the refraction of light.

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Laws of refraction of light:-

The laws of refraction of light are defined below:

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

b) The ratio of the sine of angle of incidence in the first medium to the sine of angle of refraction in the second medium is a constant.

i.e. $\frac{\sin i}{\sin r} = (\text{Constant})\ {}_1\mu_2$, for a given pair of media

Or, $\frac{\sin i}{\sin r} = \frac{\mu_2}{\mu_1} = {}_1\mu_2$

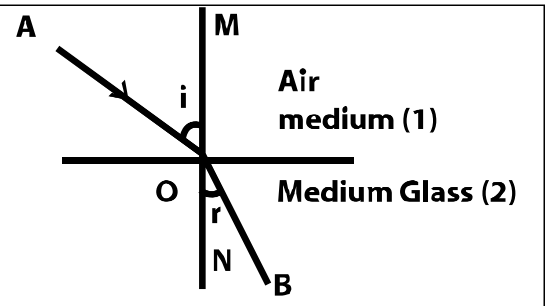
This is known as Snell's law.

$$\mu_1 \sin i = \mu_2 \sin r$$

$\therefore\ {}_1\mu_2 = \frac{\sin i}{\sin r}$: Snell's Law

${}_1\mu_2$= refractive Index of 2nd medium w.r.t that of 1st medium.

Here, ${}_1\mu_2 = \frac{\mu_2}{\mu_1}$)



Note: When light incident normally then i=0° and r = 0°. In this case, Snell's law doesn't hold but Refractive index can be obtained.

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Refractive index interms of speed of light:

(It has no units and it is a pure number)

→ The refractive index of second medium w.r.t. 1st medium (${}_1\mu_2$) is defined as the ratio of speed of light in the first medium (v_1)to that in the second medium(v_2). i.e. ${}_1\mu_2 = \frac{\mu_2}{\mu_1} = \frac{v_1}{v_2}$

Also, ${}_1\mu_2 = \frac{\lambda_1}{\lambda_2}$ since, $v = f\lambda$

This is **Relative refractive index.**

→ The ratio of speed of light in vacuum (air) to the speed of light in medium is called **Absolute refractive index.**

i.e.$\mu = \frac{\text{speed of light in air/vacuum}}{\text{speed of light in medium}} = \frac{c}{v}$

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NOTE:

$$\mu_1 = \frac{c}{v_1}\text{............(i)}$$

$$\mu_2 = \frac{c}{v_2}\text{............(ii)}$$

$$\frac{\mu_2}{\mu_1} = \frac{c/v_2}{c/v_1} = \frac{v_1}{v_2}$$

$$\therefore\ {}_1\mu_2 = \frac{\mu_2}{\mu_1} = \frac{v_1}{v_2}$$

Similarly, $\mu_w = \dfrac{c}{v_w}$

$$\mu_g = \frac{c}{v_g}$$

$${}_w\mu_g = \frac{\mu_g}{\mu_w}$$

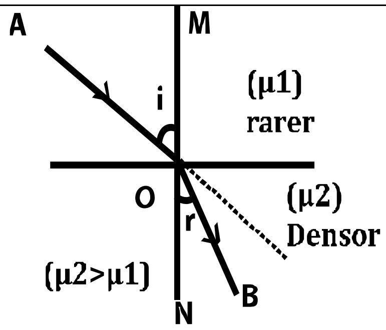

Fig (a) Light bend forward normal

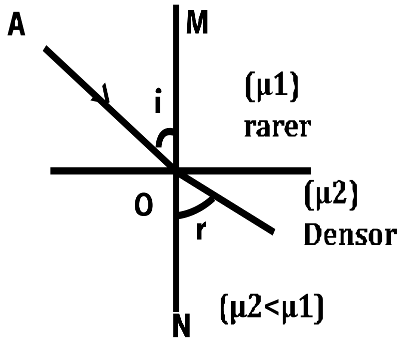

Fig (b) Light bend away forward normal

Principle of Reversibility of light:

It states that when the direction of a ray of light is reversed, the ray retraces its path.

For media (1) and (2) we have

$${}_1\mu_2 = \frac{\mu_2}{\mu_1} = \frac{\sin i}{\sin r}\ \text{........ (1)}$$

For media (2) and (1) we have

$${}_2\mu_1 = \frac{\sin r}{\sin i}\ \text{...........(2)}$$

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Multiplying (1) and (2)

$_1\mu_2 \times {}_2\mu_1 = 1$

$_1\mu_2 = 1/[{}_2\mu_1]$ ....(3)

This relation tells us that RI of 1st medium is w.r.t 2nd medium is reciprocal of R.I. of 2nd medium w.r.t. 1st medium.

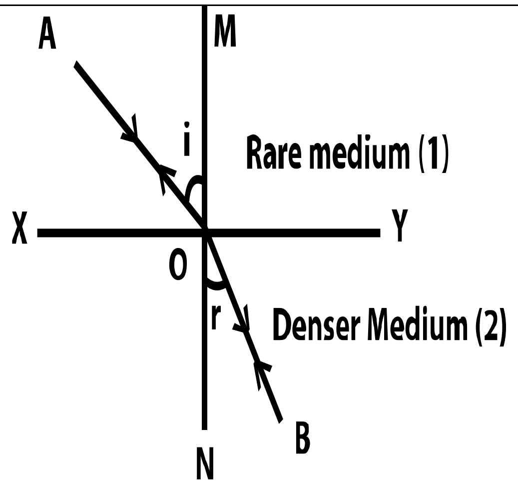

Fig (I) Reversibility of light

Relation between relative refractive index and Absolute refractive index:

Using Snell's Law for air-water media:

$$_a\mu_w = \frac{\sin i}{\sin r_1} \text{ .... } (1)$$

Again, for water-glass media,

$$_w\mu_g = \frac{\sin r_1}{\sin r_2} \text{........ } (2)$$

Similarly for, glass-air media

$$_g\mu_a = \frac{\sin r_2}{\sin i} \text{........ } (3)$$

Multiplying (1), (2), (3):

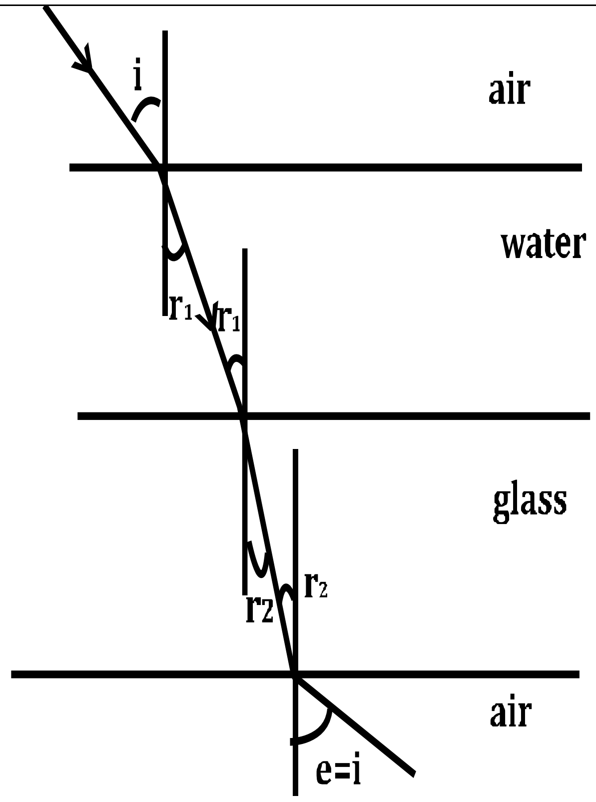

Fig (I) Refraction of light

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$$ {}_a\mu_w \times {}_w\mu_g \times {}_g\mu_a = \frac{\sin i}{\sin r_1} \times \frac{\sin r_1}{\sin r_2} \times \frac{\sin r_2}{\sin i} $$

or, $ {}_a\mu_w \times {}_w\mu_g \times {}_g\mu_a = 1 $

or, $ {}_w\mu_g \times \frac{1}{{}_a\mu_g} = \frac{1}{{}_a\mu_w} $ $\left[\because {}_g\mu_a = \frac{1}{{}_a\mu_g}\right]$

or, $ {}_w\mu_g = \frac{{}_a\mu_g}{{}_a\mu_w} $

This is the required relation between them.

Difference between Relative refraction index and Absolute refractive index:

Relative refraction index	Absolute refractive index
→ It is the R.I. of a medium w.r.t. any medium other then air or vacuum.	It is the R.I. of a medium w.r.t air or vacuum.
→ ${}_1\mu_2 = \frac{\mu_2}{\mu_1} = \frac{v_1}{v_2}$	→ $\mu = \frac{c}{v}$
→ It may be greater than or less than one.	→ It is always greater than one.

Lateral shift depends on

a) Thickness of the slab

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b) Refractive index of the material of slab and that of surrounding medium.
c) Angle of incidence and
d) Wavelength of incident light.

Q. Define Lateral Shift and derive an expression for it due to a parallel edged glass slab. Show in graph the variation of Lateral shift with the angle of incidence.(2076, 2073, 2072, 2070, 2067, 4 marks)

Lateral shift:-
The perpendicular distance between the direction of incident ray produced and the emergent ray is called lateral shift or lateral displacement. It is denoted by L.

Let us consider a glass slab ABCD of thickness t. When a ray of light RA is incident on the surface of the slab at O, it is refracted along OP and at last emerges out along PS as shown in Fig. (1).
MN and M'N' are Normal drawn at O and P respectively. PQ is perpendicular distance between the direction of

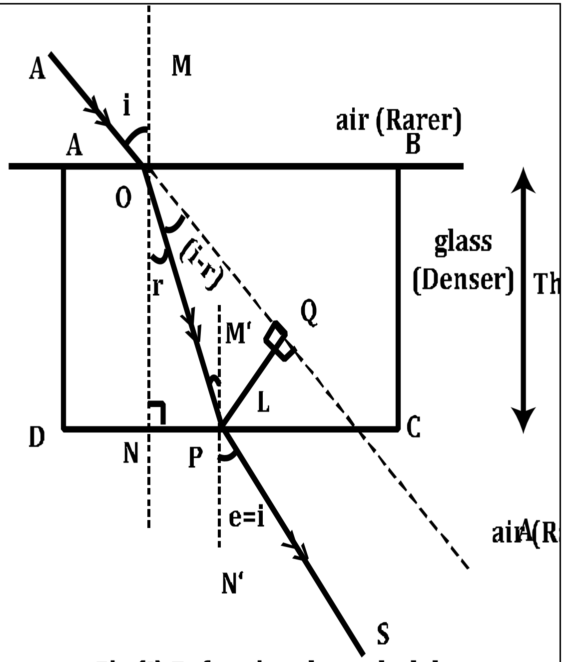

Fig (I) Refraction through slab

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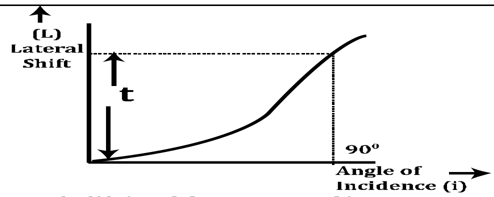
incident ray and emergent ray, which is called as Lateral Shift.	 Fig (2) Graph between L and i

Now, In ΔOQP, we have

$$\sin(i - r) = \frac{PQ}{OP}$$

Or, $PQ = OP \sin(i - r)$, ...(1)

Again, from ΔONP, we have

$$\cos r = \frac{ON}{OP} = \frac{t}{OP}$$

Or, $OP = \frac{t}{\cos r}$, ...(2)

From (1) and (2): $PQ = \frac{t}{\cos r} . \sin(i - r)$

or, $L = \frac{t \sin (i-r)}{\cos r}$, ...(3)

This is the required expression for the lateral shift.

When i=90°, then from equation (3):

$L = \frac{t\sin (90-r)}{\cos r} = \frac{t \cos r}{\cos r} = t$

:. L = t

i.e. Lateral shift is equal to the thickness of glass slab if angle of incidence is 90°, (Shown in fig (2)).

From fig.(2), we see that the value of Lateral Shift Slightly increases on increasing incident angle and become highest on incident angle of 90°.

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Q. Deduce the relation: $\mu = \dfrac{\text{Real depth}}{\text{Apparent depth}}$ (4 marks,2074)

Let us consider an object 'O' is placed in a denser medium (i.e. water) is viewed from Rarer medium (i.e. air), it appears to be raised at point I which is the virtual image of the object 'O'. Thus,

OA = Real depth

AI = Apparent depth of the object (Shown in fig (1)).

According to Snell's law, for water-air media, R.I. is,

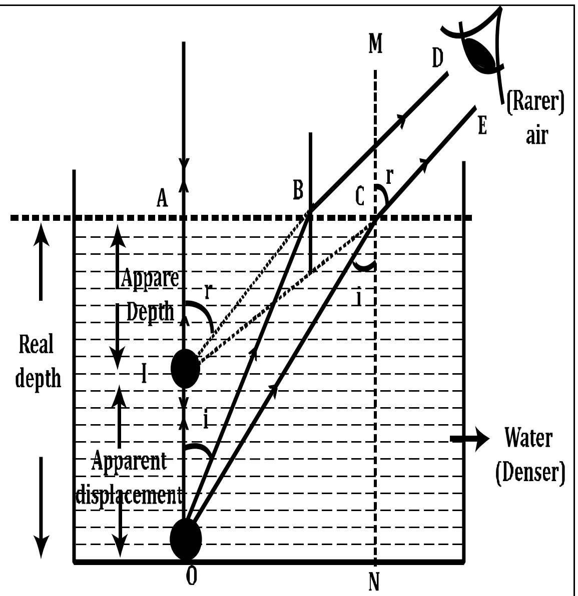


Fig (1) Real and Apparent Depth

$${}_{w}\mu_{a} = \frac{\sin i}{\sin r}, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

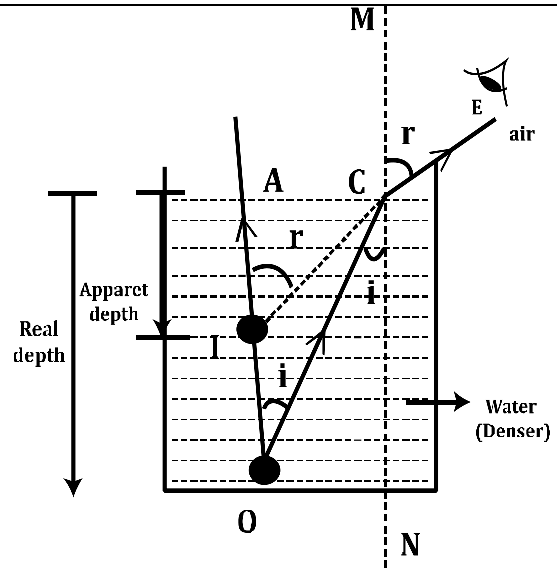
From figure, $\angle OCN = \angle AOC = i$

$\angle MCE = \angle AIC = r$

$$\left.\begin{aligned} \text{From } \Delta OAC\,;\ \sin i &= \frac{AC}{OC} \\ \text{From } \Delta IAC;\ \text{Sin } r &= \frac{AC}{IC} \end{aligned}\right\} \ldots\ldots\ldots(2)$$

Use equation (2) in (1):

$$\frac{\frac{AC}{OC}}{\frac{AC}{IC}} = \frac{IC}{OC}, \ldots\ldots\ldots\ldots(3)$$



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Since, C is very close to A so IC$\approx$ IA and OC $\approx$ OA

$$\therefore\ {}_{w}\mu_{a} = \frac{IA}{OA}$$

$$\left[\text{since, } {}_{w}\mu_{a} = \frac{1}{{}_{a}\mu_{w}}\right]$$

$$\text{or, } \frac{1}{{}_{a}\mu_{w}} = \frac{IA}{OA}$$

$$\therefore\ {}_{a}\mu_{w} = \frac{OA}{IA} = \frac{\text{real dpth}}{\text{Apparent depth}}$$

This is the required relation between real depth, apparent depth and refractive Index.

Note: ${}_{a}\mu_{w} = \dfrac{\sin r}{\sin i}$

i.e.light passes from denser to rarer medium.

Note: Apparent Shift Or Apparent displacement

The apparent displacement (OI) = OA - IA

$$= OA\left(1 - \frac{IA}{OA}\right)$$

$$= t\,(1 - {}_{w}\mu_{a})$$

$$= t\left(1 - \frac{1}{{}_{a}\mu_{w}}\right)$$

$$= \text{Real depth}\left[1 - \frac{1}{\text{Refractive Index}}\right]$$

Q. What do you mean by critical angle and Total internal reflection? Derive a relation between critical angle and Refractive index.

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(2056, 2052, 4 marks)

Critical Angle:

The angle of incidence in denser medium for which the angle of refraction in rarer medium is 90°, is called the critical angle of the medium. It is denoted by 'C'.

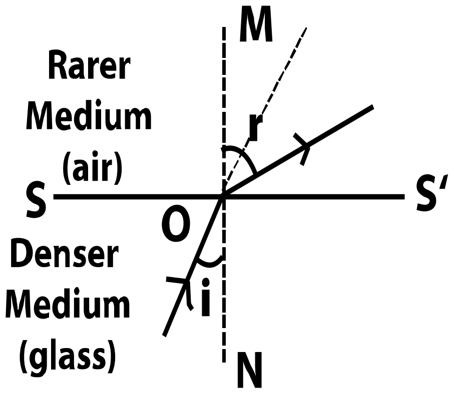

Fig (I) i<r
(Light trarel froms Denser to Rarer)

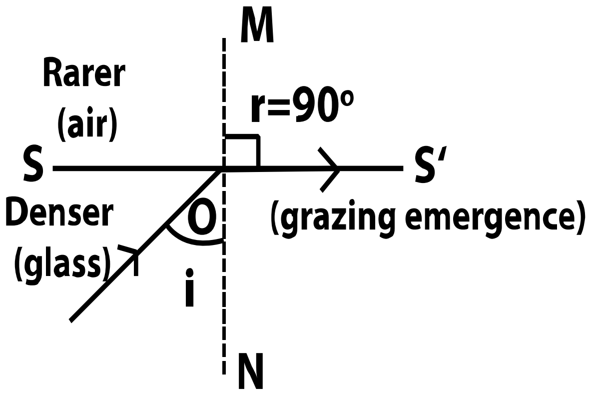

Fig (II) i=c(Critical angle)
(Light trapes from Denser to Rarer)

As the angle of is gradually increased, the corresponding angle of refraction will also increase until a limit is reached. When $r = 90°$ then refracted ray travels parallel to surface of separation between two media (Shown in fig (II) and corresponding incident ray is called critical angle (i.e. i=c)

Total Internal Reflection (TIR):

When the angle of incidence in Denser medium is made slightly greater than critical angle (i.e. i>c), the light is reflected in the same denser medium obey in

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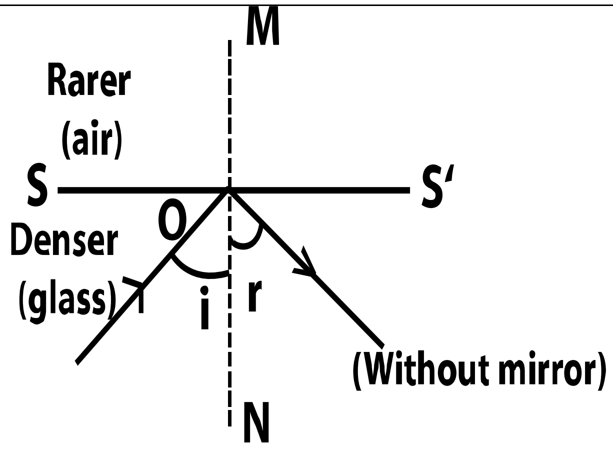
the laws of reflection and lost laws of refraction. This is known as total internal reflection (TIR)

Snell's law doesn't apply to the total internal reflection because it takes place according to law of reflection of light. Reflection is 100% so in practical, no loss of light in total internal reflection but in reflection from a mirror, a small part of light is absorbed.	 Fig (III) i>c

Condition of Total internal reflection:

(I) The light must pass from Denser to Rarer medium.

(II) Angle of Incidence must be greater than critical angle i.e. i>c.

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Relation between Critical angle and Refractive index:

When light travels from Denser medium to Rarer medium then according to Snell's law, we can write

$$\mu_2 \sin i = \mu_1 \sin r$$

$$\text{or}, \mu_2 \sin C = \mu_1 \sin 90°$$

$$or, \mu_2 \sin C = \mu_1 \times 1$$

$$\text{or } \sin C = \frac{\mu_1}{\mu_2}$$

$$\text{or}, \frac{\mu_2}{\mu_1} = \frac{1}{\sin c}$$

$$\text{or}, \ {}_1\mu_2 = \frac{1}{\sin C}$$

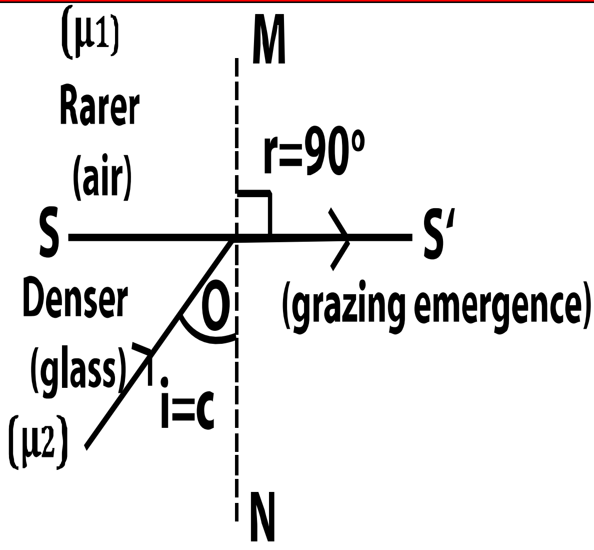

Fig (I) refraction at i=c

i.e. Refractive index of denser medium w.r.t. Rarer medium = $\frac{1}{\text{sine of critical angle}}$

Here, R.I. and critical angle both depends upon wavelength of light and different colors have different wavelengths.

Application of Total Internal Reflection:-

1) The brightness of diamonds and precious stones due to total internal reflection:

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→ The refractive index of diamond is 2.47 which is very large and critical angle for it is 24°. Due to low value of critical angle, a diamond can be cut into a number of faces. A ray of light on entering t from one face undergoes repeated total internal reflection from other faces. The faces, through which the light emerges, shine very brightly.

2) Mirage: An optical illusion which is produced due to total internal reflection of light generally occurred in hot region or cold region is called mirage.

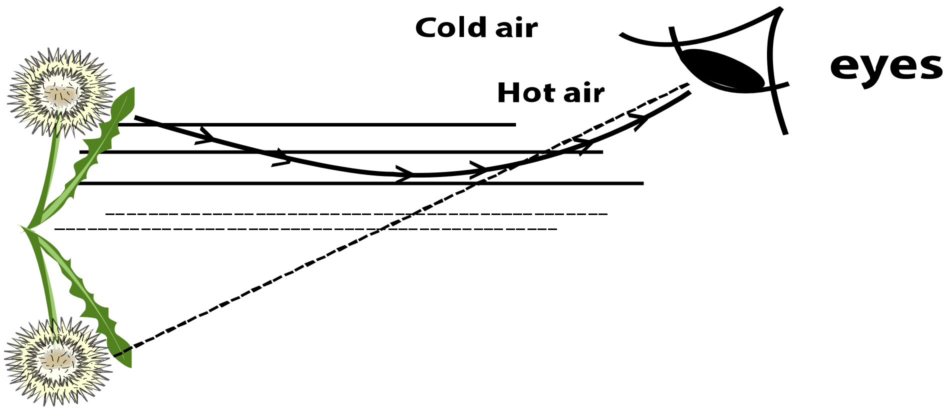

Fig (I) Mirage in a desert

3) Optical Fibers: (John Tyndall, British Physicist (1870))

→ An optical fiber is a transparent fiber used to conduct light through the phenomena of total

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internal reflection. The fibers are extremely thin (diameter $=2 \times 10^{-4}$cm) and long strands of glass.

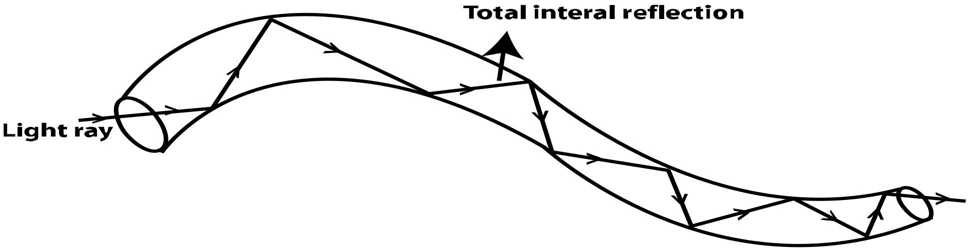

Fig (I) Transmission of communication of signal through optical fiber

Applications:

- Used for measuring blood flow in the heart
- Used in telecommunications
- Used to measure temperature, pressure and flow of liquids.
- Used to enlarge or diminish optical images.
- Used to transmit and receive electrical signals.
- Used in medical and optical examination.

NOTE: Endoscopy: Visually examine of inner parts of stomach and intestines.

THE END

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