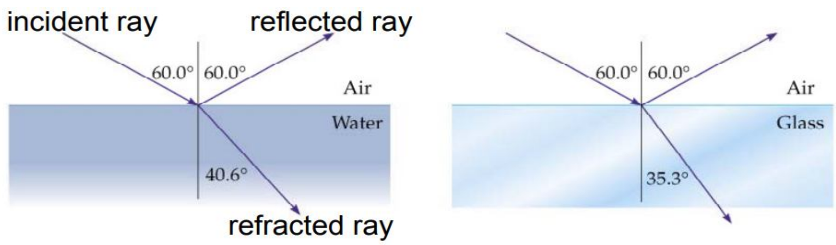
Refraction of Light

The bending of the ray of light passing from one medium to the other medium is called refraction.

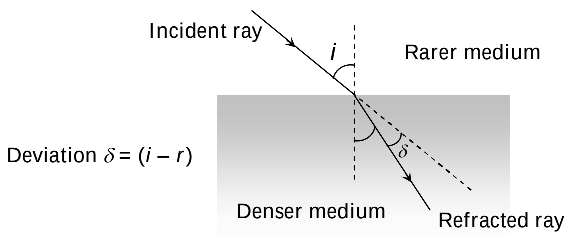


(1) The refraction of light takes place on going from one medium to another because the speed of light is different in the two media.

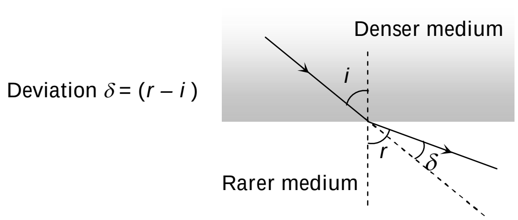
(2) Greater the difference in the speeds of light in the two media, greater will be the amount of refraction.

(3) A medium in which the speed of light is more is known as optically rarer medium and a medium is which the speed of light is less, is known as optically denser medium.

(4) When a ray of light goes from a rarer medium to a denser medium, it bends towards the normal.



(5) When a ray of light goes from a denser medium to a rarer medium, it bends away from the normal.



(6) **Snell's law :** The ratio of sine of the angle of incidence to the angle of refraction (r) is a constant called refractive index

i.e. $\frac{\sin i}{\sin r} = \mu$ (a constant). For two media, Snell's law can be written as ${}_1\mu_2 = \frac{\mu_2}{\mu_1} = \frac{\sin i}{\sin r}$

$\Rightarrow \mu_1 \times \sin i = \mu_2 \times \sin r$ *i.e.* $\mu \sin\theta =$ constant

Also in vector form : $\hat{\boldsymbol{i}} \times \hat{\boldsymbol{n}} = \mu(\hat{\boldsymbol{r}} \times \hat{\boldsymbol{n}})$

Refractive Index

(1) Refractive index of a medium is that characteristic which decides speed of light in it.

(2) It is a scalar, unit less and dimensionless quantity.

(3) **Absolute refractive index :** When light travels from vacuum to any transparent medium then refractive index of medium *w.r.t.* vacuum is called it's absolute refractive index *i.e.* ${}_{\text{vacuum}}\mu_{\text{medium}} = \frac{c}{v}$

Absolute refractive indices for glass, water and diamond are respectively

$\mu_g = \frac{3}{2} = 1.5,\ \mu_w = \frac{4}{3} = 1.33$ and $\mu_D = \frac{12}{5} = 2.4$

(4) **Relative refractive index :** When light travels from medium (1) to medium (2) then refractive index of medium (2) *w.r.t.* medium (1) is called it's relative refractive index *i.e.* ${}_1\mu_2 = \frac{\mu_2}{\mu_1} = \frac{v_1}{v_2}$ (where v_1 and v_2 are the speed of light in medium 1 and 2 respectively).

(5) When we say refractive index we mean absolute refractive index.

(6) The minimum value of absolute refractive index is 1. For air it is very near to 1. ($\cong 1.003$)

(7) Cauchy's equation : $\mu = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4} + ...$

($\lambda_{\text{Red}} > \lambda_{\text{violet}}$ so $\mu_{\text{Red}} < \mu_{\text{violet}}$)

(8) If a light ray travels from medium (1) to medium (2), then

$${}_1\mu_2 = \frac{\mu_2}{\mu_1} = \frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2}$$

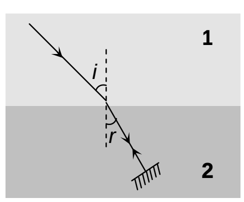
(9) **Dependence of Refractive index**

(i) Nature of the media of incidence and refraction.

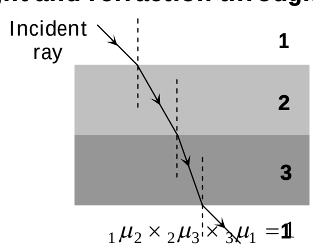
(ii) Colour of light or wavelength of light.

(iii) Temperature of the media : Refractive index decreases with the increase in temperature.

(10) **Reversibility of light and refraction through several media**



(A) ${}_1\mu_2 = \frac{1}{{}_2\mu_1}$



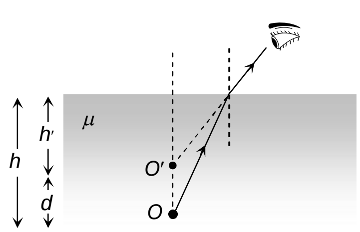
${}_1\mu_2 \times {}_2\mu_3 \times {}_3\mu_1 = 1$

(B) or ${}_2\mu_3 = \frac{{}_1\mu_3}{{}_1\mu_2}$

Real and Apparent Depth

If object and observer are situated in different medium then due to refraction, object appears to be displaced from it's real position.

(1) **When object is in denser medium and observer is in rarer medium**



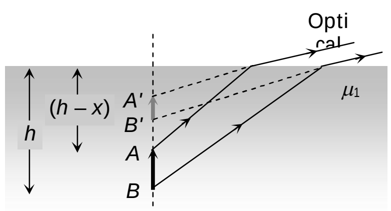
(i) $\mu = \dfrac{\text{Real depth}}{\text{Apparent depth}} = \dfrac{h}{h'}$

(ii) Real depth > Apparent depth

(iii) Shift $d = h - h' = \left(1 - \dfrac{1}{\mu}\right)h$. For water $\mu = \dfrac{4}{3} \Rightarrow d = \dfrac{h}{4}$;

For glass $\mu = \dfrac{3}{2} \Rightarrow d = \dfrac{h}{3}$

(iv) Lateral magnification : consider an object of height *x* placed vertically in a medium μ_1 such that the lower end (*B*) is a distance *h* from the interface and the upper end (*A*) at a distance (*h* – *x*) from the interface.



Distance of image of *B* (*i.e. B'*) from the interface = $\dfrac{\mu_2}{\mu_1}h$

Distance of image of *A* (*i.e. A'*) from the interface $= \dfrac{\mu_2}{\mu_1}(h-x)$

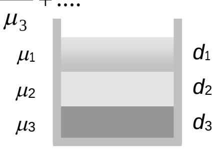
Therefore, length of the image $\dfrac{\mu_2}{\mu_1}x$

or, the lateral magnification of the object $m = \dfrac{\mu_2}{\mu_1} = \dfrac{1}{\mu}$

(v) If a beaker contains various immiscible liquids as shown then

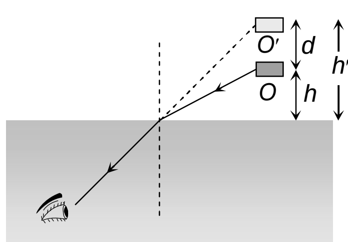
Apparent depth of bottom $= \dfrac{d_1}{\mu_1} + \dfrac{d_2}{\mu_2} + \dfrac{d_3}{\mu_3} + ...$

$\mu_{\text{combination}} = \dfrac{d_{AC}}{d_{App.}} = \dfrac{d_1 + d_2 + ...}{\dfrac{d_1}{\mu_1} + \dfrac{d_2}{\mu_2} + ...}$



(In case of two liquids if $d_1 = d_2$ than $\mu = \dfrac{2\mu_1\mu_2}{\mu_1 + \mu_2}$)

(2) **Object is in rarer medium and observer is in denser medium**



(i) $\mu = \frac{h'}{h}$

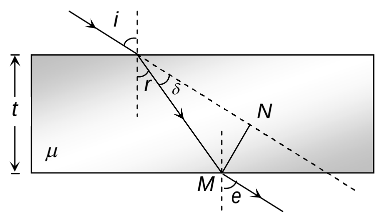
(ii) Real depth < Apparent depth.

(iii) $d = (\mu - 1)h$

(iv) Shift for water $d_w = \frac{h}{3}$; Shift for glass $d_g = \frac{h}{2}$

Refraction Through a Glass Slab

(1) **Lateral shift :** The refracting surfaces of a glass slab are parallel to each other. When a light ray passes through a glass slab it is refracted twice at the two parallel faces and finally emerges out parallel to it's incident direction *i.e.* the ray undergoes no deviation $\delta = 0$. The angle of emergence (e) is equal to the angle of incidence (i)



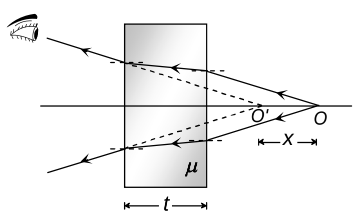
The Lateral shift of the ray is the perpendicular distance between the incident and the emergent ray, and it is given by

***MN* = *t* sec *r* sin (*i* – *r*)**

(2) **Normal shift :** If a glass slab is placed in the path of a converging or diverging beam of light then point of convergence or point of divergence appears to be shifted as shown

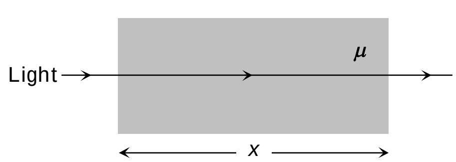
Normal shift

$$OO' = x = \left(1 - \frac{1}{\mu}\right)t$$



(3) **Optical path :** It is defined as distance travelled by light in vacuum in the same time in which it travels a given path length in a medium.

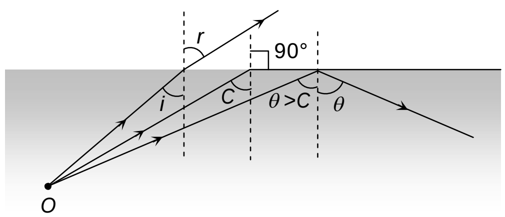
Time taken by light ray to pass through the medium $= \frac{\mu x}{c}$; where x = geometrical path and μx = optical path



Total Internal Reflection (TIR)

When a ray of light goes from denser to rarer medium it bends away from the normal and as the angle of incidence in denser medium increases, the angle of refraction in rarer medium also increases and at a certain angle, angle of refraction becomes 90°, this angle of incidence is called critical angle (*C*).

When Angle of incidence exceeds the critical angle than light ray comes back in to the same medium after reflection from interface. This phenomenon is called Total internal reflection (TIR).



(1) $\mu = \frac{\mathbf{1}}{\mathbf{sin}\ \boldsymbol{C}} = \mathbf{cosec}\ \boldsymbol{C}$ where $\mu \rightarrow {}_{\text{Rarer}}\mu_{\text{Denser}}$

(2) **Conditions for TIR**

(i) The ray must travel from denser medium to rarer medium.

(ii) The angle of incidence *i* must be greater than critical angle *C*

(3) **Dependence of critical angle**

(i) Colour of light (or wavelength of light) : Critical angle depends upon wavelength as $\lambda \propto \frac{1}{\mu} \propto \sin C$

(a) $\lambda_R > \lambda_V \Rightarrow C_R > C_V$

(b) Sin *C* $= \frac{1}{{}_R\mu_D} = \frac{\mu_R}{\mu_D} = \frac{\lambda_D}{\lambda_R} = \frac{v_D}{v_R}$ (for two media)

(ii) Nature of the pair of media : Greater the refractive index lesser will be the critical angle.

(a) For (glass- air) pair $\rightarrow C_{\text{glass}} = 42^o$

(b) For (water-air) pair $\rightarrow C_{\text{water}} = 49^o$

(c) For (diamond-air) pair $\rightarrow C_{\text{diamond}} = 24^o$

(iii) Temperature : With temperature rise refractive index of the material decreases therefore critical angle increases.

Common Examples of TIR

(1) **Looming :** An optical illusion in cold countries

(2) **Mirage :** An optical illusion in deserts

(3) **Brilliance of diamond :** Due to repeated internal reflections diamond sparkles.

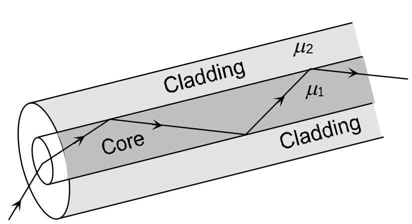
(4) **Optical fibre :** Optical fibres consist of many long high quality composite glass/quartz fibres. Each fibre consists of a core and cladding.

(i) The refractive index of the material of the core (μ_1) is higher than that of the cladding (μ_2).

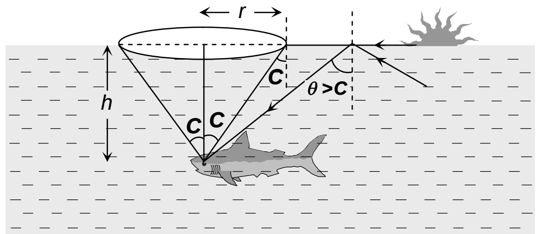
(ii) When the light is incident on one end of the fibre at a small angle, the light passes inside, undergoes repeated total internal reflections along the fibre and finally comes out. The angle of incidence is always larger than the critical angle of the core material with respect to its cladding.

(iii) Even if the fibre is bent, the light can easily travel through along the fibre

(iv) A bundle of optical fibres can be used as a 'light pipe' in medical and optical examination. It can also be used for optical signal transmission. Optical fibres have also been used for transmitting and receiving electrical signals which are converted to light by suitable transducers.



(5) **Field of vision of fish (or swimmer) :** A fish (diver) inside the water can see the whole world through a cone with.



(a) Apex angle $= 2C = 98^o$

(b) Radius of base $r = h\tan C = \dfrac{h}{\sqrt{\mu^2 - 1}}$; for water $r = \dfrac{3h}{\sqrt{7}}$

(c) Area of base $A = \dfrac{\pi h^2}{(\mu^2 - 1)}$; for water $a = \dfrac{9\pi}{7}h^2$

(6) **Porro prism :** A right angled isosceles prism, which is used in periscopes or binoculars. It is used to deviate light rays through 90^o and 180^o and also to erect the image.