Refraction of light
(plane surfaces)

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Refraction of light

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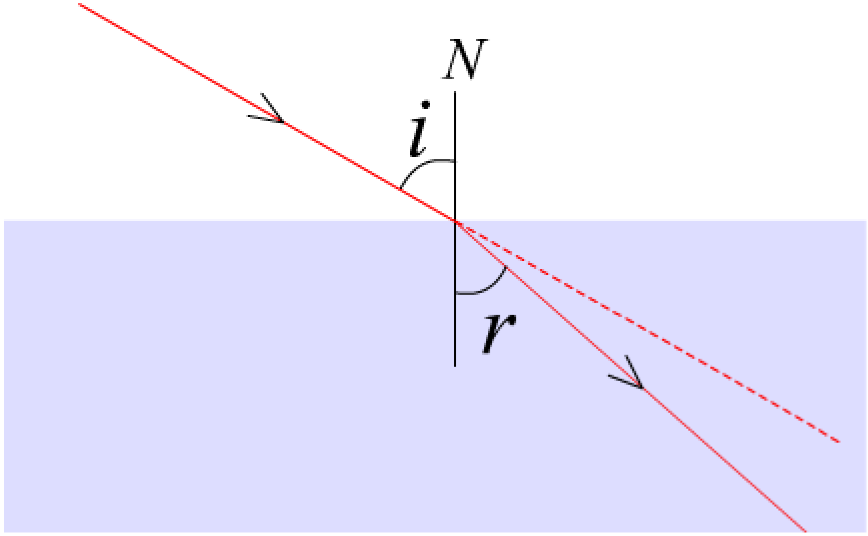
Bending of light at the interface of two media is called refraction

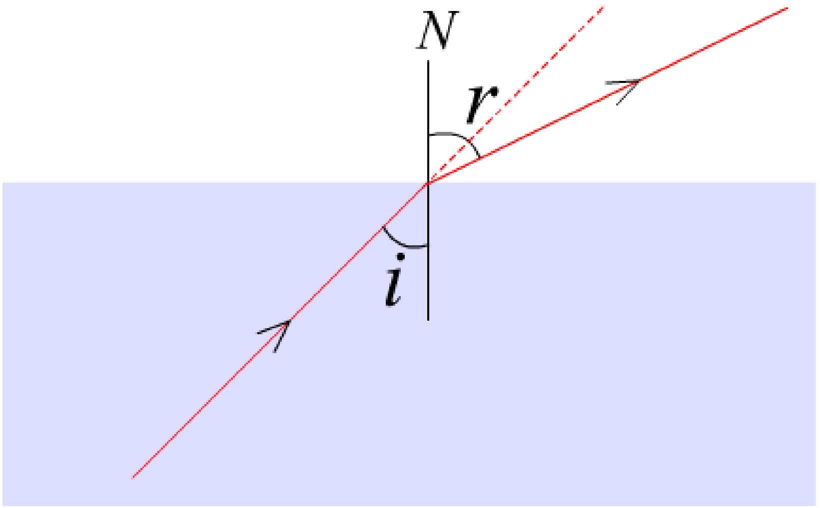
Rarer to denser medium

As light propagates from a rarer medium to a denser medium it bends towards the normal



Denser to rarer medium

As light propagates from a denser medium to a rarer medium it bends away from normal



Laws of refraction

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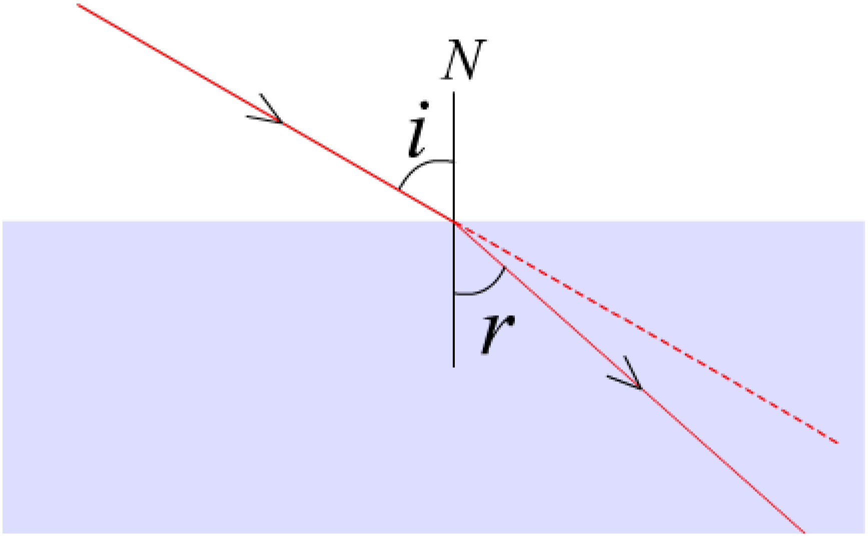
1. Incident ray, refracted ray and the normal to the point of incidence lie in the same plane.

2. Snell's law : Ratio of sine of angle of incidence to sine of angle of refraction is constant for a particular wavelength of light and a particular pair of media.

$$\boxed{n_1 \sin(i) = n_2 \sin(r)}$$



Note : As light propagates from one medium to another, its frequency remains constant while it speed and wavelength change accordingly

Critical angle

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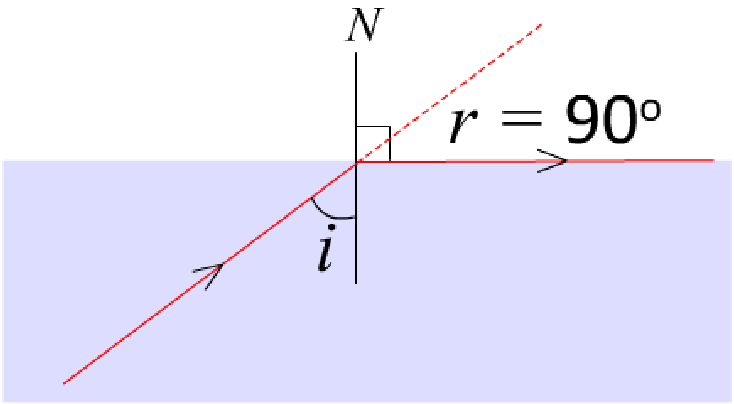
It is the angle of incidence, in denser medium, for which the angle of refraction in rarer medium is 90°.



Using Snell's law

$$n_{\text{denser}} \sin(C) = n_{\text{rarer}} \sin(90^{\circ})$$

$$n_{\text{denser}} \sin(C) = n_{\text{rarer}}$$

$$\boxed{\sin(C) = \frac{n_{\text{rarer}}}{n_{\text{denser}}} = \frac{n_2}{n_1}}$$

Total internal reflection

When angle of incidence in denser medium is greater than critical angle, the light ray is reflected back into the denser medium.

Such a reflected ray follows laws of reflection.

Absolute refractive index and relative refractive index

Absolute refractive index : (of a medium) is defined as the ratio of speed of light in vacuum to the speed of light in that medium.

$$n = \frac{c_{\text{vacuum}}}{c_{\text{medium}}} = \frac{\lambda_{\text{vacuum}}}{\lambda_{\text{medium}}}$$

Absolute refractive index cannot be less than 1

Relative refractive index : Refractive index of one medium w.r.t. the other.

$$n_{\text{AB}} = \frac{n_{\text{A}}}{n_{\text{B}}} = \frac{c_{\text{B}}}{c_{\text{A}}} = \frac{\lambda_{\text{B}}}{\lambda_{\text{A}}}$$

Relative refractive index may be less or greater than or equal to 1

Refractive index of air is approximated as 1.

Refractive index of vacuum = 1

Optical density and mass density

Optical density : Optical density is a measure of the relative speed of light in vacuum to the speed of light in the medium. Light propagates with lesser speed in a medium with higher optical density.

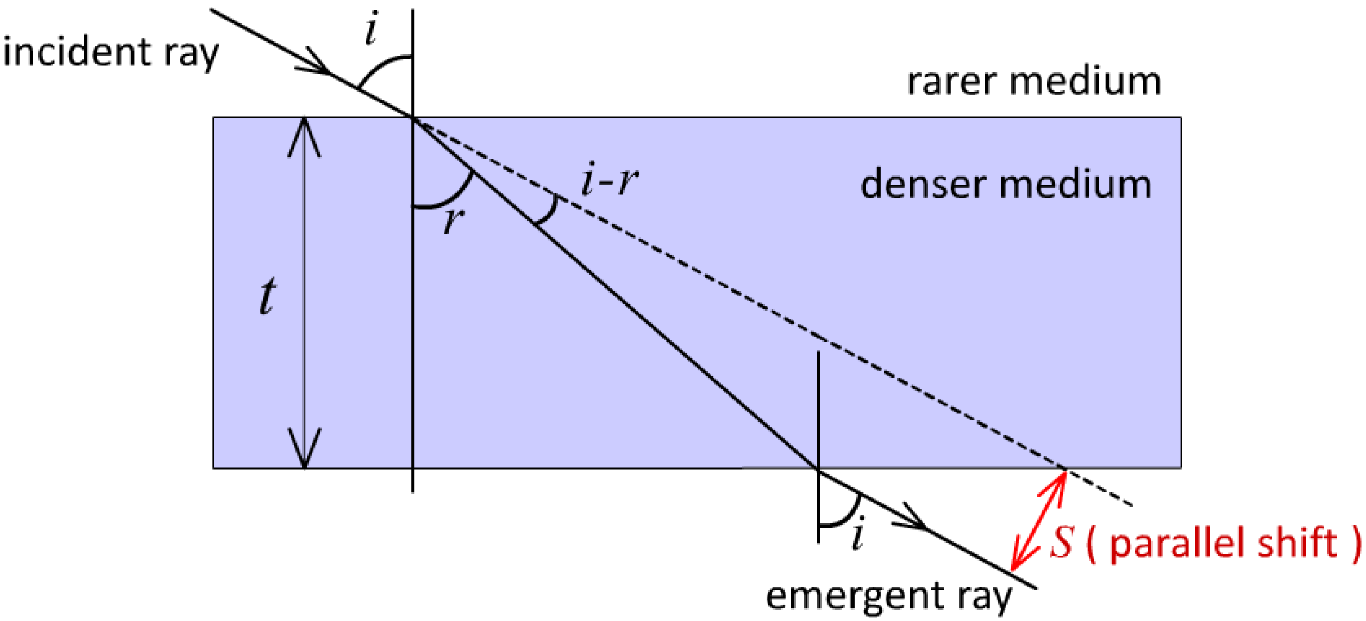
It is a measure of the amount of refraction that occurs in a material. A material with high value of refractive index is said to be optically denser.
It does not have any units.

Mass density : It is a measure of the closeness of packing of atoms/molecules in a material. It is defined as the mass per unit volume of the material.
SI unit is kg m^{-3}.

Mass density of turpentine is less than that of water but its optical density is higher.

Parallel shift or lateral shift (S)

When a ray of light is incident on a parallel sided glass slab, then emergent ray is found to be shifted parallel to the incident ray. This is called parallel shift or lateral shift.



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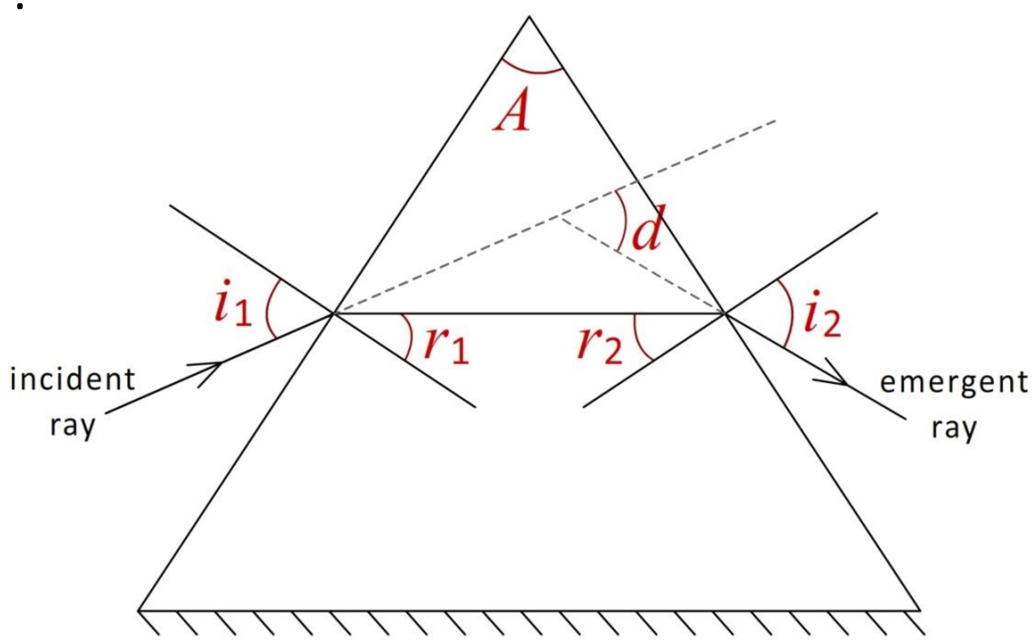
$$S = \frac{t \sin(i - r)}{\cos(r)}$$

Parallel shift (S) depends on angle of incidence and refractive indices of the media. There is *no deviation* in the ray of light.

Refraction through prism

When alight ray passes trough a prism it undergoes refractions at both refracting surfaces resulting in a net deviation. Refractive index of the material of the prism can be determined in terms of the minimum possible deviation (d_{m}) and the angle of the prism (A) .



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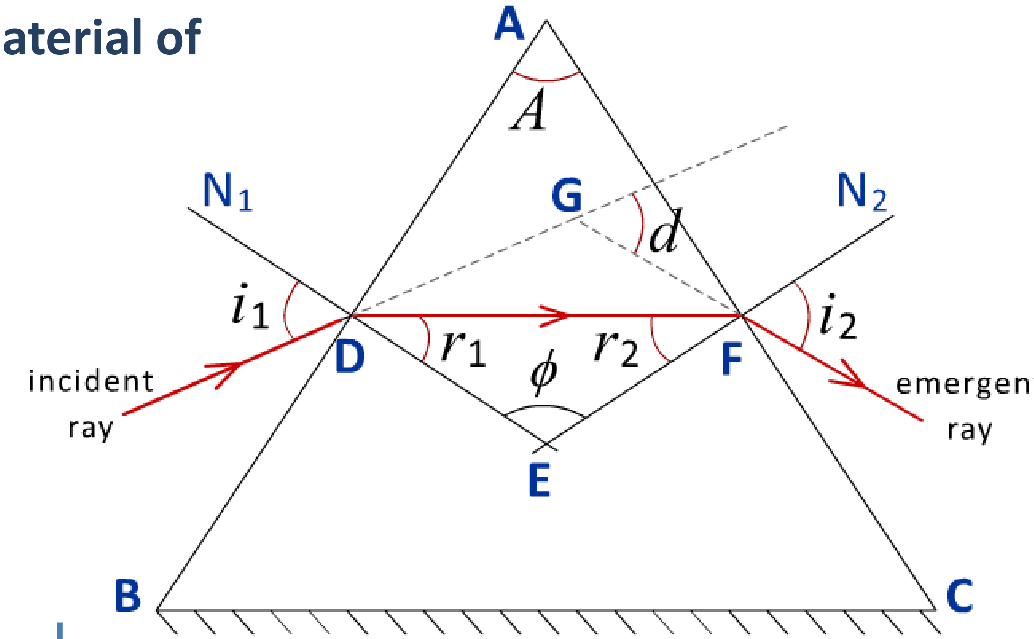
Determination of refractive index of material of prism



Determination of refractive index of material of a prism in terms of the angle of prism and angle of minimum deviation of light ray through the prism.

Considering triangle DGF

$$d = (i_1 - r_1) + (i_2 - r_2)$$

$$d = (i_1 + i_2) - (r_1 + r_2) \quad (1)$$

Considering triangle DEF

$$r_1 + r_2 + \phi = 180 \quad (2)$$

Considering quadrilateral ADEF

$$A + 90 + \phi + 90 = 360$$

$$A + \phi = 180 \quad (3)$$

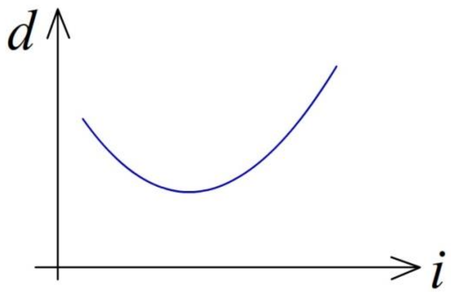
Comparing (2) and (3) we get

$$A = r_1 + r_2 \quad (4)$$

Substituting in (4) equation (1)

$$d = (i_1 + i_2) - A \quad (5)$$

From the graph of angle of deviation as a function of angle of incidence it is observed that angle of deviation decreases, reaches a minimum and then again increases



At minimum deviation (d_m)

$$i_1 = i_2 = i \quad \text{and} \quad r_1 = r_2 = r$$

Therefore from eq (4) we get

$$A = 2r$$

$$r = \frac{A}{2} \qquad 6$$

Similarly from eq (5) we get

$$d_m = 2i - A$$

$$i = \frac{A + d_m}{2} \qquad 7$$

Using Snell's law

$$n_1 \sin(i) = n_2 \sin(r)$$

Substituting values of r and i from eqs 6 and 7 we get

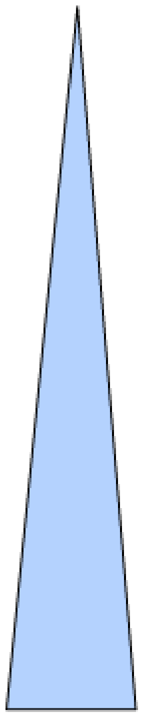
$$n_1 \sin\left(\frac{A + d_m}{2}\right) = n_2 \sin\left(\frac{A}{2}\right)$$

Considering $n_1 = 1$ and $n_2 = n$ we get

$$n = \frac{\sin\left(\frac{A + d_m}{2}\right)}{\sin(A/2)} \qquad 8$$

Refraction through a thin angled prism

When the angle of prism is very small, then the angle of deviation is also small. In this case, using small angle approximation we get



$$\boxed{n = \frac{\sin\left[(A+d_{\text{m}})/2\right]}{\sin(A/2)}}$$

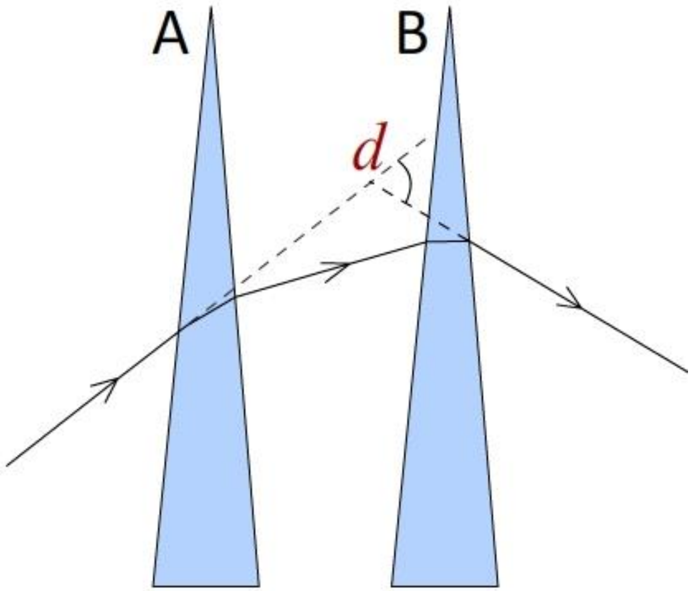
$$n = \frac{(A+d)/2}{(A/2)}$$

$$nA = A+d$$

$$\boxed{d = A(n-1)}$$

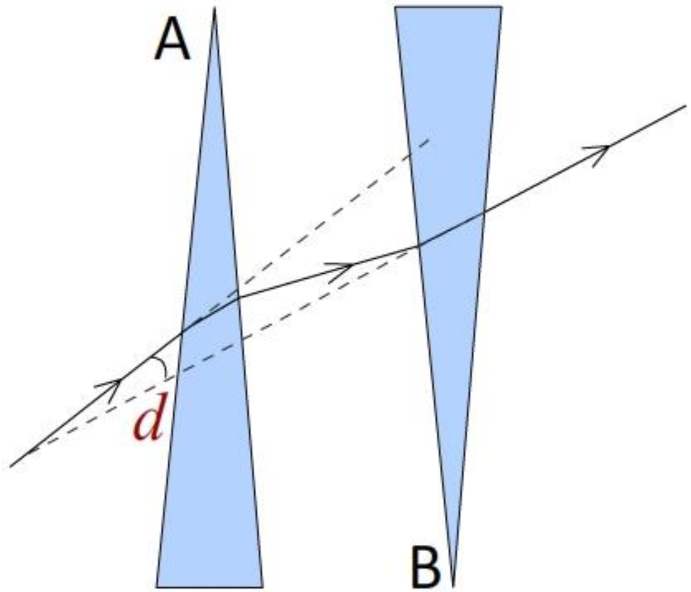
Combination of prisms

When two prisms are aligned in the same direction then the total deviation in a ray of light is the sum of individual deviations due to each prism.



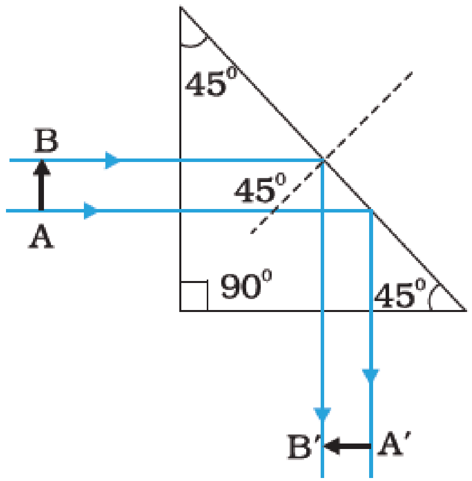
$$d_{\text{net}} = d_1 + d_2$$

When the prisms are aligned in opposite directions then the net deviation is the difference of individual deviations.

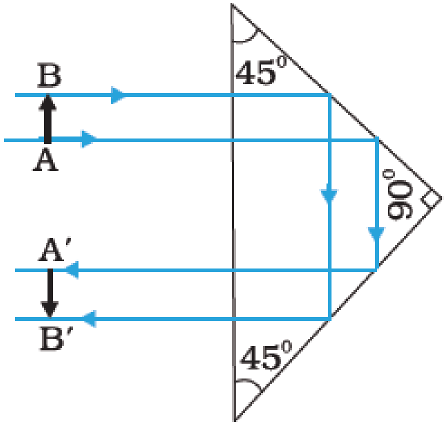


$$d_{\text{net}} = d_1 - d_2$$

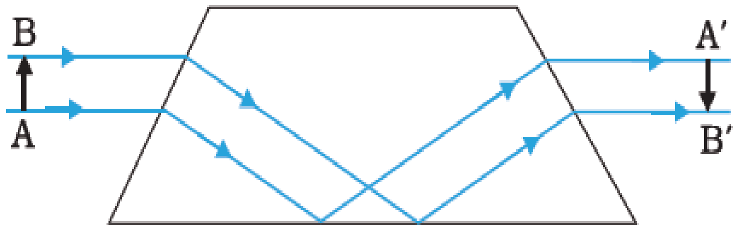
Use of prism to change path of a beam



(a)



(b)



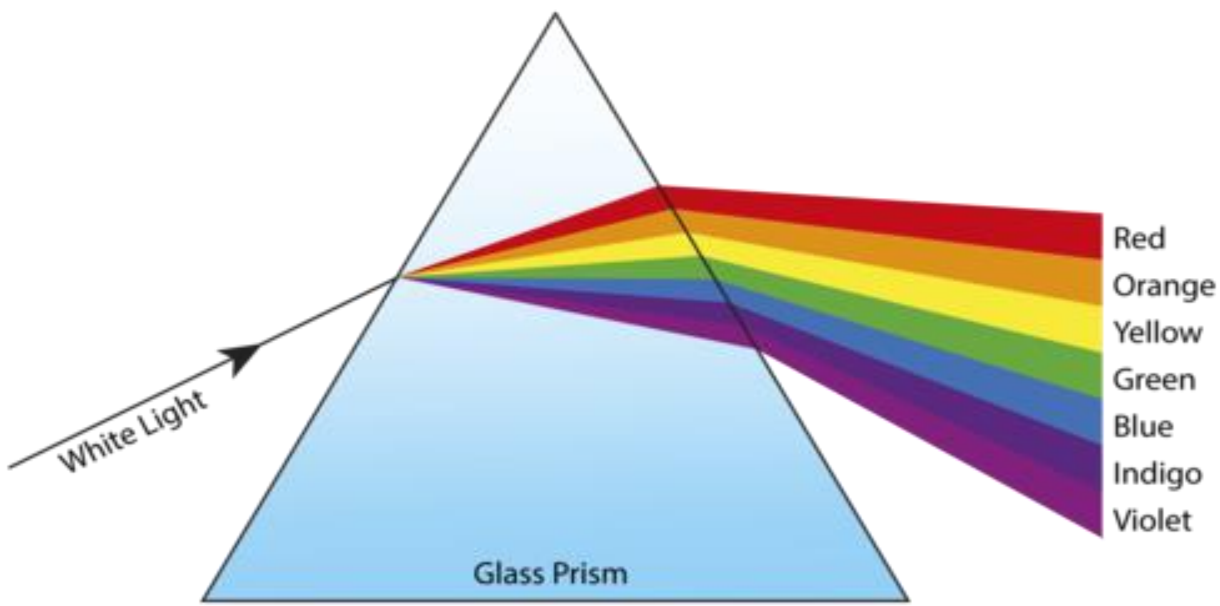
(c)

Dispersion of light due to prism

Dispersion : Splitting of white light into its individual components .

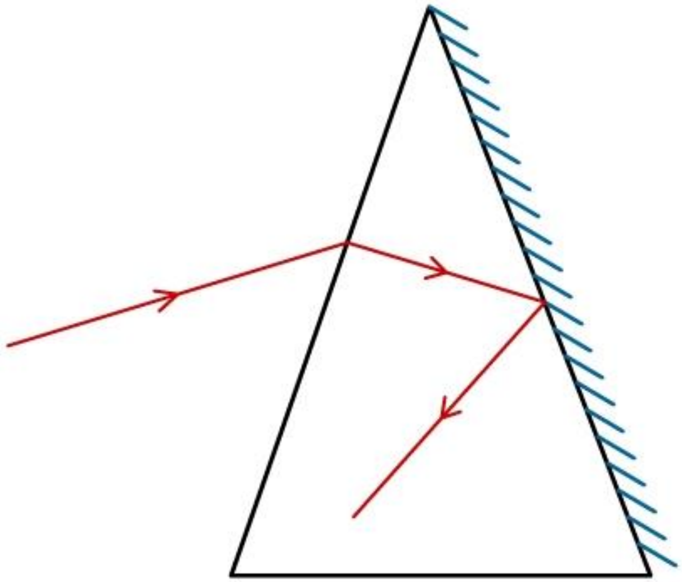
Dispersion occurs due to variation of refractive index of a medium with wavelength (colour) of light.

As refractive index for red is less than that for violet, their deviations are different and they are separated as they pass through a prism.



Silvered prisms

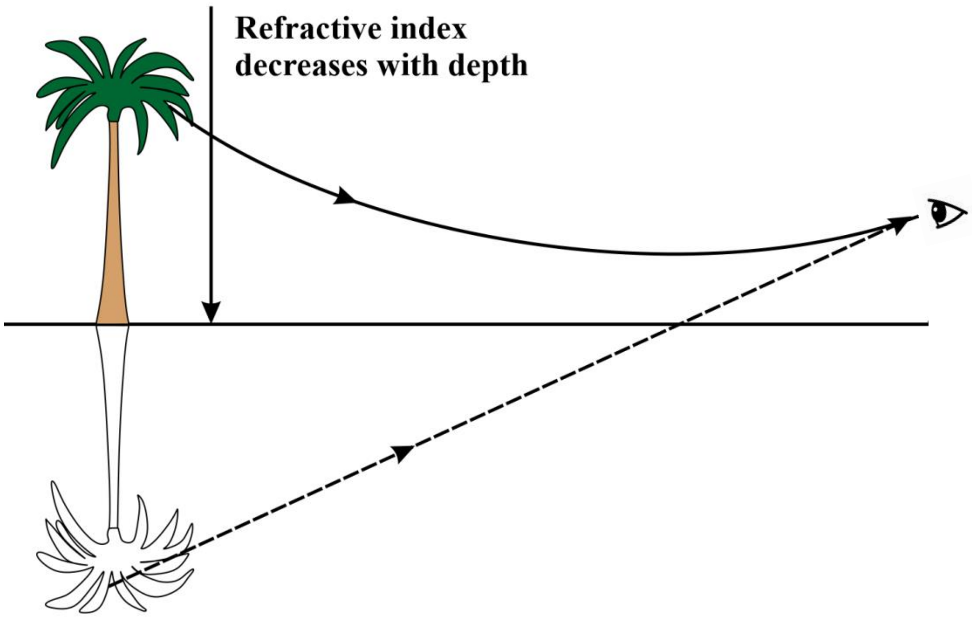
When one of the refracting surfaces of a prism is silvered then a ray of light incident on the other surface of the prism is refracted at the first surface and then reflected at the other surface (and does not meet the condition based on the critical angle)



Some naturally occurring phenomena

Formation of a mirage

On hot summer days, the air near the ground is hotter than the air at higher levels. Refractive index of air increases with its density and hence as light from a tall object , such as a tree, passes through this medium of decreasing refractive index the ray successively bends away from the normal.



If the angle of incidence is larger than critical angle (as in case of distant objects) the ray undergoes total internal reflection. The light appears to be coming from somewhere below the ground. The observer naturally assumes that light is being reflected from the ground, say, by a pool of water near the tall object. This phenomenon of optical illusion due to such inverted images of distant tall objects is called *mirage.*

Some naturally occurring phenomena

<u>Sun is visible before the actual sunrise</u>

Sun is visible to use before the sun appears at the horizon. This is because rays from the sun propagate from outer space (rarer medium) to our atmosphere (denser medium). This causes the rays to bend towards the normal. As these rays reach us we are able to see the sun.

Apparent flattening of sun during sunrise and sunset is also due to refraction.

Some naturally occurring phenomena

Optical fibers

These are the devices used for communication. They work on the principle of total internal reflection.

The three important regions of an OFC are

- Core : This is a region of higher refractive index. All the message signals (light) propagate in this region.
- Cladding : This is a region surrounding the core. This is a medium f relatively less refractive index allowing total internal reflection to take lace in the core of OFC.
- Buffer or Sheath : This form the outermost layer. It provides the electrical and mechanical insulation to cladding and the core of OFC.

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