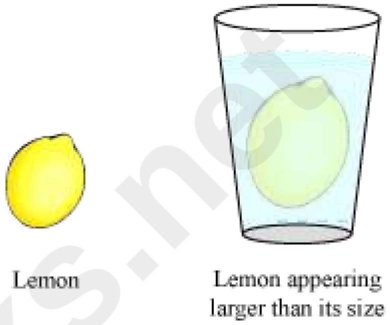
Refraction of Light

Refraction and Speed of Light

Ben was surprised to see a lemon appear larger than its size when he placed it in a glass filled with water.

What is the reason behind this?

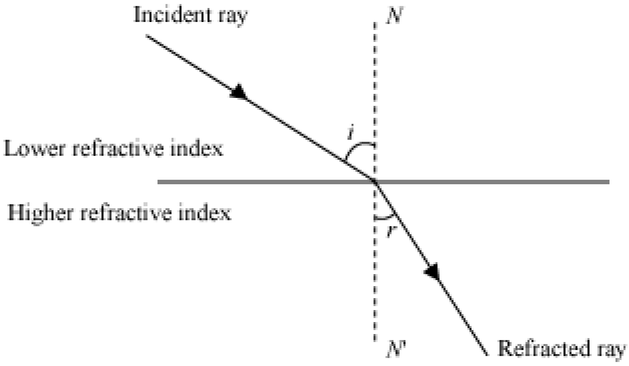


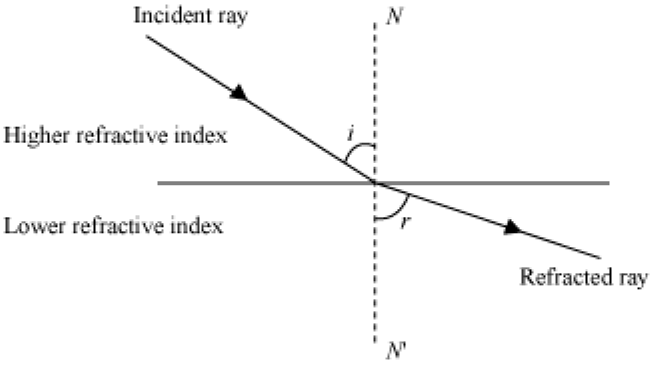
When a light ray travels from one transparent medium to another, it bends at the surface that separates the two media. Hence, the lemon appears larger than its actual size. This happens because different media have different optical densities.

The phenomenon of bending of light as it travels from one medium to another is known as **refraction of light**.

The phenomenon of refraction shows that the speed of light is different in different media.

As a ray of light moves from an optically rarer medium to an optically denser medium, it bends towards the normal at the point of incidence. Therefore, the angle of incidence (*i*) is greater than the angle of refraction (*r*). Hence, ***i* > *r***.



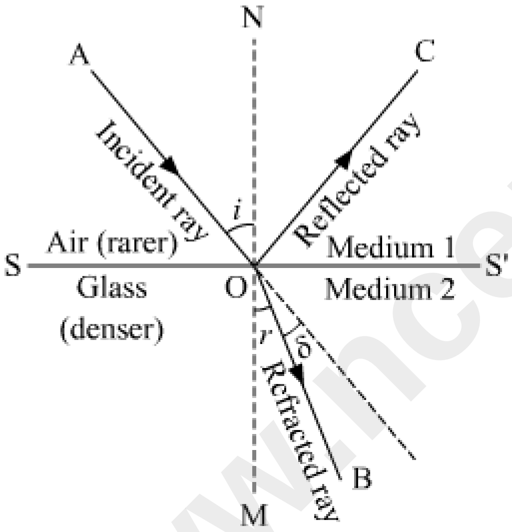


As a ray of light moves from an optically denser medium to an optically rarer medium, it bends away from the normal. Therefore, the angle of incidence (*i*) is less than the angle of refraction (*r*).

Hence, ***i* < *r***.

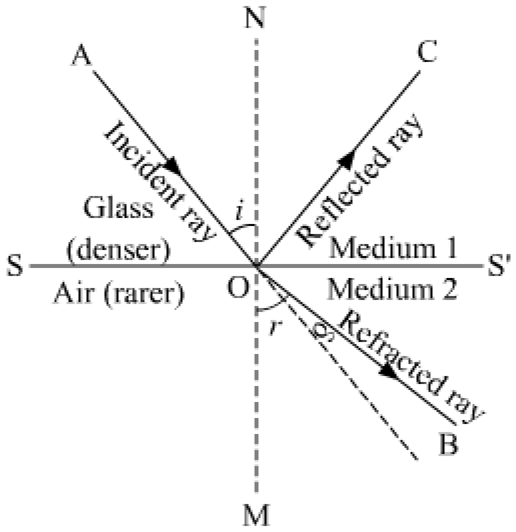
Partial reflection and refraction of light at the boundary of two medium

Case I: Refraction from rarer to denser medium



When light travels from rarer to denser medium, suppose from air to glass, the partially refracted light bends towards the normal and partially reflected light returns back into the same medium.

Case II: Refraction from denser to rarer medium



When light travels from denser to rarer medium, suppose from glass to air, the partially refracted light bends away from the normal and partially reflected light returns back into the same medium.

Effect on various characteristics of light on reflection and refraction:

Characteristics	Partially reflected light	Partially refracted light	
		Rarer to denser	Denser to rarer
Speed of light	No change	Decreases	Increases
Frequency of light (f)	No change	No change	No change
Wavelength of light ($\lambda = \frac{v}{f}$)	No change	Decreases	Increases

Speed of Light

Light changes its speed when it enters one medium from another. The velocities of light in various media are given in the following table.

Medium	**Velocity**
Air	3×10^8 m/s
Water	2.25×10^8 m/s

Glass	1.8×10^8 m/s

From the table, we can easily see that light travels with lesser speed through glass and water than it does through air. Therefore, we can say that water and glass are optically denser than air, or air is optically rarer than water and glass.

Refraction of light occurs because of this change in the speed of light due to a change in the medium. When light enters an optically denser medium from an optically rarer medium, the speed of light slows down and light bends towards the normal. The opposite happens when light enters an optically rarer medium from an optically denser medium.

The extent of bending of light depends on the **refractive index** of the medium. Refractive index (*μ*) of a medium is defined as the ratio of the speed of light in vacuum to that in the medium.

That is,

$$\boxed{\text{Refractive index } (\mu) = \frac{\text{Speed of light in vacuum}}{\text{Speed of light in the medium}}}$$

Therefore, an optically denser medium has a higher refractive index than an optically rarer medium. So, we can say that the refractive index of water is higher than that of air.

Factors affecting refracting index of a medium:

- Nature of the medium
- Temperature of the medium
- Wavelength of the light used

Grasshopper−Frog Relation

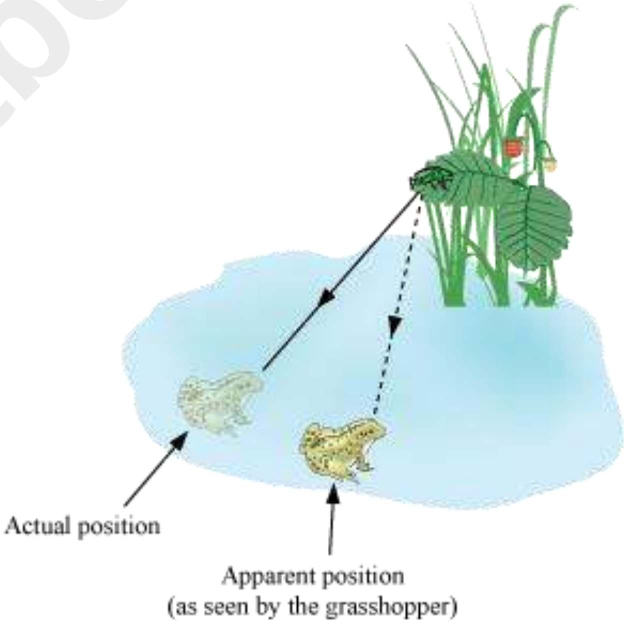
Consider a situation where a frog is sitting inside a pond (refractive index μ_2), while a grasshopper is sitting on a bush slightly above in air (refractive index μ_1), as shown in the given figure.

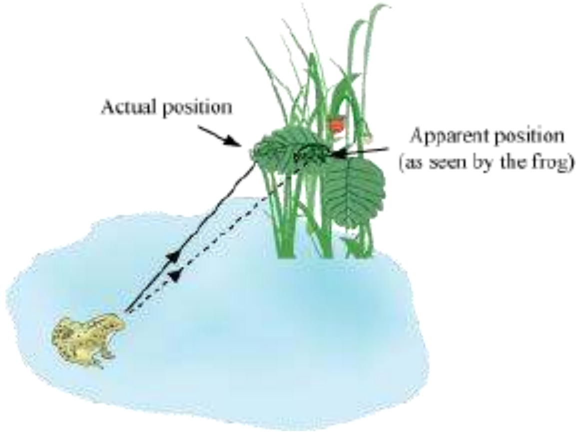
Two situations arise in this case.

Situation I

The grasshopper is looking towards the frog.

In this case, light is travelling from air to water. The refractive index of air (μ_1) is less than that of water (μ_2). Therefore, light gets slightly bent towards the normal. Hence, the frog appears closer to the grasshopper.





Situation II

The frog is looking towards the grasshopper.

In this case, light is travelling from a denser to a rarer medium as the refractive index of water (μ_2) is greater than that of air (μ_1). Therefore, light will bend away from the normal. Hence, the grasshopper appears farther to the frog.

Refraction Through Glass Slab

Laws of refraction

There are two laws of refraction.

First law of refraction

The incident ray, the refracted ray, and the normal to the interface of two media at the point of incidence – all lie in the same plane.

Second law of refraction

The ratio of the sine of the angle of incidence to the sine of the angle of refraction is constant, for the light of a given color and for given pair of media. This is known as **Snell's law**. Mathematically, it can be given as follows:

$$\boxed{\frac{\sin i}{\sin r} = \text{constant} = {}^{a}\mu_{b}}$$

Here, ${}^{a}\mu_{b}$ is the relative refractive index of medium b with respect to medium a.

Conditions for light ray to pass undeviated on refraction

- The angle of incidence of light ray at the edge of two media should be zero degree
- The refractive index of the two medium should be same

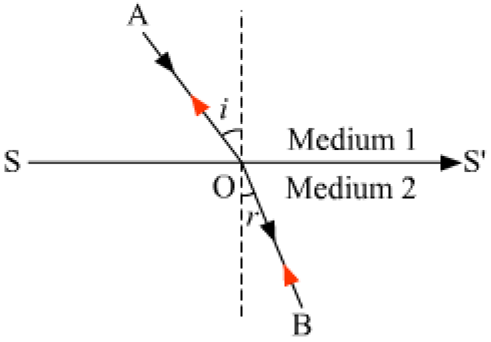
If any one of the above two conditions fulfils, then the ray of light will pass undeviated on travelling from one medium to another.

Principle of reversibility of path of light

Principle of reversibility states that the path of a ray of light is reversible. When a light ray AO travelling from rarer (medium 1) to denser medium (medium 2) is incident at an angle *i* to the surface separating the two media, it gets refracted along OB making an angle *r* with the normal to the surface. Thus, the refractive index of medium 2 w.r.t. medium 1 is

$$\mu_2^1 = \frac{\mu_2}{\mu_1} = \frac{\sin\ i}{\sin\ r} = \frac{v_1}{v_2} \quad .....(1)$$

where v_1 and v_2 is the speed of light in medium 1 and medium 2, respectively.



Principle of reversiblity

Similarly, if the light ray travels from denser to rarer medium along BO and incidents at the surface at an angle *r*, then it is going to get refracted only along the direction OA making an angle *i* with the normal in medium 1 and in no other direction than OA. Thus, the refractive index of medium 1 w.r.t. medium 2 is

$$\mu_1^2 = \frac{\mu_1}{\mu_2} = \frac{\sin\ r}{\sin\ i} = \frac{v_2}{v1} \quad .....(2)$$

From (1) and (2), we get

$$\mu_2^1 \times \mu_1^2 = 1$$

$$\Rightarrow \mu_2^1 = \frac{1}{\mu_1^2}$$

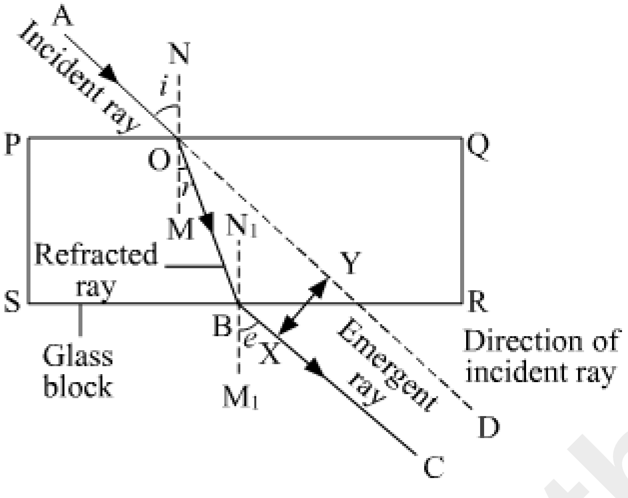
So, what are the key points of the experiment?

- When a light ray enters from air (rarer medium) to glass (denser medium), it bends towards the normal.
- When a light ray emerges from the glass (denser medium) to air (rarer medium), it bends away from the normal.

Since refraction occurs at two parallel surfaces RS and PQ, therefore angle $i_1 = r_2$ by the principle of reversibility of the path of the light ray. Hence, when a light ray is incident on a rectangular glass slab, the light ray emerges parallel to the incident ray from the opposite side of the slab.

Interestingly, when a light ray is incident on a glass slab normally, it gets out straight without any deflection i.e., i = 0, r = 0.

Lateral Displacement



Refraction through a rectangular glass block

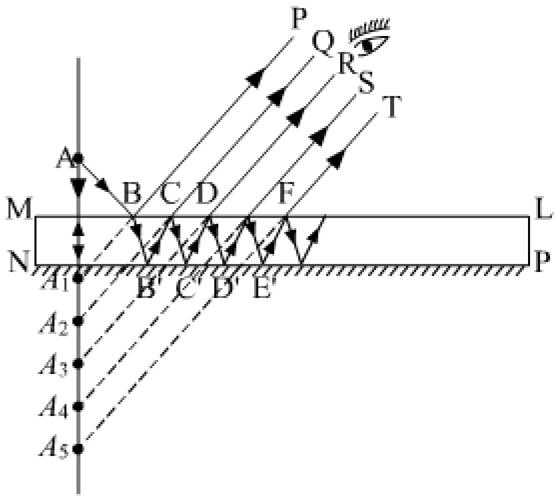
The path of the incident ray AO in the absence of glass block has been shown in the above figure by dotted line OD. Now, the incident ray AO is parallel to the emergent ray BC and is going in the same direction but not along the same line. It means emergent ray has been displaced by the rectangular glass slab. And the shortest distance between the path of emergent ray BC and the direction of incident ray OD is known as **lateral displacement** (here XY).

The lateral displacement is

- directly proportional to angle of incidence
- directly proportional to the thickness of the block or medium
- directly proportional to the refractive index of the medium. As refractive index increases with decrease in wavelength of light, this means lateral displacement increases with decrease in the wavelength of light.

Multiple images in a thick plane glass plate or thick mirror

When an illuminated object is placed in front of a plane glass mirror of adequate thickness and is viewed obliquely, a number of images are seen. And from all the images, the second image is the brightest, while rest are of decreasing brightness.



Multiple reflections in a thick mirror

Considering two rays from object A falls on the glass mirror MNPL. One ray is falling normally (AM) and the other ray (AB) obliquely on the given mirror. Now a small part of light ray AB is reflected in the direction of BP and forms a virtual image at A_1, while larger part of light is refracted along BB' inside the glass mirror.

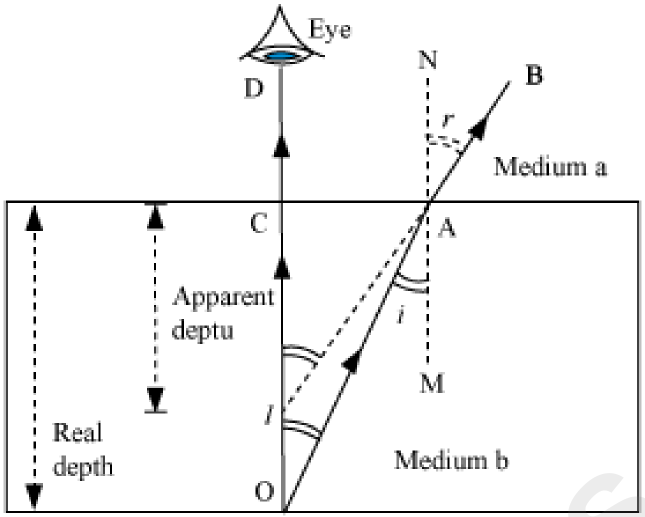
The ray BB' which strikes at B', is now strongly reflected back by the silvered surface PN inside the glass as B'C. Again, the ray is then partially refracted along CQ in air and partially reflected along CC' within the glass. The refracted ray CQ forms the virtual image A_2. The image A_2 is the brightest image because it is due to the light suffering a strong first reflection at the silvered surface PN.

In the similar manner, the ray CC' suffers multiple reflections at C', D, D' and so on and undergoes refractions at D, E, F and so on within the thickness of glass slab and thus give rise to multiple virtual images A3, A4, A5 and so on of gradually decreasing brightness.

Effects of Refraction

Refraction shows various effects in everyday life. Some of these effects are explained as under.

1. **Real and Apparent Depth**



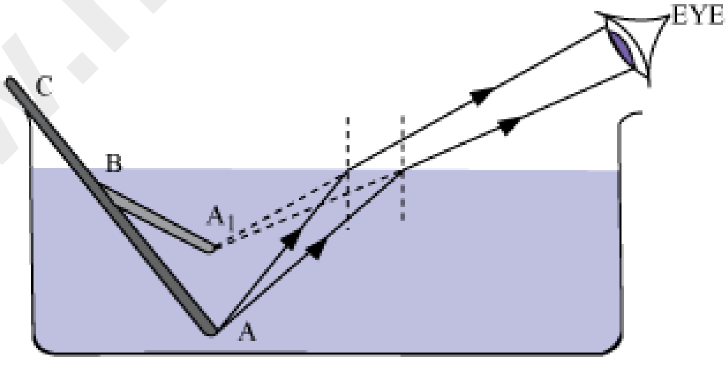
Real depth — the actual depth at which object is situated is called real depth.

Apparent depth — the depth at which image of the object is formed is called apparent depth.

As we can see in the figure that ‘b’ is denser medium than a thus the image formed is above the position of the object.

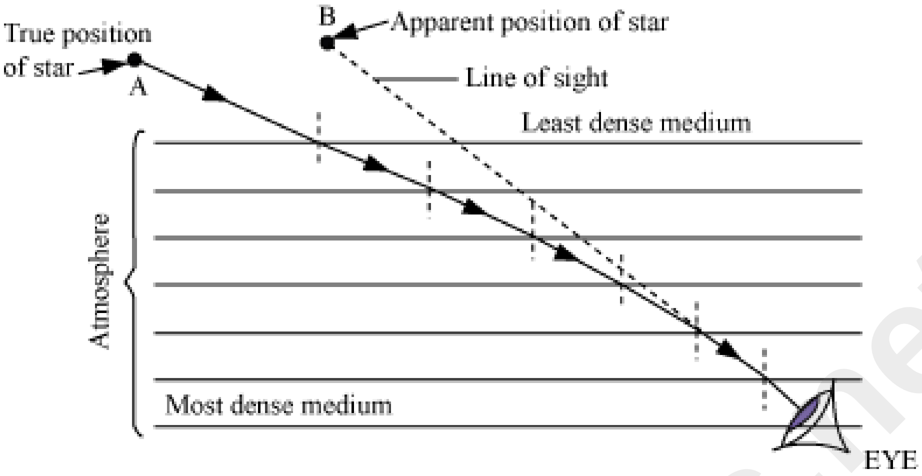
$$\text{Refractive index} = \frac{\text{Real depth}}{\text{Apparent depth}}$$

2. **Bending of Stick**



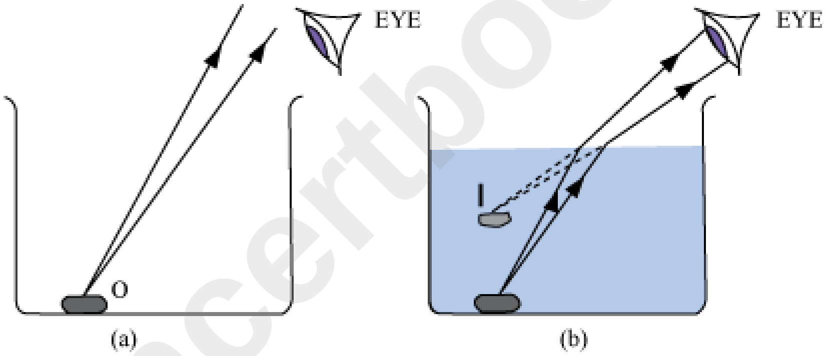
On the similar principle of refraction we see the stick bend and shorten when immersed in water.

3. **Twinkling of stars**



4. **Raised beaker bottom**

Stars appear to twinkle due to refraction at various layers of the atmosphere.

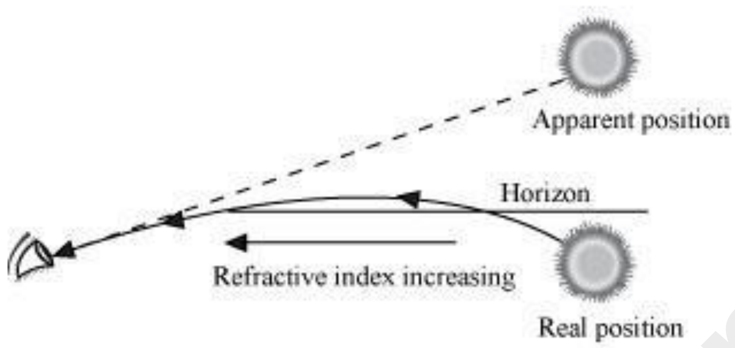


(a) (b)

5. **Early sunrise and delay sunset**

Sun appears a few minutes earlier before it actually rises above the horizon. Also, it is seen for a few minutes longer after it actually sets. The cause of these two phenomena is the atmospheric refraction.

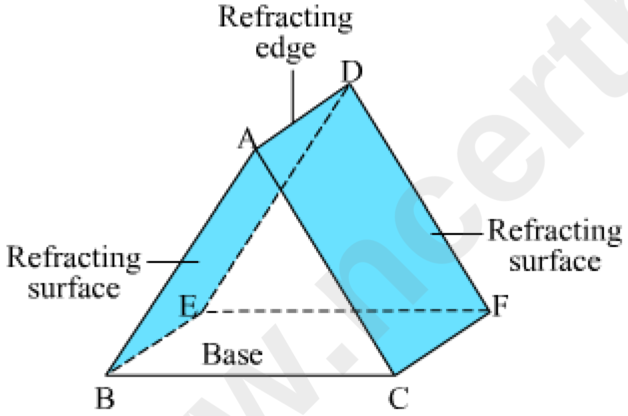
The layers near the Earth's surface are denser than those above. So, when the Sun is just below the horizon, the light ray coming from it, suffers refraction from a rarer to denser medium causing the light ray to bend towards the normal at each refraction. Due to this continuous bending of light rays, we are able to see the Sun even when it is actually below the horizon.



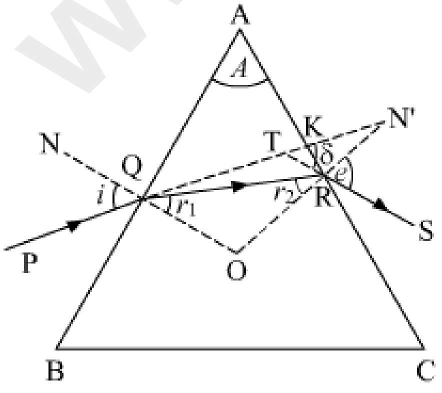
Refraction Through a Prism

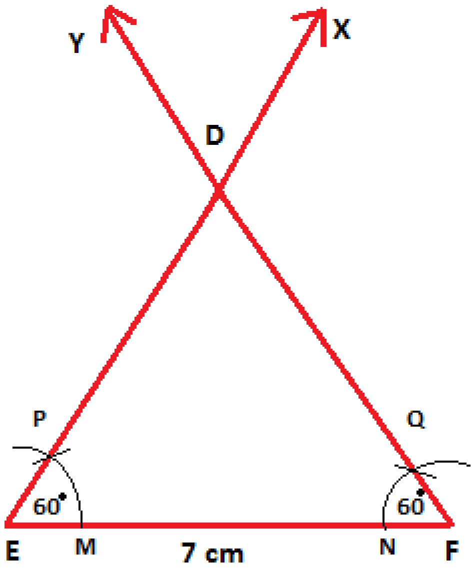
Prism

A transparent refracting medium which is bounded by five plane surfaces and having a triangular cross section is known as prism.



The figure below shows the passage of light through a triangular prism ABC.





The angles of incidence and refraction at first face AB are ∠i and ∠r_1.

The angle of incidence at the second face AC is ∠r_2 and the angle of emergence ∠e.

δ is the angle between the emergent ray RS and incident ray PQ and is called the angle of deviation.

Here, ∠PQN = i

$\angle SRN' = e$

∠RQO = r_1

∠QRO = r_2

∠KTS = δ

∵ ∠TQO = i and ∠RQO = r_1, we have

∠TQR = $i - r_1$

∠TRO = e and ∠QRO = r_2

∠TRQ = $e - r_2$

In triangle TQR, the side QT has been produced outwards. Therefore, the exterior angle δ should be equal to the sum of the interior opposite angles.

i.e, $\delta = \angle TQR + \angle TRQ = (i - r_1) + (e - r_2)$

$\delta = (i + e) - (r_1 + r_2)$ …(i)

In triangle QRO,

$r_1 + r_2 + \angle ROQ = 180°$ …(ii)

From quadrilateral AROQ, we have the sum of angles ($\angle AQO + \angle ARO = 180°$). This means that the sum of the remaining two angles should be 180°.

i.e , $\angle A + \angle QOR = 180°$ [$\angle A$ is called the angle of prism]

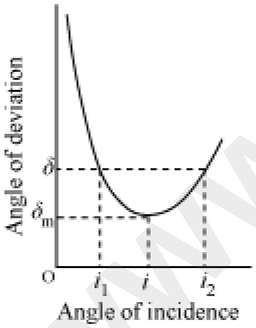
From equations (i) and (ii),

$r_1 + r_2 = A$ (iii)

Substituting (iii) in (i), we obtain

$\delta = (i + e) - A$

$A+\delta=i+eA+\delta=i+e$



If the angle of incidence is increased gradually, then the angle of deviation first decreases, attains a minimum value (δ_m), and then again starts increasing.

When angle of deviation is minimum, the prism is said to be placed in the minimum deviation position.

There is only one angle of incidence for which the angle of deviation is minimum.

When

$\delta = \delta_m$ [prism in minimum deviation position],

$e = i$ and $r_2 = r_1 = r$ …(iv)

$\because r_1 + r_2 = A$

From equation (iv), $r + r = A$

$r = A/2$

Also, we have

$A + \delta = i + e$

Setting,

$\delta = \delta_m$ and $e = i$

$A + \delta_m = i + i$

$$i = \frac{(A+\delta_m)}{2}$$

$$\because \mu = \frac{\sin\ i}{\sin\ r}$$

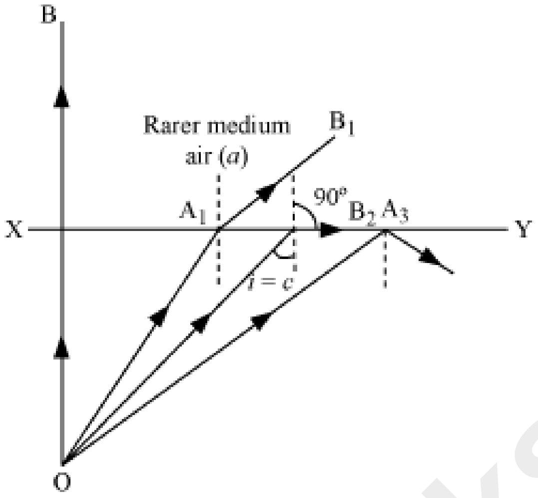
$$\therefore \mu = \frac{\sin\left(\frac{A+\delta_m}{2}\right)}{\sin\left(\frac{A}{2}\right)}$$

Factors affecting angle of deviation

- Angle of incidence (i)
- Angle of prism (A)
- Refractive index (μμ) of the material of the prism
- Colour or wavelength (λλ) of light

Total Internal Reflection

TOTAL INTERNAL REFLECTION



Total internal reflection is the phenomenon of reflection of light into a denser medium from an interface of the denser medium and the rarer medium.

Two essential conditions for total internal reflection:

- Incident ray should travel in the denser medium and refracted ray should travel in the rarer medium.

- Angle of incidence (*i)* should be greater than the critical angle for the pair of media in contact.

Relation between refractive index and critical angle (*C*):

When, $i = C$ and $r = 90°$:

Applying Snell's law at A_2,

$\mu_b \sin C = \mu_a \sin 90° = \mu_a \times 1$

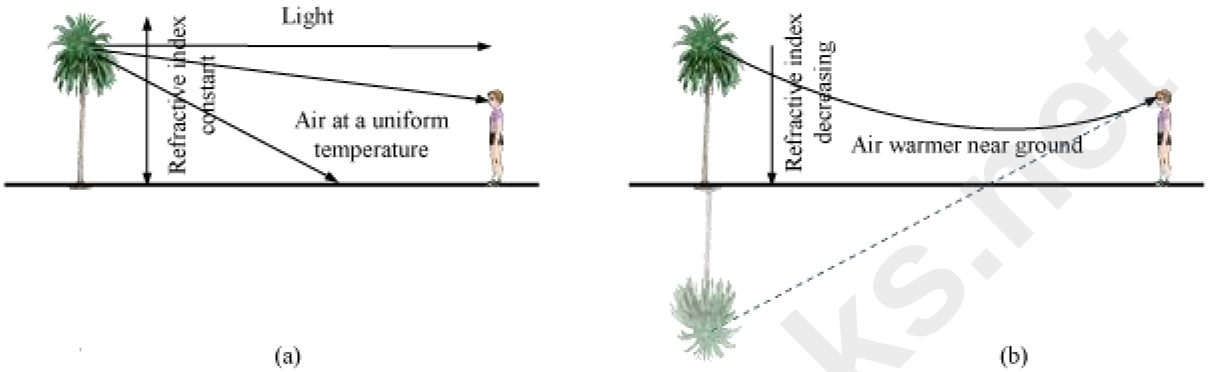
$$\frac{\mu_b}{\mu_a} = \frac{1}{\sin C}$$

$${}^{a}\mu_b = \frac{1}{\sin C}$$

Some applications of total internal reflection:

- **Brilliance of diamond** − The critical angle for diamond-air interface is 24.4°. The diamond is cut suitably, so that light entering the diamond from any face falls at an angle greater than 24.4°, suffers multiple total internal reflections at the various faces and remains within the diamond. Hence, the diamond sparkles.

- **Mirage** → It is an optical illusion in which an object, such as a tree, appears to be inverted.



This happens due to uneven heating of the different layers of air due to which density and refractive index of air go on increasing slightly with height above the surface of the earth.

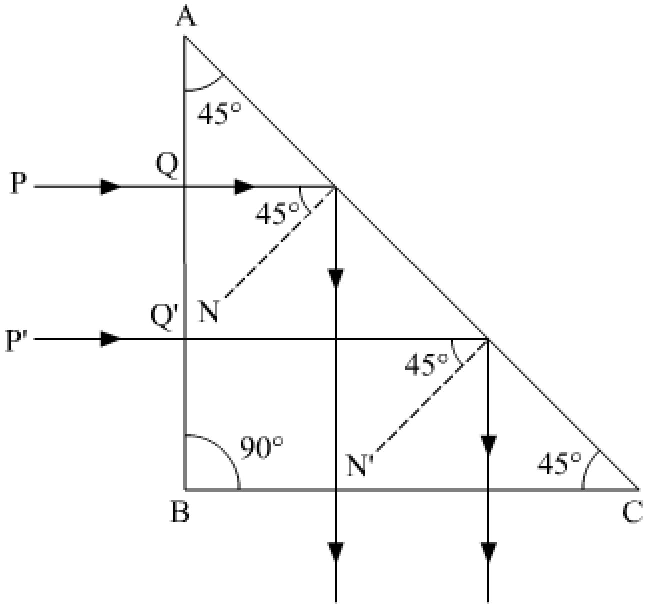
As a result of this, light from a tall object, such as a tree, passes through a medium whose refractive index decreases towards the ground. Thus, a ray of light undergoes total internal reflection. To a distant observer, the light appears to be coming from somewhere below the ground.

Total internal reflection through prism − When a ray of light falls normally on one of the surfaces of a right angled isosceles prism or an equilateral prism, then it is able to totally reflect the light ray internally.

Case I: Total internal reflection through an isosceles right angled prism: The prism can be used

(1) to deviate a ray of light through 90°
(2) to bend a ray of light through 180°
(3) to erect an inverted image without producing a deviation in its path

(1) Deviation of light ray through 90 degrees:

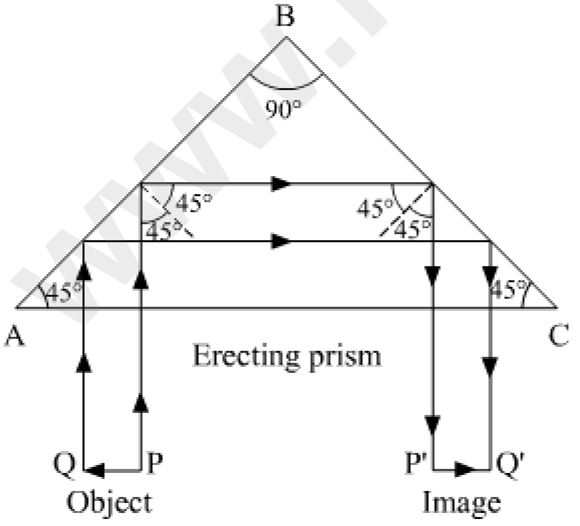


Deviation through 90°

A total reflecting prism ABC is used for deviating light through 90 degrees. A ray of light incident normally on the face AB, passes un-deviated into the prism and strikes the face AC at angle of incidence of 45 degrees. Now, the light suffers total internal reflection at face AC because the incidence angle is greater than the critical angle (for glass-air interface, critical angle is approximately equal to 42 degrees).

Now, the reflected beam inside the prism strike the face BC normally and therefore passes undeviated. Hence, the incident ray gets deviated by 90 degrees.

(2) Deviation of light ray through 180 degrees:

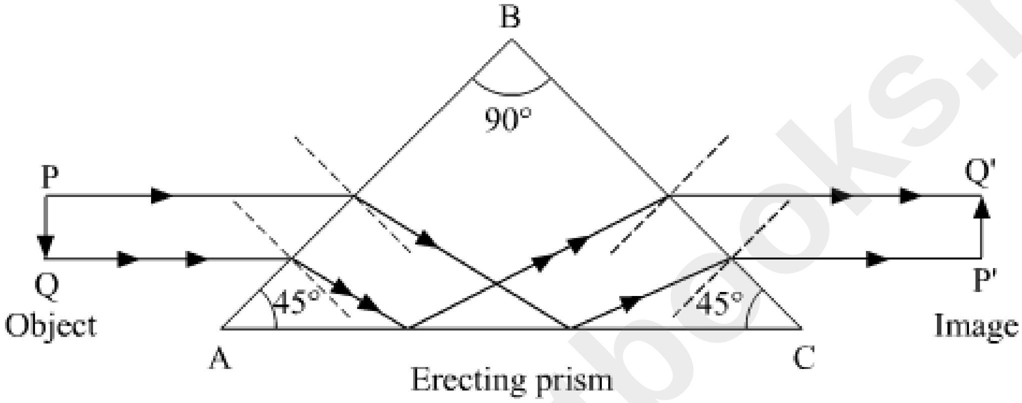


Deviation through 180°

In this case, when an object is placed in front of face AC, the incident rays fall normally on it and enter the prism un-deviated. Now, these rays incident on face AB at an angle of incidence of 45 degrees greater than critical angle of glass-air interface and suffer total internal reflection. The reflected beam inside the prism strikes the face BC with an angle of incidence equal to 45 degree greater than the critical angle and again suffers total internal reflection.

The beam now falls normally on the face AC and therefore passes un-deviated out of the prism, forming an image P'Q' of the object PQ. Hence, the incident ray gets deviated by 90 degrees at each reflection and therefore total deviation due to two reflection becomes 180 degrees.

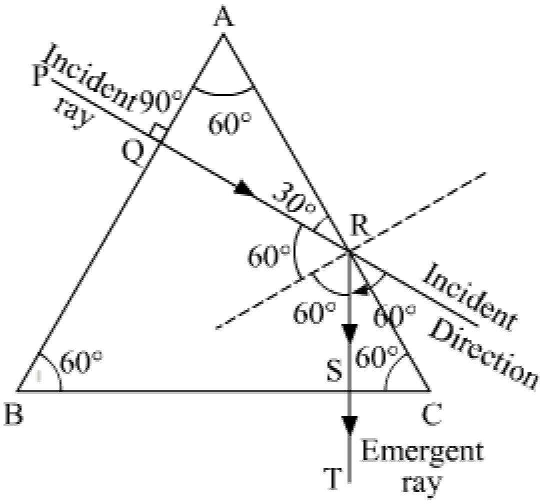
(3) Erection of inverted image without deviating path of light ray:



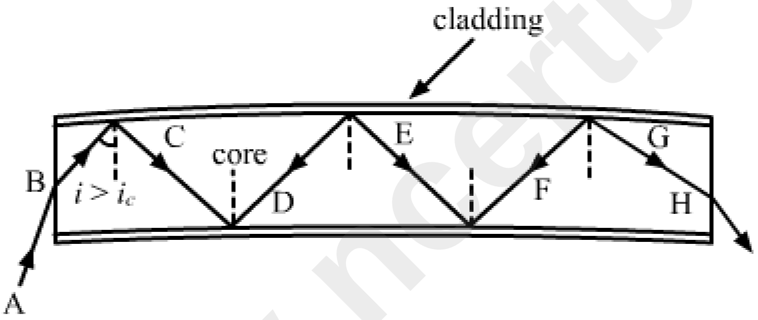
Here, the incident beam of an object PQ falls parallel to the face AC. It bends towards the normal at the air-glass interface AB and strikes the face AC of the prism. The incident angle of the beam at face AC is 45 degrees which is greater than the critical angle of the glass-air interface and thus the beam suffers total internal reflection at this face.

The totally reflected beam strikes the face BC at an angle less than the critical angle of glass-air interface and bends away from the normal at the interface. Hence, the beam emerges parallel to face AC as result of refraction. On emergence, the rays coming from the object PQ get inverted and thus an erect image P'Q' is obtained for PQ.

Case II: Total internal reflection through an equilateral prism: In this case, the incident ray bends through an angle of 60 degrees from its initail direction. This is shown in the figure below.



- **Optical fibres -** Optical fibres consist of thousands of very long thin fibres of fine quality glass or quartz. The central part of the fibres is made up of material with refractive index 1.7; it is called **core**.The fibres are coated with a material of refractive index 1.5 called **cladding**. Thus, the core is denser then the cladding.



Working:

When a ray of light is incident at one end of the fibre, it undergoes repeated total internal reflection inside the fibre. The only condition is that the light must be incident on the wall of the fibre at an angle greater then the critical angle. Thus, light finally comes out at the other end of the fibre without any loss in intensity.

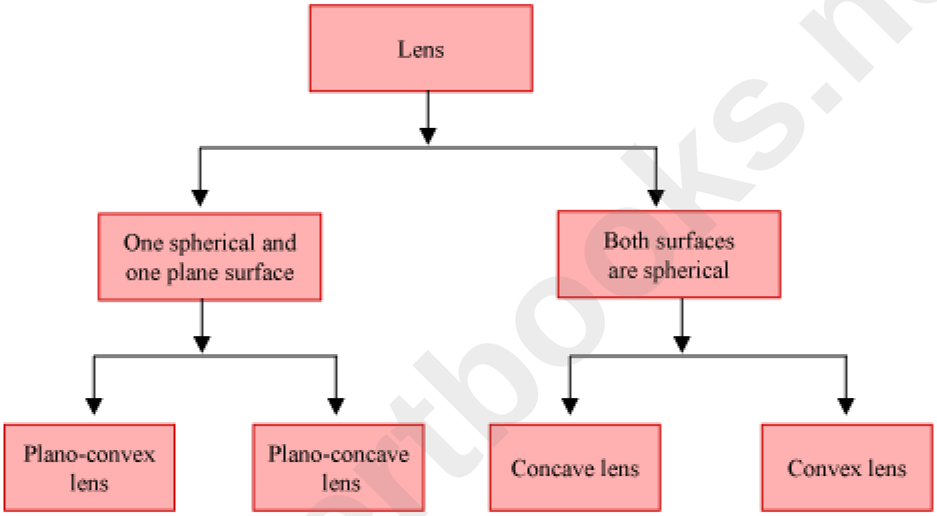
Uses:

- Optical fibres are extensively used for transmitting audio and video signals through long distances.
- They are used in endoscopes for medical examinations of inner parts of the body of a patient.

Refraction of Light by Spherical Lenses (Concave And Convex)

Ankit went to an optician and noticed different types of spectacles there. He observed that while the glasses of some spectacles were relatively thicker in the middle, other glasses were thicker on the edge. The glasses of these spectacles are examples of lenses.

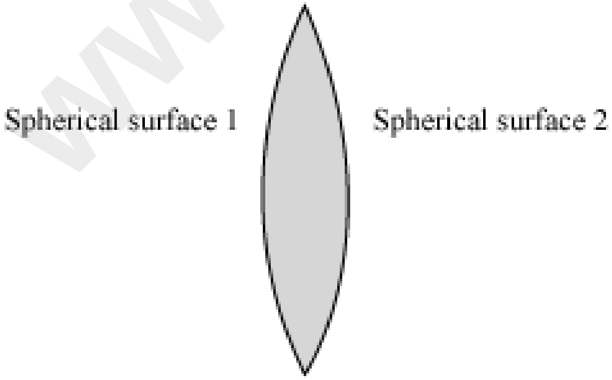
A lens is a transparent material bound by two curved surfaces. Lenses are broadly classified into two categories depending on their surfaces.



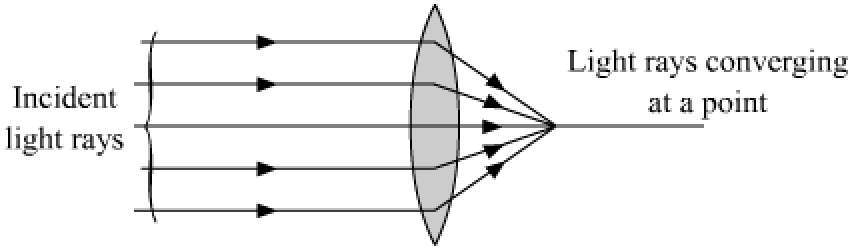
However, we will discuss only double spherical lenses here.

Convex lens

A convex lens is made by joining two spherical surfaces in such a way that it is thicker at the centre. Its thickness gradually reduces as we move towards the edge.



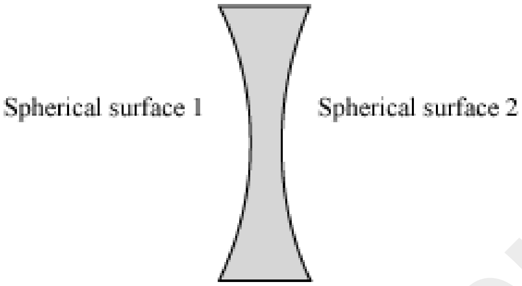
A convex lens



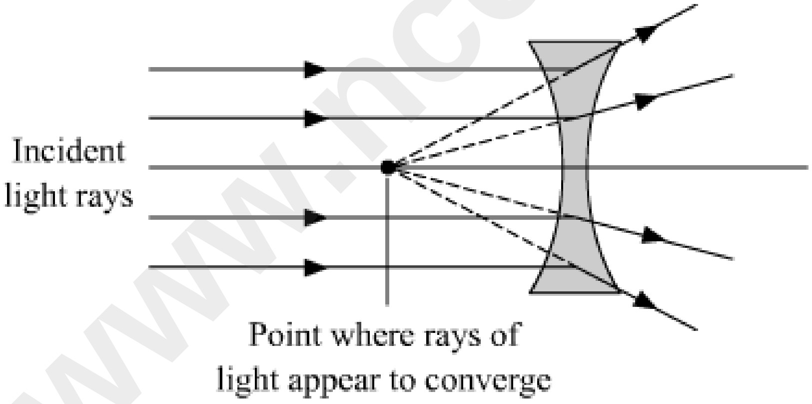
A convex lens has the ability to converge the light rays to a point that are incident on it. Thus, it is called a **converging lens**.

Concave lens

A concave lens is made by joining two curved surfaces in such a way that it is thinner at the centre. Its thickness gradually increases as we move towards the edge.



A concave lens



A concave lens has the ability to diverge a beam of light rays incident on it. Thus, it is called a **diverging lens**.

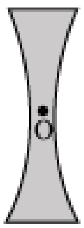
Differences between a spherical mirror and a lens

The following table lists some common differences between spherical mirrors and lenses

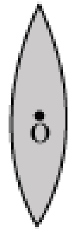
Spherical mirror	Spherical lens
Image is formed by reflection of light.	Image is formed by refraction of light.
A spherical mirror has only one focus.	A spherical lens has two foci.
The centre of the spherical mirror is termed as its pole.	The centre of the spherical lens is termed as its optical centre.

The second difference arises due to the fact that a lens has two spherical surfaces (i.e. it can be made from the arc of two spheres of equal radius).Therefore, light is refracted twice before it comes out of the lens.

Terms Associated with Lenses:



optical centre of a concave lens



optical centre of a convex lens

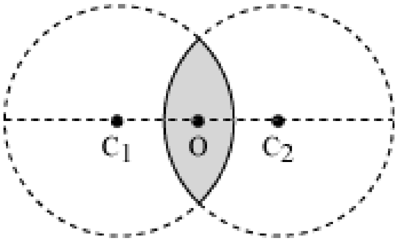
Optical centre

Optical centre is a point at the centre of the lens. It always lies inside the lens and not on the surface. It is denoted by **‘O’**.

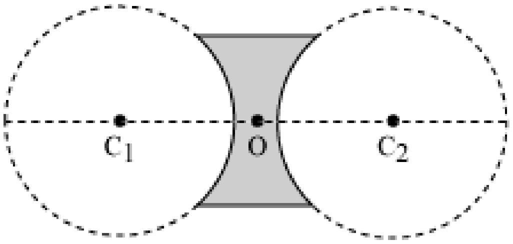
Centre of curvature

It is the centre point of arcs of the two spheres from which the given spherical lens (concave or convex) is made. Since a lens constitutes two spherical surfaces, it has two centers of curvature.

The distance of the optical centre from either of the centre of curvatures is termed as the **radius of curvature**.



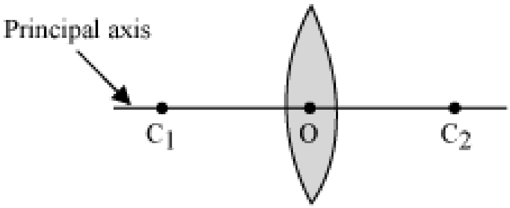
Centre of curvatures of a convex lens



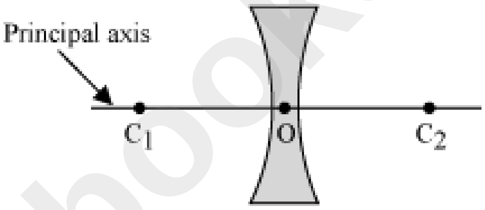
Centre of curvatures of a concave lens

Principal axis

The imaginary straight line joining the two centers of curvature and the optical centre **(O)** is called the **principal axis** of the lens.



Convex lens

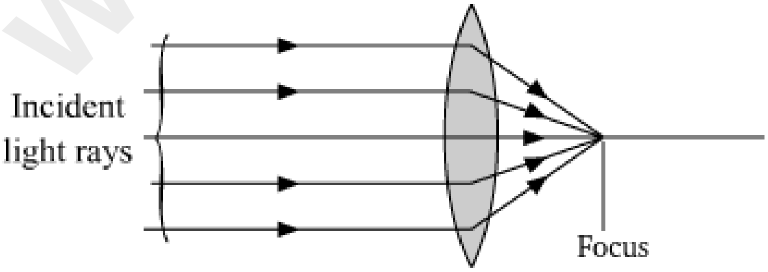


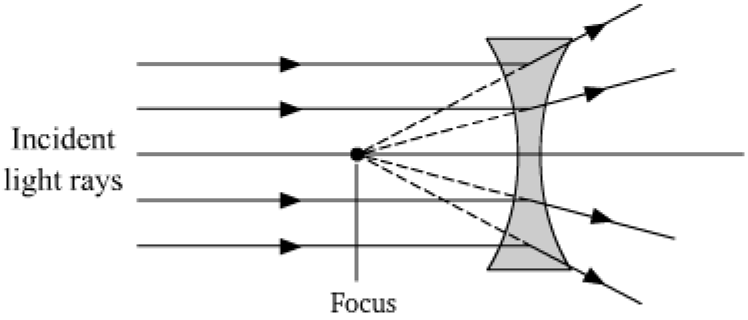
Concave lens

Hold a convex lens and direct it against the sunlight. You will find a bright spot appear on the wall. **Can you explain the formation of this bright spot?** Light, after refracting through the lens, converges at a very sharp point. Try to obtain the brightest possible spot. Now, place a paper on the wall and observe what happens in the next few minutes.

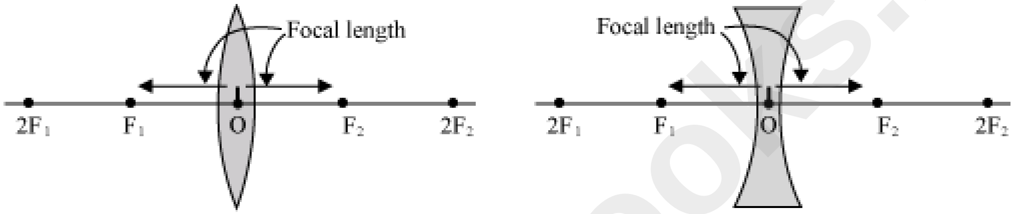
Focus

The focus **(F)** is the point on the principal axis of a lens where all incident parallel rays, after refraction from the lens meet or appear to diverge from. For lenses there are two foci (**F_1** and **F_2**) depending on the direction of incident rays.





The distance between the focus (**F_1** or **F_2**) and the optical centre (**O)** is known as the **focal length** of the lens.

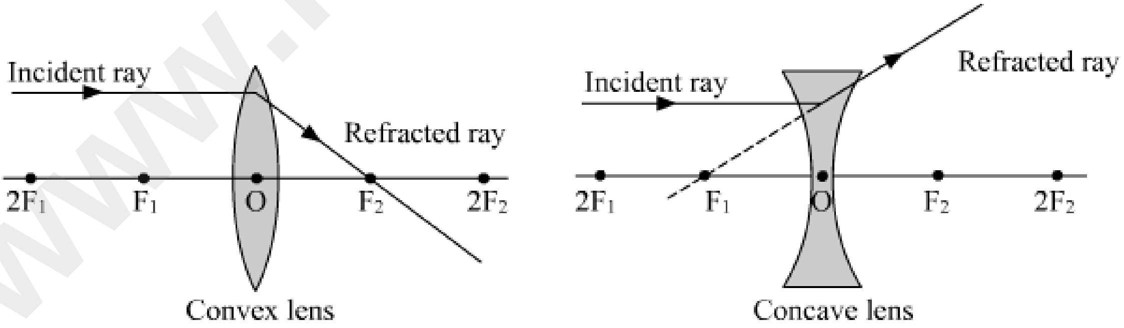


Refraction by Spherical Lenses

Refraction by a spherical lens can be categorized into three cases.

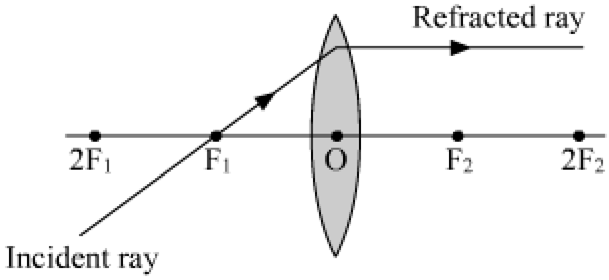
Case I. When the incident light ray is parallel to the principal axis

In this case, the refracted ray will pass through the second focus F_2 for a convex lens, and appear to diverge from the first focus F_1 for a concave lens.

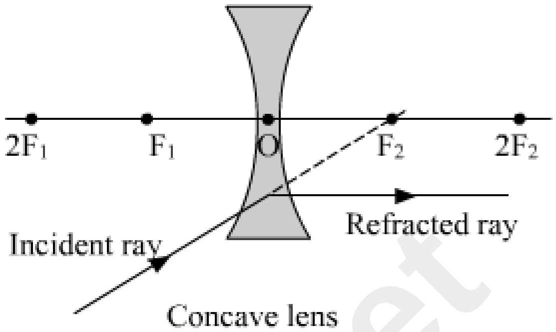


Case II. When the incident light ray emerges from the first focus F_1 of a convex lens, or appears to emerge from the second focus F_2 of a concave lens

In this case, light after refraction from both the lenses will move parallel to the principal axis.



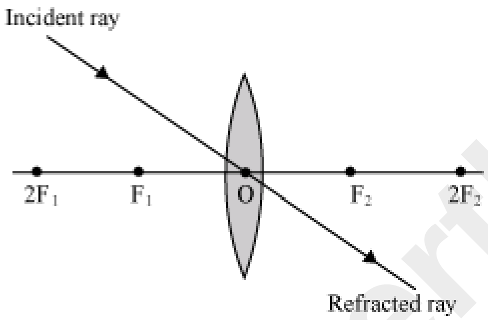
Convex lens



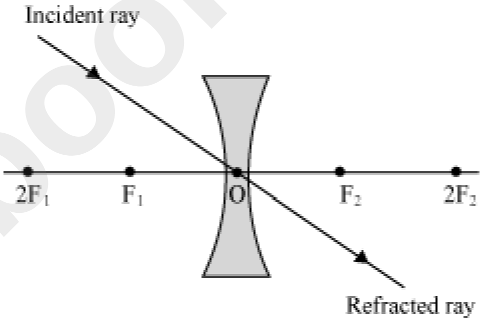
Concave lens

Case III. When the light ray passes through the optical centre (O) of a lens

In this case, the light ray will pass through both the lenses without suffering any deviation.

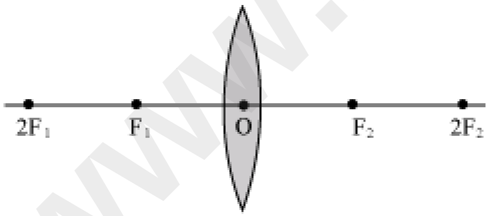


Convex lens



Concave lens

Image Formed by Spherical Lenses



Take a convex lens of known focal length. Draw five equidistant points on a table and put the lens on the central line. Mark the lines as $2F_1$, F_1, O, F_2, $2F_2$ (as shown in the figure).

Take a candle and placed it behind $2F_1$. Observe the nature and size of the image formed on a screen placed on the other side of the lens. An inverted image of the candle flame can be seen easily. Now, repeat the process by changing the position of the candle by bringing it towards the lens, and list your observations.

Lenses are able to form images by refracting incident light rays. Although, a light source emits infinite number of light rays in all possible directions, we will consider only two light rays for the sake of convenience. It allows us to show clearly the nature and position of the image formed on a screen.

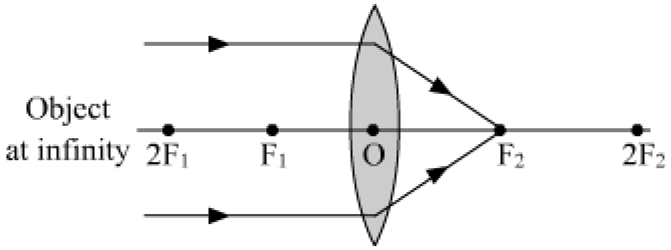
Images Formed by a Convex Lens

A convex lens can produce real as well as virtual images. The nature of the images formed depends primarily on the position of the object on the principal axis.

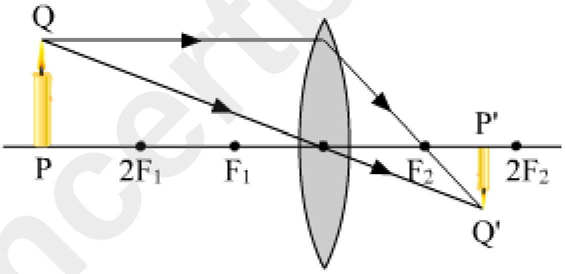
Consider the following cases:

The ray diagrams for all the cases are as follows:

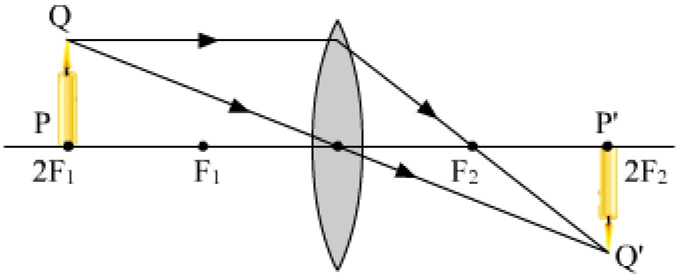
I. When the object is at infinity.



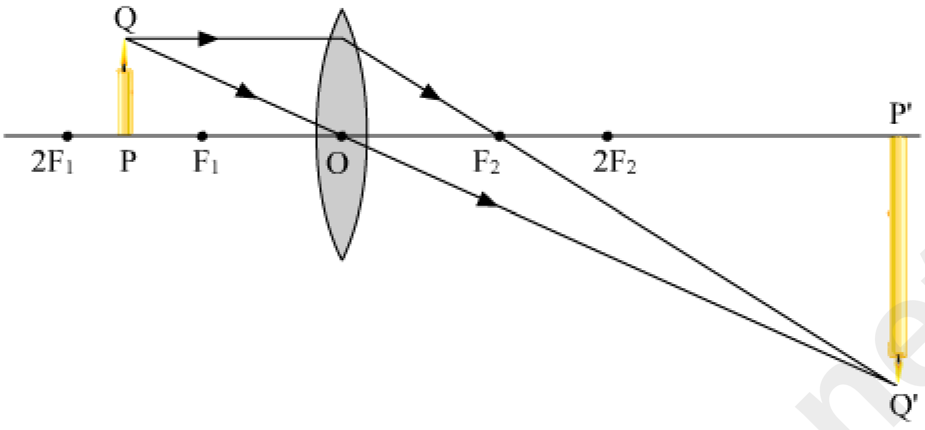
II. When the object is beyond the centre of 2F₁.



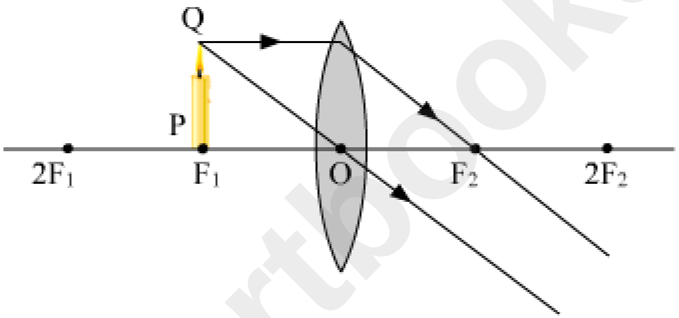
III. When the object is at the centre of curvature 2F₁.



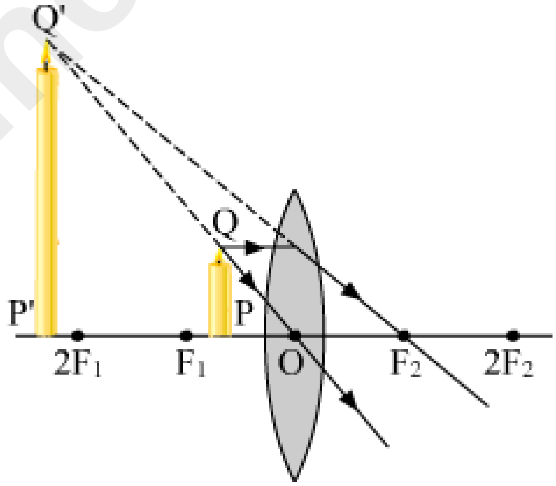
IV. When the object is placed between the focus F₁ and 2F₁.



V. When the object is placed at focus F1.



VI. When the object is placed between the focus F1 and optical centre O.



The position, size, and nature of the image formed by a convex lens can be summarized in the table below.

Object position	**Image position**	**Size of image**	**Nature of image**
At infinity	At F_2	Extremely small	Real and inverted
Behind $2F_1$	Between F_2 and $2F_2$	Small	Real and inverted
At $2F_1$	At $2F_2$	Same as that of the object	Real and inverted
Between $2F_1$ and F_1	Beyond $2F_2$	Enlarged	Real and inverted
At F_1	At infinity	Highly enlarged	Real and inverted
Between F_1 and O	Same side of the lens	Enlarged	Virtual and erect

Images Formed by a Concave Lens

A concave lens always produces virtual and erect images that are extremely small in size.

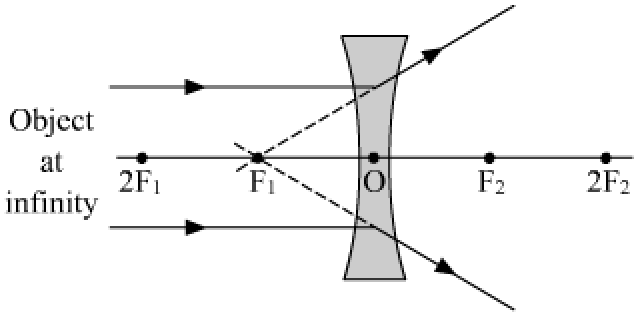
The images formed by a concave lens are divided into two cases.

I. When the object is placed at infinity.

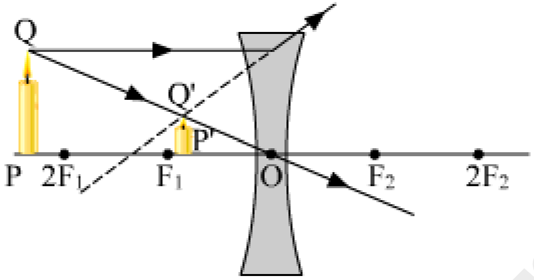
II. When the object is placed beyond $2F_1$.

The ray diagrams for all the cases are as follows:

I. When the object is placed at infinity.



II. When the object is placed beyond 2F₁.



The position, size, and nature of the image formed can be summarized in the table as follows:

Object position	Image position	Size of image	Nature of image
At infinity	At focus F_1	Extremely small	Virtual and exact
Between O and X (X lies beyond $2F_1$)	Between O and F_1	Small	Virtual and exact

Jai places a sharp edge in front of a spherical lens. He observes that the image formed is inverted and extremely small in size. **Can you guess the nature of the lens used and the position of the edge? Where should he place this edge to obtain an erect image?**

Lens Formula, Magnification, and Power

Usually in image formation, we are interested in calculating **the distance of the image formed from the lens, size of the image, power of the lens etc**. These problems can be solved with the help of a lens formula. For this, we use a set of sign conventions applicable for refraction of light by spherical lenses. In this convention, the optical centre (**O)** is treated as the origin.

Sigh Convention for Lenses

I. Object is always placed to the left of the lens i.e., the light must fall on the lens from left to right.

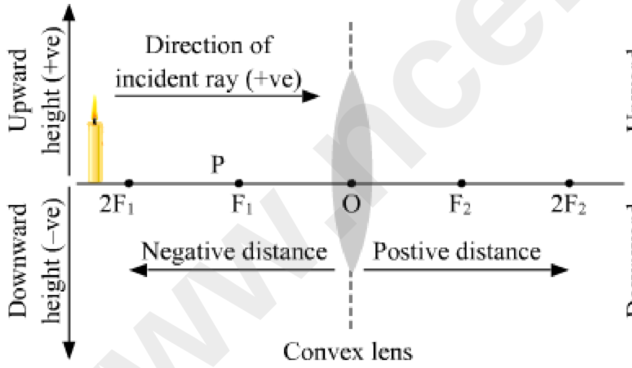
II. All distances parallel to the principal axis are measured from the optical centre of the lens.

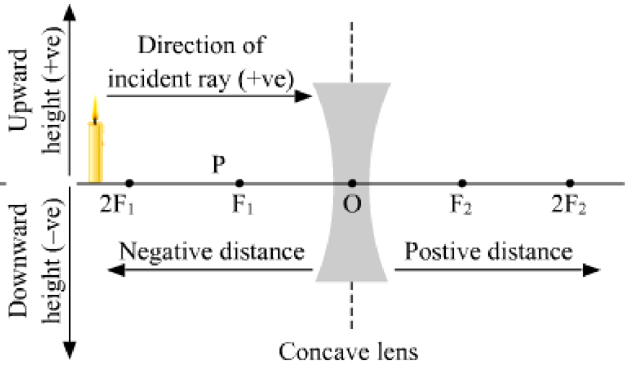
III. Distances along the direction of incident rays (along positive *x*-axis) are taken as positive, while distances opposite to the direction of incident rays (along negative *x*-axis) are taken as negative.

IV. Distances measured above the principal axis (along positive *y*-axis) are taken as positive.

V. Distances measured below the principal axis (along negative *y*-axis) are taken as negative.

These sign conventions are represented in the following diagram:





The following table summarizes the sign conventions of concave and convex lenses:

Types of lens	**Object distance (*u*)**	**Image distance (*v*)**		**Focal length (*f*)**	**Height of object (H_o)**	**Height of image (H_I)**	
		Real	**virtual**			**Real**	**Virtual**
Convex	Negative	Positive	Negative	Positive	Positive	Negative	Positive
Concave	Negative	*	Negative	Negative	Positive	*	Positive

***** A Concave lens always forms a virtual image.

Lens Formula:

The lens formula is given by

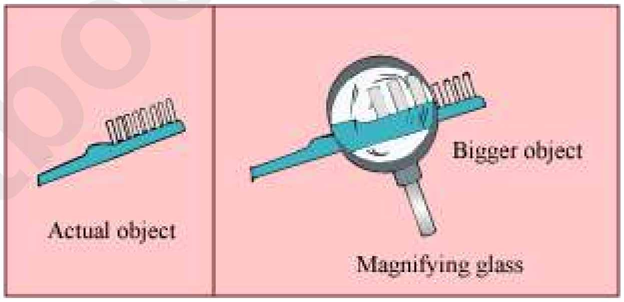
$$\frac{1}{f}=\frac{1}{v}-\frac{1}{u}$$

Here,

f → focal length of the spherical lens

v→ distance of the image from the optical centre

u → distance of the object from the optical centre

Deepak takes a magnifying glass and tries to look at some objects through it. He observes that the objects look bigger than their actual size. **How is this possible?**	

The apparent change in the size of the object is because of the magnification produced by the lens.

Magnification

The magnification of a spherical lens gives the relative extent to which the image of an object is magnified with respect to the object size.

Magnification is expressed by the ratio of the image height (H_I) to the object height (H_O).

$$m=\frac{\text{Image height }\left(H_I\right)}{\text{object height }\left(H_O\right)}=\frac{H_I}{H_O}$$

Magnification (*m*) is also related to the object distance (*u*) and image distance (*v*) by the relation

$$m = \frac{\text{Image distance}}{\text{Object distance}}$$

$$m = \frac{v}{u}$$

Hence, the magnification formula can be written as

$$m = \frac{H_I}{H_o} = \frac{v}{u}$$

- If magnification is positive, the image will be virtual and erect.
- If magnification is negative, the image will be real and inverted.

Power of a Lens

The degree of converge/diverge a beam of light rays by a lens is expressed in terms of its **power** (***P***). It is the inverse of focal length, ***f*** (in metres).

Hence, power of a lens is given by the relation

P=1f (in metres)P=1f (in metres)

The SI unit of power is **dioptre** (**D)**.

Power of Combination of Thin Lenses in Contact

When two or more lenses are placed in contact with each other the net power (*P*) of the combination is given by the algebraic sum of the individual powers of the lenses.

Net power, $P = P_1 + P_2 + P_3 + ...$

Example 1:

A convex lens has a focal length of 10 cm. If the image produced by it is 15 cm behind from the optical centre, then determine the distance at which the object is placed? Also, find the magnification produced by the lens.

Solution:

For the given convex lens,

Focal length (f) = 10 cm

Image distance (*v*) = 15 cm

Object distance (*u*) =?

Using the lens formula:

$$\frac{1}{f}=\frac{1}{v}-\frac{1}{u}$$
$$\frac{1}{10}=\frac{1}{15}-\frac{1}{u}$$
$$\Rightarrow\frac{1}{u}=\frac{1}{15}-\frac{1}{10}$$
$$=\frac{10-15}{15\times10}=\frac{-5}{150}$$
$$\frac{1}{u}=-\frac{1}{30}\Rightarrow u=-30\text{ cm}$$

Here, the negative sign indicates that the object was placed to the left of the lens.

Now magnification, $m=\frac{v}{u}$

$$=\frac{15}{-30}$$
$$=-0.5$$

Hence, the image size will be half of the object size. The negative sign of magnification implies that the image formed is real and inverted.

What will be the image distance if an object is placed at a distance of 30 cm before a concave lens of focal length 10 cm?

Example 2:

What is the power of a convex mirror whose focal length is 25 cm?

Solution:

Power = $\frac{1}{f\left(\text{In meters}\right)}$

Given that focal length, *f* = 25 cm

$= \frac{25}{100}$ = 0.25 m

$$\therefore\ P = \frac{1}{0.25\ \text{m}} = \frac{100}{25} = 4\,\text{D}$$

Hence, power of the given lens is 4 **D**.

Note that if the lens was concave, then the focal length would have been, $f = -25$ cm = −0.25 m

In this case, power will be −4 **D**.

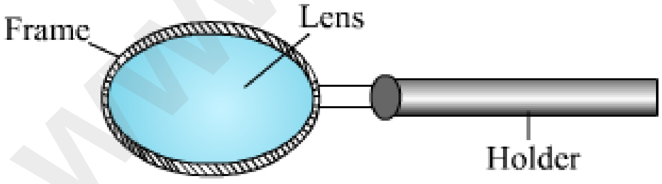
Magnifying Glass or Simple Microscope

Simple Microscope or Magnifying Glass

An eye is not able to see a object distinctly, which when placed at a least distance of distinct vision (*D)* from the eye, subtends an angle less than 1' (1/60°) at it because the size of image formed on the retina for this object is very small. This is because the size of the image of an object on the retina is decided by the angle subtended at the eye by the object.

Smaller the angle subtended by the object, smaller will be its image size on the retina. So, a simple microscope is used to see such small object distinctly which subtends an angle smaller than 1' when placed at *D* from the eye.

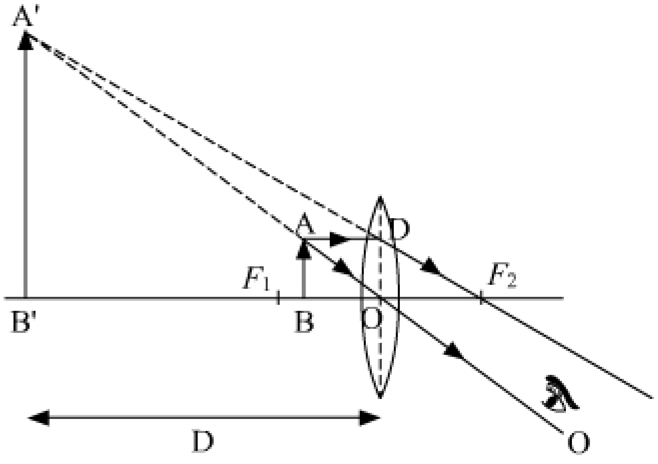
Construction : It uses a convex lens of short focal length which is mounted in a lens holder.



Magnifying glass (or simple microscope)

Principle: Simple microscope is placed in front of our eye at such a distance that the object lies within the focal length of its lens so as to enable the lens to form an erect, virtual and magnified image on the same side and behind the object at a distance *D*. This image is now seen distinctly by our eye because magnified image is subtending an angle greater than 1' on the eye.

Ray diagram of the image formed by a convex lens



Ray diagram for location of image in a magnifying glass

An object AB, let say a small word, is placed in between the optical centre (O) and focus (F_1) of the convex lens such that its image A'B is formed at the least distance of distinct vision i.e. *D*. Here, the rays AD and AO when refracted by convex lens do not actually meet, but they appear to meet at point A' when produced backward.

Hence, A' is the virtual image of point A and similarly B' is the virtual image of point B. Therefore, we get a virtual and magnified image of the object. To observe the image, the eye is kept very near to the lens on the other side of the object as shown in the ray diagram.

Magnifying power (*m*) of a simple microscope or magnifying glass

$$m = 1 + \frac{D}{f} \text{.....(1)}$$

where *f* is the focal length of the lens and *D* is the least distance of distinct vision. Form the equation (1), we note that the magnifying power of a simple microscope can be increased using a convex lens of shorter focal length.

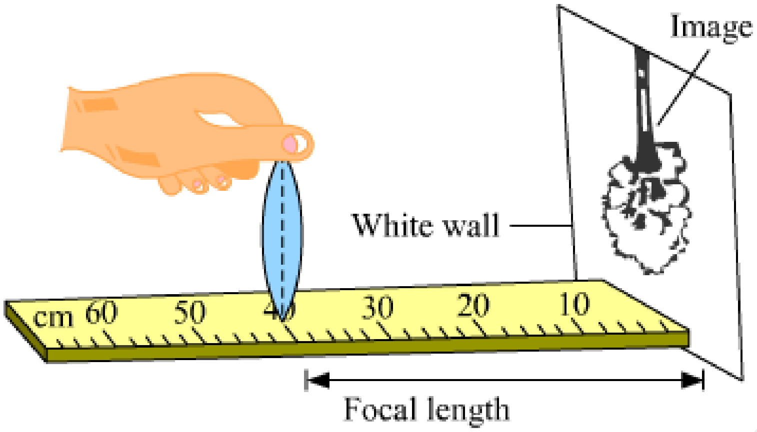
Uses of simple microscope

- To read small letters
- Used by watch makers while manufacturing and repairing watches
- In optical instruments such as travelling microscope, spectrometer, etc. as a reading lens to read the vernier scale accurately.

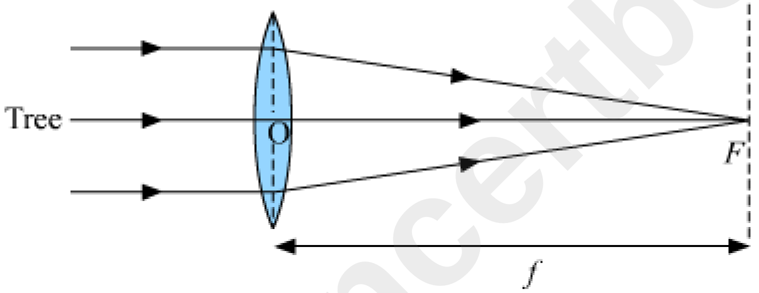
Experimental determination of focal length of convex lens by different methods

(1) Distant object method:

Principle: A beam of parallel rays from a distant object incident on a convex lens gets converged in the focal plane of lens.



Determination of focal length of a convex lens by the distant object method

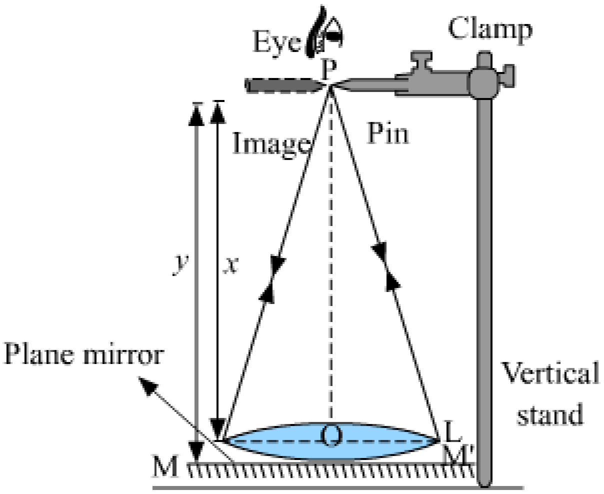


Ray diagram showing the focal length of a convex lens

Method: Using a metre scale, a convex lens, a screen (a wall) and distance object (a tree), we can easily find the focal length of a convex lens. Place the metre scale horizontally with its 0 cm touching the screen and its other end towards the distant object. Now, hold the given lens vertically on a metre scale and adjust its position so as to focus the distant object on the screen.

Since, the incident light rays from a distant object are nearly parallel to the principal axis of the convex lens, the image formed on the screen is almost at the focus of the lens. This gives us the approximate value of the focal length of the lens.

(2) Auxiliary plane mirror method:



Determination of focal length of a convex lens by an an auxilary plane mirror

This method gives the exact focal length of the convex lens under observation. In this method we use a vertical stand, a plane mirror, a convex lens and a pin. The arrangement has been shown in the above figure. In the arrangement, it should be taken care that the tip of the pin P is vertically above the centre O of the lens L.

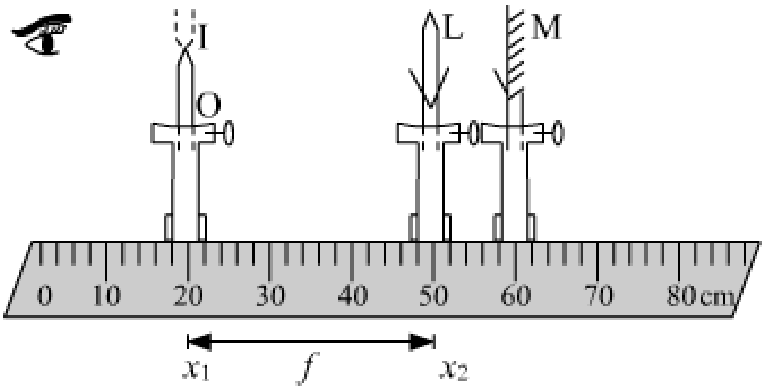
Here, we adjust the height of the pin till it has no parallax with its inverted image as seen from vertically above the pin. To check that there is no parallax we need to keep the eye vertically above the tip of the pin P at a distance nearly 25 cm from it and move it sideways. If the pin and its image, shift together, then there is no parallax.

Now, measure the distance *x* and *y* using the measuring tape. Then, calculate the average of the two distances which would give us the focal length of the lens i.e.

$$f = \frac{x+y}{2}$$

(3) One pin method using an optical bench

This is an alternative method to find the exact focal length of a convex lens by placing a plane mirror (M), a convex lens (L) and an object pin (O) on separate vertical stands of an optical bench. The setup is shown in the figure below.



Determination of focal length of a convex lens by one pin method using an optical bench

Adjust the height of the object pin (O) such that it lies at the centre of the convex lens (L). Now, move the object pin away from the lens on the optical bench till its inverted image is seen at the least distance of distinct vision (*D*) when viewed by keeping the eye behind the object pin (O).

Now, adjust the object pin position such that its tip coincides with the tip of its inverted image and in such a situation if the eye is moved sideways, then both the tip of the object pin and tip of the image will appear to move together.

Note down the readings x_2 and x_1 and take their difference. This difference will give us the exact value of focal length of the lens i.e.

$f = x_2 - x_1$

Application of Lenses

- A convex lens is used as an objective lens in telescope, camera, slide projector, etc.
- Eye has lens which is convex in nature.
- A convex lens is used in a simple microscope and collimator of a spectroscope.
- A concave lens is used in the Galilean telescope as an objective lens to obtain the final erect image of an object.
- Spectacles having concave lens is worn by people suffering myopia. (Myopia is an eye defect in which person is unable to see distant object clearly)

Two methods to differentiate a convex lens from a concave lens

- By touching: If the lens is thick in the middle and thin at the edges, the lens is convex and if the lens is convex is thin in the middle and thick at the edges, the lens is concave.
- By seeing the image: On placing the lens near a printed page, if letters appear magnified, the lens is convex and if the letters appear diminished, the lens is concave.

Composition of White Light

Chandu was surprised when he came to know that white light is actually a combination of lights of different colours.

On rainy days, you see a rainbow in the sky. You must have seen colours reflecting on the surface of a compact disc (CD) in the presence of sunlight. You might have wondered where these colours come from.

The common point among the above examples is the presence of sunlight. To understand these phenomena, it is necessary to learn about the composition of sunlight.

Composition of sunlight

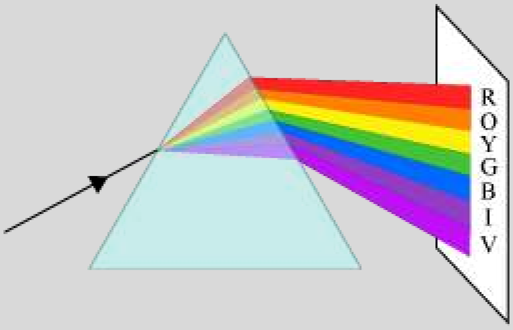
The seven coloured disc that you have seen in the activity is known as **Newton Disc.**

So, you have learned that light emitted by the sun is composed of **seven** different colours. These colours are red, orange, yellow, green, blue, indigo and violet.

You can remember the seven colours of sunlight by the mnemonic **VIBGYOR**. Each letter represents the initial letters of the colours.

Newton and his Prism

Isaac Newton (1642 − 1726) was one of the greatest physicists and mathematicians that the world has ever seen. He was the first scientist to resolve white sunlight into its component colours. He used a transparent optical object called prism, which is made of glass, to separate the seven colours of white light. He allowed sunlight to enter a dark room through a hole. He then placed a prism to obstruct sunlight inside the room. He saw a band of seven colours on the dark wall. He published a paper depicting his findings about the constituent colours of white light.



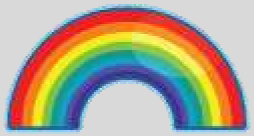
Try to obtain and observe the seven colours using a prism. Now, place a red transparent plastic sheet in front of sunlight. Are you able to see the seven colours? Perform similar experiments using other coloured transparent sheets. **What do your findings suggest?** Discuss the result with your friends.

On placing a red transparent sheet in front of sunlight, you observe that the spectrum of colours vanishes and only red-coloured light is obtained on the screen. Similarly, you will obtain only blue-coloured light on the screen for a blue transparent sheet and so on.

Try to observe the seven colours of sunlight on the surface of a soap bubble.

Take a wide tub filled with water and place it in sunlight. Observe the surface of water carefully. Is any colour of sunlight visible? Now, pour five to ten drops of petrol in water. Petrol will spread over the entire surface of water. Observe the water surface carefully. You will observe that the colours of a rainbow are present in the tub. **Is it correct to infer that petrol can act as a prism?** Discuss and confirm this with your teacher.

A rainbow appears in the sky only when it rains. Which substance or object acts as a prism to separate the various components of sunlight to form a rainbow?



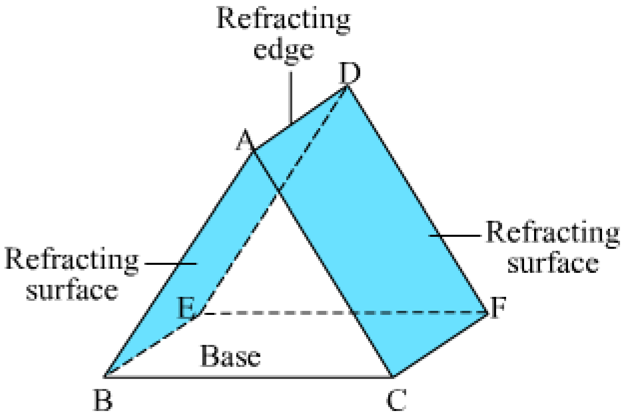
Dispersion of White Light in Prism

When a ray of light is incident on a rectangular glass slab, after refracting through the slab, it gets displaced laterally. As a result, the emergent ray comes out parallel to the incident ray. **Does the same happen if a ray of light passes through a glass prism?**

Unlike a rectangular slab, the sides of a glass prism are inclined at an angle called the angle of prism. Therefore, a ray of light incident on its surface, after refraction, will not emerge parallel to the incident light ray (as seen in the case of a rectangular slab).

Prism

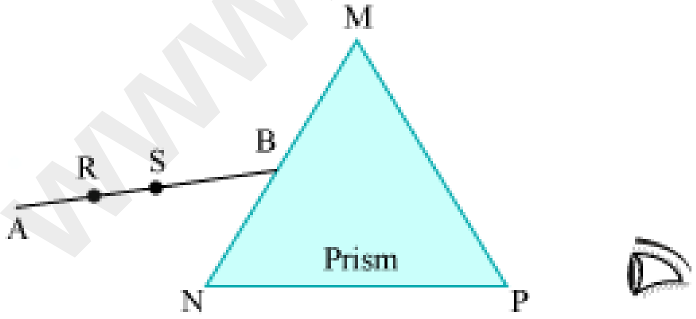
A transparent refracting medium which is bounded by five plane surfaces and having a triangular cross section is known as prism.



Refraction of light through a glass prism

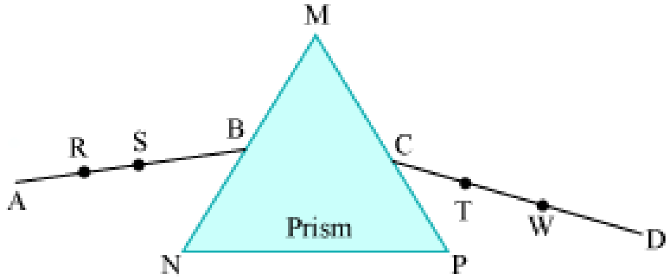
To observe the refraction of light through a glass prism, we can perform the following activity.

Take a triangular glass prism, paper sheet, and a few drawing pins. Fix the sheet on a drawing board with the help of drawing pins. Now, place the glass prism on the sheet and draw the outline **MNP** of the prism on the sheet (as shown in the figure). Draw a straight line **AB** on the sheet in such a way that it makes some angle with the face **MN** of the prism. Now, fix two pins on this line and mark them as **R** and **S** respectively.

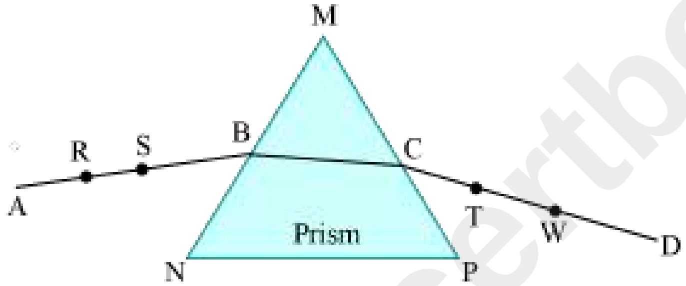


Now, observe the pins **R** and **S** through the other side of the prism. Move your head laterally to see the two pins **R** and **S** in a straight line. Fix a pin on the sheet near the prism on your side and mark it as **T**.

Repeat the same step and try to observe the three pins **R, S**, and **T** in a straight line. Fix another pin on the sheet so that all four pins appear to be in a straight line when looked through the prism. Draw a straight line **CD** that passes through the third and the fourth pin i.e., **T** and **W** respectively (see figure).



Now, remove the prism and join points **B** and **C**. The straight line **AB**, **BC**, and **CD** shows the path of the light ray. It is clear that the path of light is not a straight line since light bends towards the base **NP**.



What causes the light to bend when passed through a prism?

Light bends because of refraction that takes place at points **B** and **C** respectively, when it tries to enter and emerge from the prism.

Now, draw a straight line HH' normal to side **MN** and let it pass through point **B**. Similarly, draw a straight line GG' normal to side **MP** and let it pass through point **C**.

Here, line AB = Incident ray

Line BC = Refracted ray

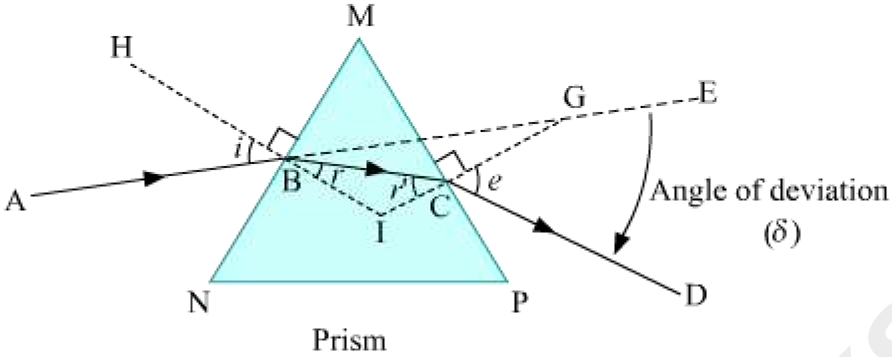
Line CD = Emergent ray

Angle *i* = Angle of incidence

Angle *r* = Angle of refraction

Angle *e* = Angle of emergence

Angle δ = Angle of deviation



Hence, you will get the path of light ray **AB** when it travels through a glass prism. The ray **AB** will bend towards the normal **HI** at point **B** and follow the path **BC**. Again, it bends away from the normal **GI** at **C**, when it tries to emerge from the prism. This is because the refractive index of air is less than that of glass. Thus, the incident ray **AB** will not follow a straight line **BE.**

The extent of deviation of the light ray from its path BE to path CD is known as the angle of deviation (δ).

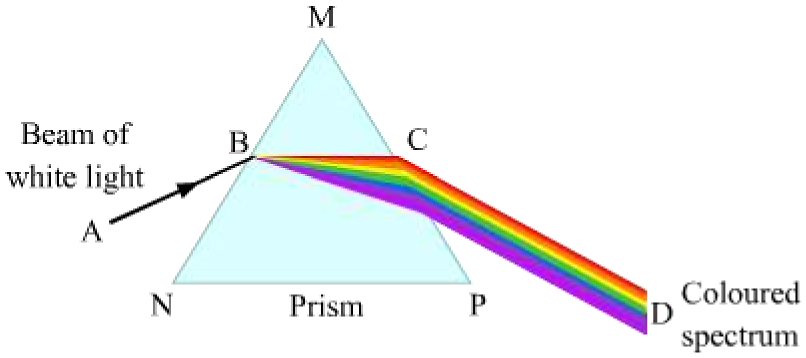
Do you know what happens when you take white light as incident ray instead of single ray?

A beam of white light will split into a band of seven colours. The splitting of a beam of white light into its seven constituent colours, when it passes through a glass prism, is called the **dispersion of light.**

Dispersion of white light by a prism

Isaac Newton was one of the greatest mathematicians and physicists the world ever saw. In 1665, with the help of an experiment he showed that white sunlight is actually a mixture of seven different colours. These constituent colours of white light can be separated with the help of a glass prism.

Take a glass prism and allow a narrow beam of sunlight to fall on one of its rectangular surfaces. You will obtain a coloured spectrum with red and violet colour at its extreme. Try to obtain a sharp coloured band on the screen by slightly rotating the prism. Count the colours of the band and write the sequence of the colours.



Do you know why white light gets dispersed into seven colours?

When a beam of white light AB enters a prism, it gets refracted at point B and splits into its seven constituent colours, viz. violet, indigo, blue, green, yellow, orange, and red. The acronym for the seven constituent colours of white light is VIBGYOR.

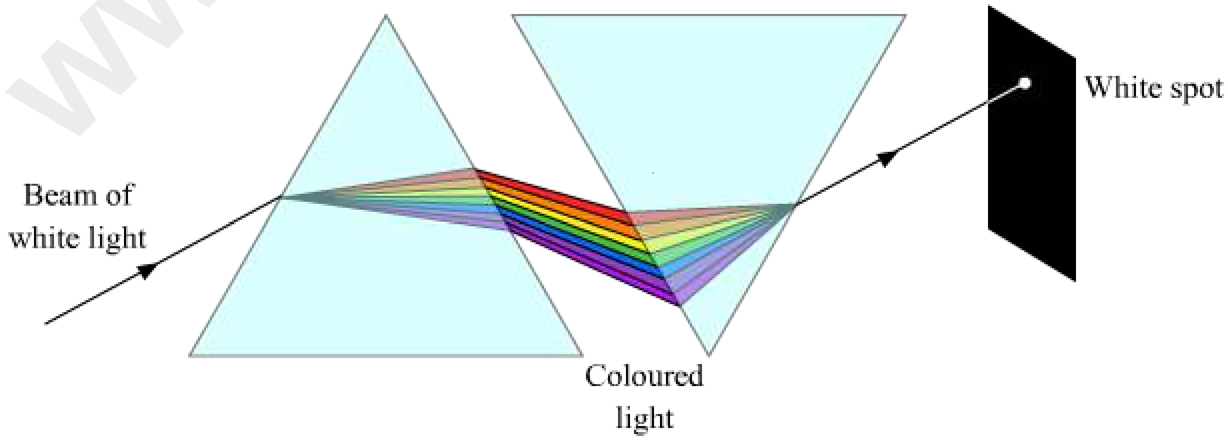
This splitting of the light rays occurs because of the different angles of bending for each colour. Hence, each colour while passing through the prism bends at different angles with respect to the incident beam. This gives rise to the formation of the colour spectrum.

Can you say which colour undergoes maximum deviation?

Violet light bends the most whereas red colour deviates least.

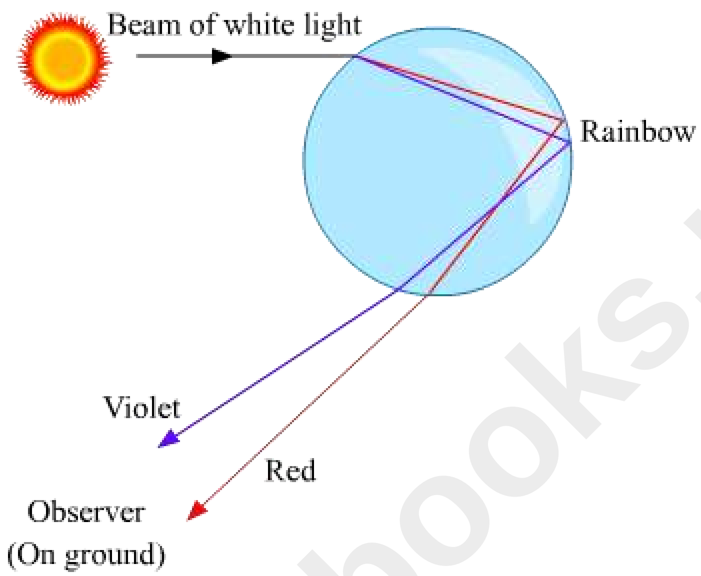
However, Newton did not stop at this point. He thought that if seven colours can be obtained from a white light beam, **is it possible to obtain white light back from the seven colours?**

For this, he placed an inverted prism in the path of a colour band. He was amazed to see that only a beam of white light comes out from the second prism. It was at this point that Newton concluded that white light comprises of seven component colours.



Formation of a rainbow

The rainbow is a natural phenomenon in which white sunlight splits into beautiful colours by water droplets, which remain suspended in air after the rain.



Let us see how a rainbow is actually formed.

If we stand with our back towards the sun, then we can see the spectrum of these seven colours.

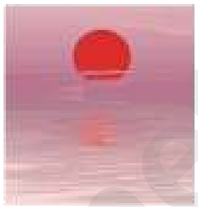
Do you know why a rainbow is shaped similar to an arc?

This is because the rainbow is formed by the dispersion of white light by spherical water droplets. It is the shape of the water droplets that gives the rainbow an arc shape.

A rainbow appears arc-shaped for an observer on ground. However, if he sees the rainbow from an airplane, then he will be able to see a complete circle. This is because he can observe the drops that are above him as well as below him.	

Scattering of Light

Do you know why the sky appears blue in colour? What causes the water, which is colourless, to appear blue in the ocean? What do you think about the red colour of the sun at sunrise and sunset?



These natural phenomena are governed by the scattering of sunlight through suspended air particles present in it from random directions. Scattered sunlight may be white or of any component of the seven colours, depending on the size of the particles that cause the scattering. This phenomenon is governed by the **Tyndall effect**.

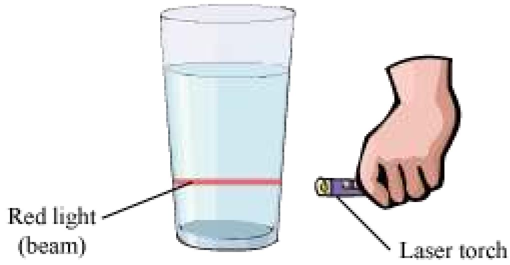
Tyndall effect

The Tyndall effect is caused by the scattering of light by very small air particles, which are suspended in the Earth's atmosphere. To observe the Tyndall effect, the particles diameter should be less than $\frac{1}{20}$ th of the wavelength of the light used.

This effect can be seen when light enters through a hole in a dark room filled with dust particles. **Have you looked at light rays coming through clouds, holes, or headlight beams during a foggy night?** These are some well known examples of the Tyndall effect.

Do You Know:

John Tyndall (1820-1893) was one of the most distinguishing physicists of the 19th century. He was the first person to explain the reason behind the appearance of sky as blue. The Tyndall effect, named after him, shows that light is scattered by the particles of the medium. His other contributions are in the field of geology and physics.



Take few mL of milk in a transparent glass and dilute it with water to make it appear cloudy. Now, take a laser torch and point the beam through the solution. Observe the solution. **Does the path of laser beam become visible in the solution? Why?**

You are able to see the path of laser light because of the scattering of laser beam by the suspended particles of milk in the solution. This is another example of the Tyndall effect.

The colour of the scattered light depends on the particle size.

- Fine particles mainly scatter blue light.
- Large particles scatter red light.

- It is observed that blue colour light scatters more easily than red colour light. This is because red colour light is of a longer wave length.

Some natural phenomena related to the Tyndall effect

1. Blue colour of the sky

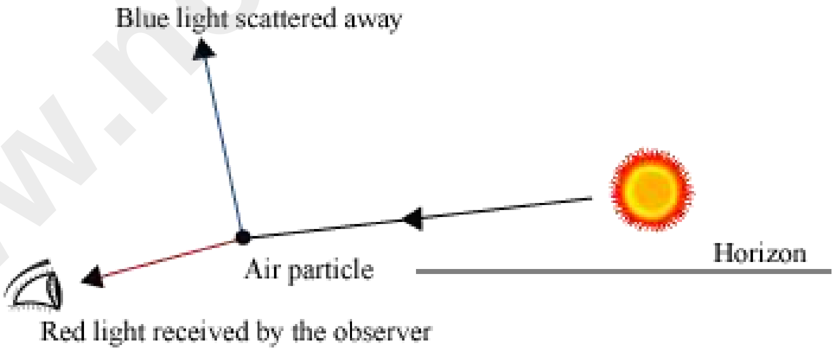
Can you tell what colour will the sky appear to be for an astronaut travelling in deep space?

If there was no atmosphere on the Earth, there would no scattering of light. Hence, in deep space, the sky will appear to be dark.

The least scattering red colour light finds its application in various fields. For example, in marking red light, danger signals etc. red colour is preferred because it is scattered least by fog, smoke, and dust particles present in air.

2. Sunrise and sunset

At sunrise or sunset, the sun is located near the horizon of the Earth. Hence, light has to travel a long distance through the Earth's atmosphere. At the time of sunrise or sunset, when white sunlight falls on suspended atmospheric particles, blue colour light scatters out in deep space, while red colour light scatters less, and reaches the observer on the surface of the Earth. Hence, when this less scattered red light reaches our eyes, the sun and its surroundings appear to be reddish.



When located overhead, why does not the sun appear reddish in colour?

This is because light travels a relatively shorter distance when located overhead. Because of this reason, scattering of blue as well as red light is much less when the sun is located overhead.

Do You Know:

- When there is no impurity present in air, the colour of the sun at sunrise and sunset appears to be yellowish. Due to the presence of salt particles in air over seas and oceans, the colour of the sun at sunrise or sunset appears to be orange.

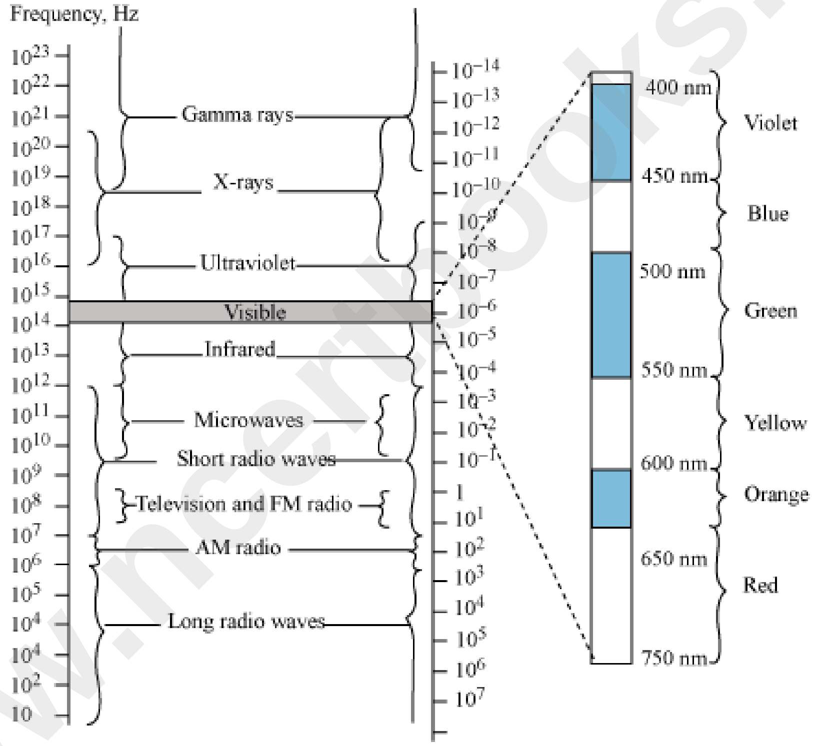
- Due to the presence of red iron-rich dust, the sky appears red from the Martian surface. All these natural phenomena take place due to the scattering of sunlight

Electromagnetic Spectrum

DIFFERENT TYPES OF ELECTROMAGNETIC WAVES			
Type	**Wavelength range**	**Production**	**Detection**
Radio	> 0.1 m	Rapid acceleration and decelerations of electrons in aerials	Receiver's aerials
Microwave	0.1 mm to 10 cm	Klystron valve or magnetron valve	Point contact diodes
Infra-red	0.4 mm to 750 nm	Vibration of atoms and molecules	Thermopiles, bolometer, infrared photographic film
Light	750 nm to 400 nm	Electrons in atoms emit light when they move from one energy level to a lower energy level.	The eye, photocells, photographic film
Ultraviolet	400 nm to 1 nm	Inner shell electrons in atoms moving from one energy level to a lower level	Photocells, photographic film

X-rays	10 nm to 10^{-2} nm	X-ray tubes or inner shell electrons	Photographic film, Geiger tubes, ionisation chamber
Gamma rays	$<10^{-2}$ nm	Radioactive decay of the nucleus	-do-

Different Types of Electromagnetic Waves



Uses of Electromagnetic radiations:

Light: It has very important role in our life. Human eye is sensitive to only this visible part of electromagnetic radiations. Anything which we able to see is because of the light.

(i) **Gamma rays:** These were first discovered radioactive emitted radiation. They are also present in cosmic radiations. Gamma rays have extensive applications,

* Most energetic electromagnetic radiations of wavelength less than 0.01 nm.

* These are used in the treatment of cancer.

* Used in γ-ray microscope.

* Acts as catalyst in the manufacturing of some chemicals.

* These are used to produce photoelectric effect.

* These rays are also used in radiography.

(ii) **X-rays:** William Rontgen was awarded Nobel prize in 1901 for his discovery of X-rays. X-rays are used in,

* Wavelength range between 0.01 nm to 10 nm.

* Fractured bones are located by the X-rays.

* X-rays are used in the treatment of cancer and skin diseases.

* These rays used to locate foreign bodies such as bullets, coins, pins etc in human body.

* X-rays are used in radiography.

* They are also used in the study of crystal structure.

(iii) **Ultraviolet radiations:** These rays were detected by J.W. Ritter in 1801. These are harmful to living tissues and are absorbed by the ozone layer present in our atmosphere. Its applications are,

* Wavelength range between 10 nm to 400 nm.

* UV rays are used as efficient sterilizers.

* UV rays are used to activate some chemical reactions.

* These are used in fluorescent lamps.

* UV rays used in identifying real gems and artificial gems.

* They are used in the treatment of skin diseases, diseases of the bone and rickets.

* They are used in synthesizing vitamin-D in our body.

* They are also used in the operation of photoelectric alarms.

(iv) **Visible light:** The electromagnetic radiations of wavelength from 400 nm to 800 nm are known as visible light. This part of the spectrum has been discovered by Newton by passing sunlight through a prism. Its applications are

* In photography

* In photosynthesis

* In enabling us to see objects around us

(v) **Infrared radiations:** It has heating effect which was first detected by W. Herschel in 1800. Its applications are,

* Wavelength range between 800 nm to 1 mm.

* Infrared spectrum is used to identify and determine molecular structure of a compound.

* Found suitable for long distance photography.

* Infrared photography is used to determine enemy movement during war, examine and detect forgery in old paintings

* These rays has a role in medical field, these are useful in the diagnosis of superficial tumours, dislocation of bones and in the treatment of sprains.

* It stimulates blood circulation.

* TV remote also uses infrared rays to control different settings.

* Infrared radiations from sun are used in the working of solar energy devices.

(vi) **Microwaves:** These are vastly used for experimental purposes. Also find applications in Radar, Satellite communication and microwave ovens.

* Wavelength range between 1 mm to 10 m.

* Found suitable for long distance photography.

* Infrared photography is used to determine enemy movement during war, examine and detect forgery in old paintings.

* These rays have role in medical field. These are useful in the diagnosis of superficial tumors, dislocation of bones and in the treatment of sprains.

* It stimulates blood circulation.

(vii) **Radio waves:** As there name suggest, these waves are used in radio and television.

* Wavelength range above 10 m.

* Short wavelength radio waves are used in communication systems including satellite systems, Radars and TV broadcasting.

* Longer wavelength radio waves are used in radio broadcasting.