Light – Refraction

REFRACTION OF LIGHT
Three different things happen when light hits a surface, it can be **reflected** (bounce off), **absorbed** or **transmitted** (pass through). Substances which transmit most of the light and only absorb or reflect a little bit are called **transparent**. Substances which completely reflect or absorb light without transmitting any are called **opaque**. Some substances, such as the plastic shopping bag, allow some light to pass through, but not all of it. This substance is **translucent**, or **semi-transparent.**

Opaque Objects
Objects through which we cannot see anything are called opaque objects. A medium that does not allow light to pass through it is called an opaque medium. Examples of opaque objects are **wood**, stone, and metals(iron). Most objects in our surroundings, like buildings and trees, are opaque objects.

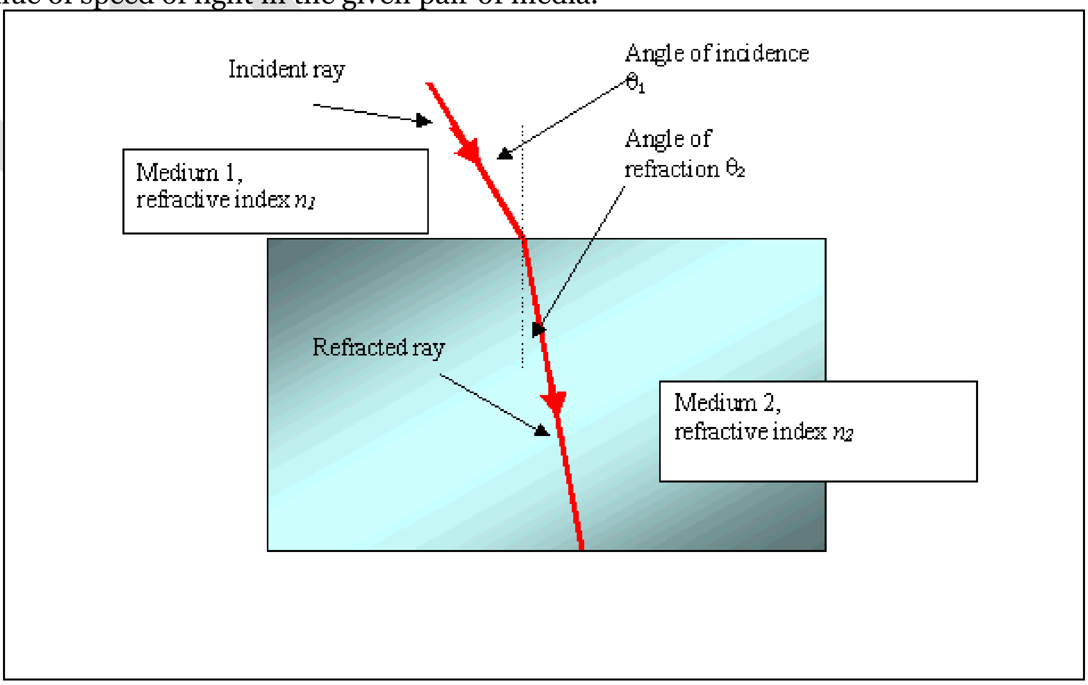
Transparent Objects
Objects through which we can see clearly are called transparent objects. A medium that allows all the light incident on it to pass through it is called a transparent medium. Examples of transparent objects are pure water, kerosene, turpentine. Glass, for example, is transparent to all visible light.

Translucent Objects
Objects through which we cannot see the objects on the other side clearly but can see some light are called translucent objects. A medium that allows only a part of the light incident on it to pass through it is called a translucent medium. Examples of translucent objects are ground glass, frosted glass, smoked glass, sun glasses and butter paper and some **plastics**

Refraction is a phenomenon of bending of light when it travels from one medium to another.
The refraction of light takes place on going from one medium to another because the speed of light is different in two media.

Speed of light:
In vacuum= 3 x10^8m/s
In air= Slightly less than the speed of light in vacuum.
Light travels with different speed in different medium. It travels fastest in vacuum.

The Refractive Index
It is denoted as ‘n’
Refractive Index is the extent of change of direction of light in a given pair of media. The refractive index is a relative value of speed of light in the given pair of media.



Thus, to calculate the refractive Index the speed of light in two media is taken.
Let the speed of light in medium 1 is v_1 and in medium 2 is v_2
Therefore,

$$Refractive\ Index\ of\ medium\ 2\ with\ respect\ to\ medium\ 1\ (n_{21}) = \frac{Speed\ of\ light\ in\ medium\ 1}{Speed\ of\ light\ in\ medium\ 2}$$

$$Or, n_{21} = \frac{v_1}{v_2}$$

Above expression gives the refractive index of medium 2 with respect to medium 1. This is generally denoted by n_{21}.
Similarly, the refractive index of medium 1 with respect to medium 2 is denoted by n_{12}.

$$Therefore, \quad n_{12} = \frac{Speed\ of\ light\ in\ medium\ 2}{Speed\ of\ light\ in\ medium\ 1} = \frac{v_2}{v_1}$$

Absolute Refractive Index:- When one medium is taken as vacuum and speed of light is taken in it, then the refractive index of second medium with respect to vacuum is called Absolute Refractive Index and it is generally denoted by n_2. The absolute refractive index of a medium is simply called its refractive index.

$$Thus, n_2 = \frac{Speed\ of\ light\ in\ vacuum}{Speed\ of\ light\ in\ given\ medium}$$

The speed of light in vacuum is slightly faster than in air.
Let speed of light in air is 'c' and the speed of light in given medium is 'v'.
Therefore,

$$Refractive\ Index\ of\ the\ given\ medium\ (n_m) = \frac{Speed\ of\ light\ in\ air}{Speed\ of\ light\ in\ given\ medium} = \frac{c}{v}$$

Absolute refractive index of some material media

Material medium	Refractive index	Material medium	Refractive index
Air	1.0003	Canada Balsam	1.53
Ice Water Alcohol	1.31 1.33 1.36	Rock salt	1.54
Kerosene	1.44	Carbon disulphide	1.63
Fused quartz	1.46	Dense flint glass	1.65
Turpentine Oil	1.47	Ruby	1.71
Benzene	1.50	Sapphire	1.77
Crown glass	1.52	Diamond	2.42

Optically denser medium and optically rarer medium:
Optical dense refers to the index of refraction. If one medium is optically denser than another, then its index of refraction is larger, meaning the speed of light in the optically denser medium is smaller.

Optically denser medium: A medium in which light travels comparatively slower than the other medium is called optically denser medium. E.g. water

Optically rarer medium: A medium in which light travels comparatively faster than the other medium is called optically denser medium. E.g. Air

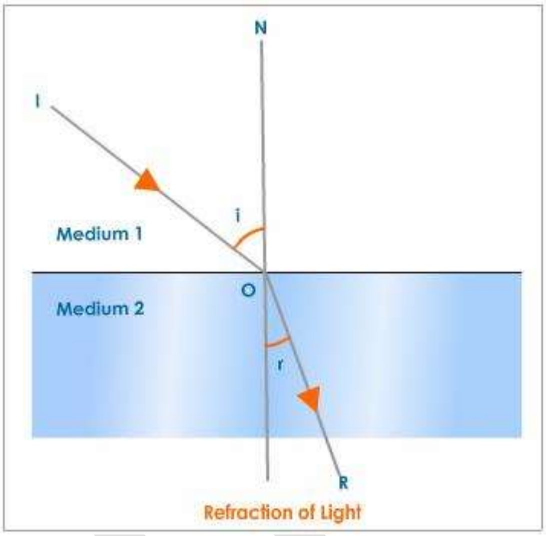
Consider two liquids namely alcohol and kerosene. The refractive index of kerosene (1.44) is more than that of alcohol (1.36).

Then we say kerosene is optically denser n alcohol is optically rarer. The more dense the medium, the slower the light moves.

Similarly, when we compare water and kerosene, kerosene is optically denser (1.44) than water (1.33). But, the mass density of kerosene is less than that of water.
In other words, there is no relation between optical density and mass density.
Optical Density–is an inverse measure of the speed of light through the medium. As the refractive index of a substance decreases the speed of light in that particular medium is more. For example, refractive index of water is 1.33 but that of turpentine is 1.47. Therefore, light travels faster in water than in turpentine.

Refractive index of medium 1 with respect to medium 2(n12) = Speed of light in medium2/speed of light in medium 1=v2/v1
Similarly,
Refractive index of medium 2 with respect to medium 1(n21) = Speed of light in medium1/speed of light in medium 1 = v1/v2
In other words, n12= 1/n21

Laws of refraction of light:

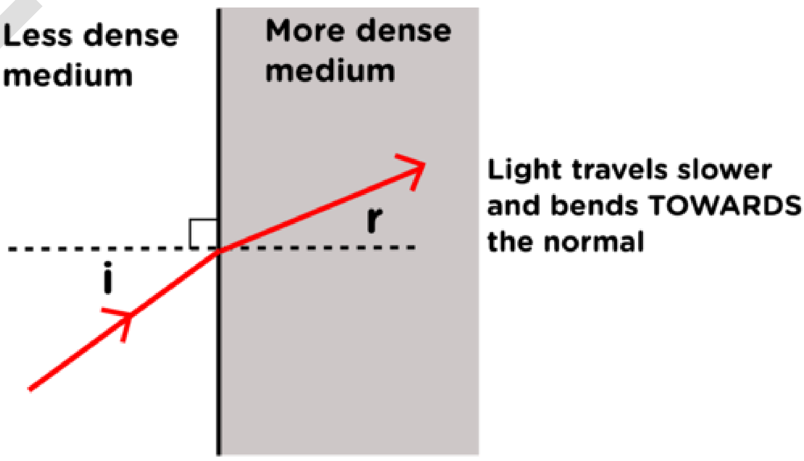


1. The incident ray, the refracted ray and the normal to the interface of two transparent media at the point of incidence, all lie in the same plane.
2. The ratio of sine of angle of incidence to the sine of angle of refraction is a constant, for the light of a given colour and for the given pair of media. This law is also known as Snell's law of refraction. If i is the angle of incidence and r is the angle of refraction, then, sin i / sin r = n21=constant

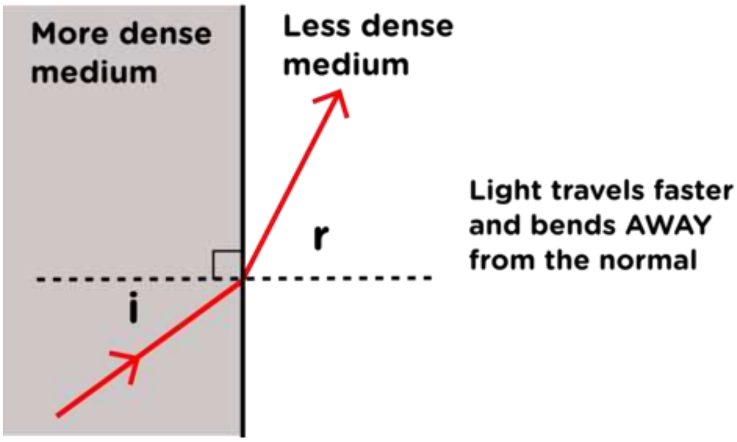
This constant value is called the **refractive index** of the second medium with respect to the first.

Bending of light

1. If light moves from a less dense medium, like air, into a denser medium, like glass, then the light slows down. The light will bend towards the normal line.



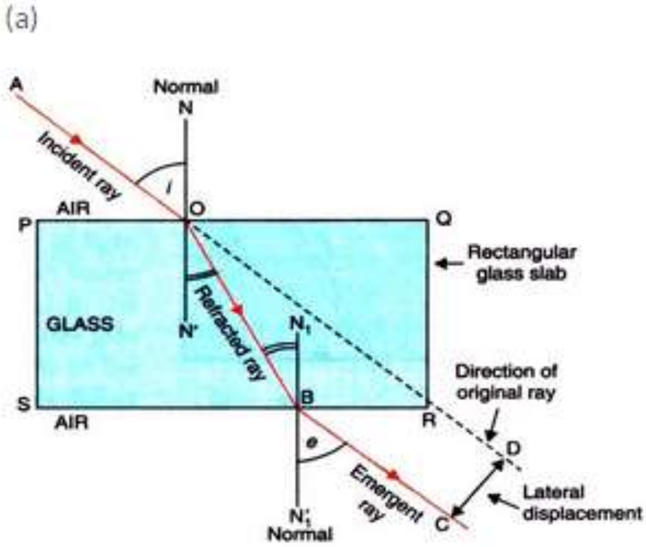
2. If light moves from a denser medium to a less dense medium then the light speeds up and moves away from the normal.



If light ray is incident perpendicularly to an interface, it does not bend.

Refraction through a Glass Slab

Air refractive index=1 and that of water
Light ray comes from rarer to denser medium. Therefore, it moves towards normal. Then it moves out of the glass slab into air. Here light rays, moves from denser to rarer medium. Therefore, it moves away from the normal.

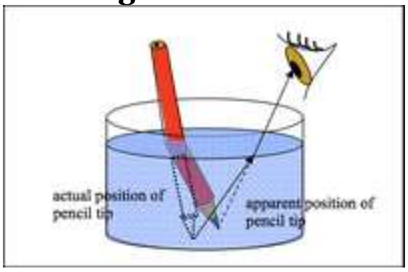


Light passing through the glass slab encounters refraction two times once at air to glass interface and other at glass to air interface. Following are the features:

- In the figure i is the angle of incidence, r is the angle of refraction and e is the angle of emergence
- When light (incident ray) travels from air to glass slab i.e. from rarer to denser medium it bends towards the normal making the angle of refraction smaller than angle of incidence.
- Now this refracted ray acts as incident ray for the second interface and bends away from the normal making the angle, angle of emergence greater than the angle of refraction.
- If the incident ray is perpendicular to the normal or does not make any angle with the normal, then the ray passes through the glass slab straight without showing any refraction.
- The emergent ray and incident ray being extended are parallel to each other but slightly displaced laterally. This displacement of the light ray is termed as lateral displacement. Lateral displacement is the distance between the original path of the incident ray and emergent ray.
- Emergent ray is parallel to incident ray because the extent of bending of the ray of light at the opposite parallel faces which are air-glass interface (PQ) and glass-air interface(SR) of the rectangular glass slab is equal and opposite.
  Angle of incidence and angle of emergence are equal as emergent ray and incident ray are parallel to each other.
- When a light ray is incident normally to the interface of two media then there is no bending of light ray and it goes straight through the medium

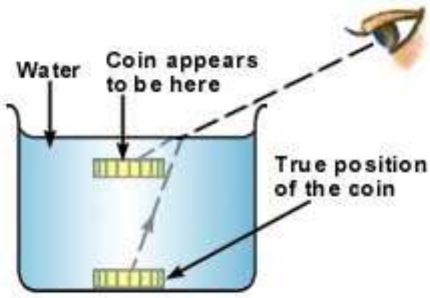
Effects of refraction of light:

1. Bending of pencil when placed in a glass with water:

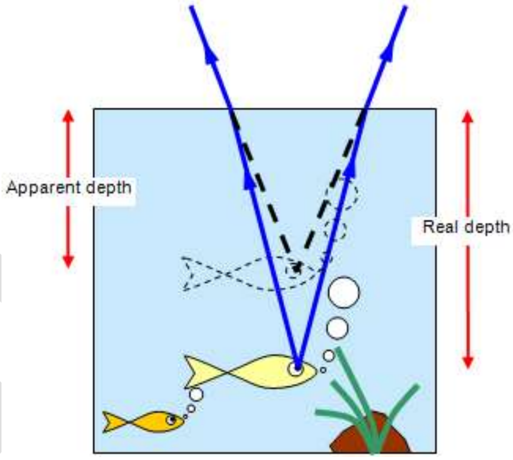


When a pencil or stick is kept in a beaker or a glass filled with water, the stick appears slightly bent. This happens because the light entering from air (rarer medium) into water (denser medium); bends towards normal to the incident which makes the appearance of pencil or stick as bent.

2. An object placed under water appears to be raised: The ray coming from the coin in the bowl bends away from the normal to the incident. We see the emergent ray which makes the appearance of coin slightly above its position.



3. A pool of water appears to be less deep than it is actually is : The refraction of light at the surface of water makes ponds and swimming pools appear shallower than they really are.



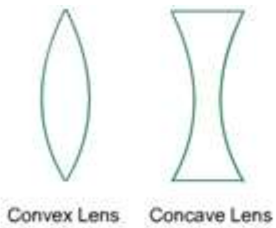
4. Letters beneath slab seems to be raised due to refraction

Refraction by spherical lens:

What is a lens?

Lens is a transparent material bound by two surfaces, of which either both spherical or one spherical and other plane.

Types of lenses:



i) Convex lens: A lens that has two spherical surfaces, bulging outwards is called a double convex lens. It is simply called a convex lens. These lenses are thicker at the centre and thinner at the ends. These are also called converging lens as these lenses converges the light rays falling on them.

ii) Concave Lens: A lens that is bounded by two spherical surfaces, curved inwards is called a double concave lens. A double concave lens is simply called a concave lens. These lenses are thinner in the middle and thicker at the ends. These are also called diverging lens as the light falling on these lenses gets diverged.

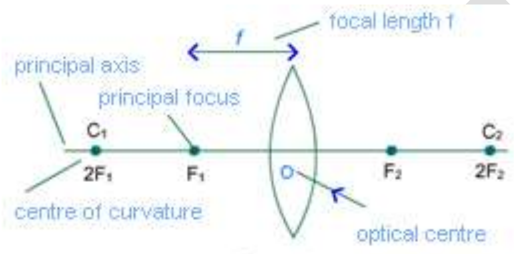
Important terms in the case of spherical lenses:

(a) Focal Length:- The distance between optical centre and principal focus is called focal length of a lens. Focal length of a lens is half of the radius of curvature.

$$i.e.\ 2f = R \quad Or, f = \frac{R}{2}$$

This is the cause that the centre of curvature is generally denoted by 2F for a lens instead of C

(b) Centre of curvature:



Convex Lens

Centre of curvature: A lens, either a convex lens or a concave lens, has two spherical surfaces. Each of these surfaces forms a part of a sphere. The centres of these spheres are called centres of curvature of the lens. The centre of curvature of a lens is usually represented by the letter C. Since concave and convex lenses are formed by the combination of two parts of spheres, therefore they have two centres of curvature. One centre of curvature is usually denoted by C_1 and second is denoted by C_2.

(c) Radius of curvature: The distance between optical centre and centre of curvature is called the radius of curvature, which is generally denoted by R.

(d) Principal Axis: An imaginary straight line that passes through the centres of curvature of a lens is called Principal axis.

(e) Optical centre: The central point of a lens is called its Optical Centre. A ray passes through optical centre of a lens without any deviation.

(f) Aperture: The effective diameter of the circular outline of a spherical lens is called its aperture.

(g) Principle focus:-

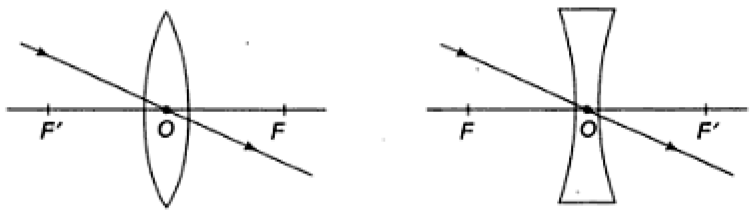
(i) Concave Lens :- The principle focus of a concave lens is a point on its principle axis from which light rays, originally parallel to the axis, appears to diverge after passing through the lens has a virtual focus represented by letter F'

(ii) Convex Lens:- The principle focus of a convex lens is a point on its principle axis to which light rays originally parallel to the principle axis converge after passing through it. A convex lens has a real focus represented by letter f.

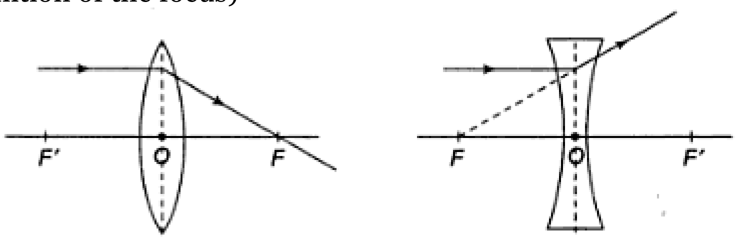
Image Formation by Lenses

The rules for image formation in lenses are-

• A ray passing through the optical centre (O) of the lens proceeds undeviated through the lens.



• A ray passing parallel to the principal axis after refraction through the lens passes or appears to pass through the focus(F). (By definition of the focus)



• A ray through the focus or directed towards the focus(F'), after refraction from the lens, becomes parallel to the principal axis. (Principal of reversibility of light)

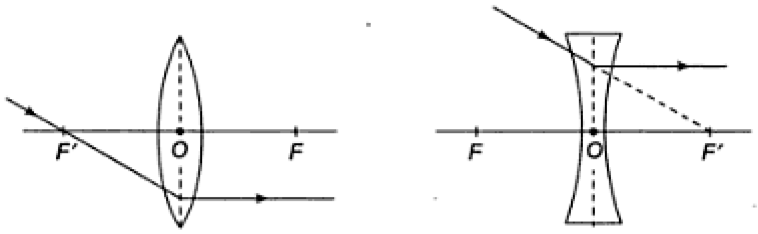
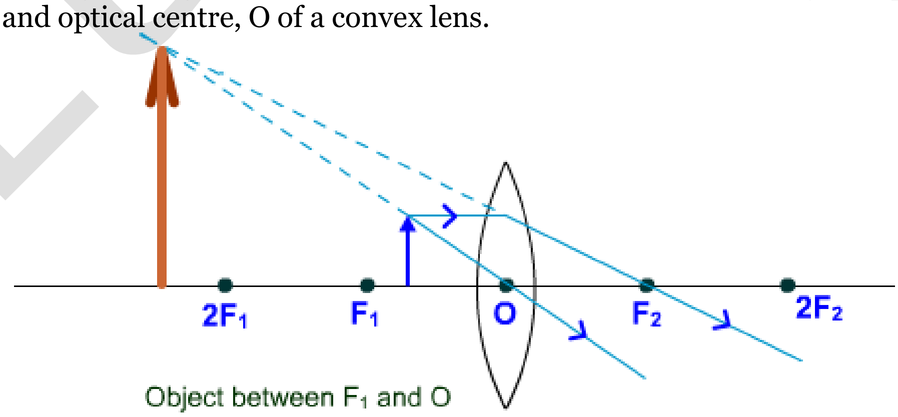


Image formation by convex lens by placing objects in the following positions:

1. Object between principal focus, F and optical centre, O
2. Object at principal focus, F
3. Object between centre of curvature, C and principal focus, F
4. Object at centre of curvature, C
5. Object beyond centre of curvature, C
6. Object at infinity

(a) *Between principal focus, F1 and optical centre, O:-*

A virtual, erect and enlarged image is formed at the same side of lens, when an object is placed between principal focus, F1 and optical centre, O of a convex lens.



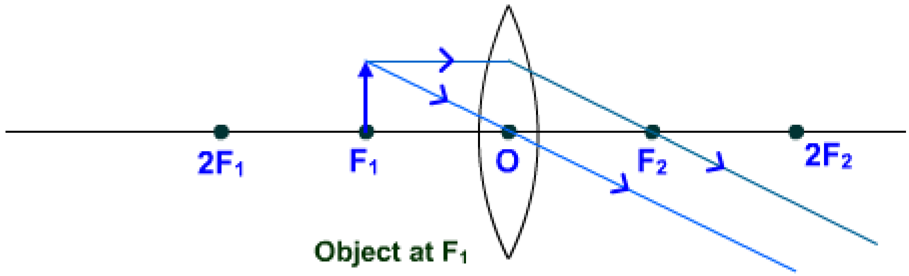
Position of image: Beyond 2F1

Nature of image: Virtual and erect

Size of image: Enlarged.

b) Object at principal focus, F1:-

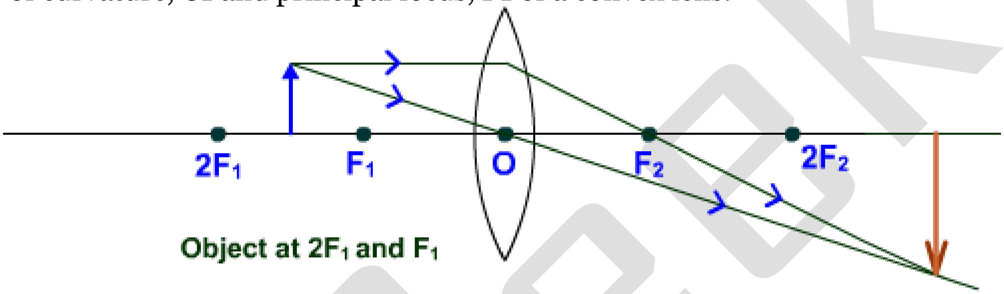
An infinitely large, real and inverted image is formed at infinity when object is placed at principal focus, F1 of a convex lens.



Position of image: At infinity
Nature of image: Real and inverted
Size of image: Highly enlarged

c) Object between centre of curvature, C1 and principal focus, F1:

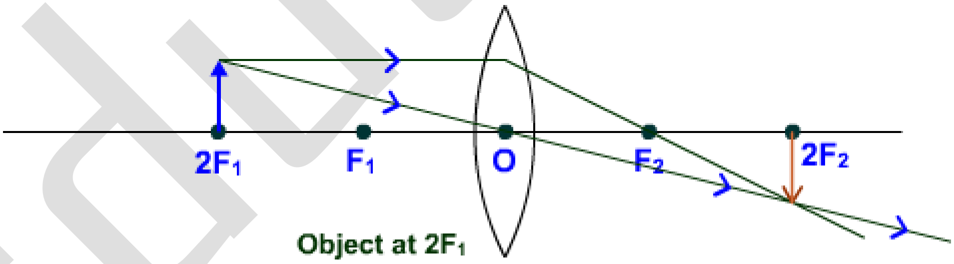
An enlarged, real and inverted image is formed beyond centre of curvature, C2 when an object is placed between centre of curvature, C1 and principal focus, F1 of a convex lens.



Position of image: Beyond 2F2
Nature of image: Real and inverted
Size of image: Enlarged

d) Object at centre of curvature, C1 or 2F1:

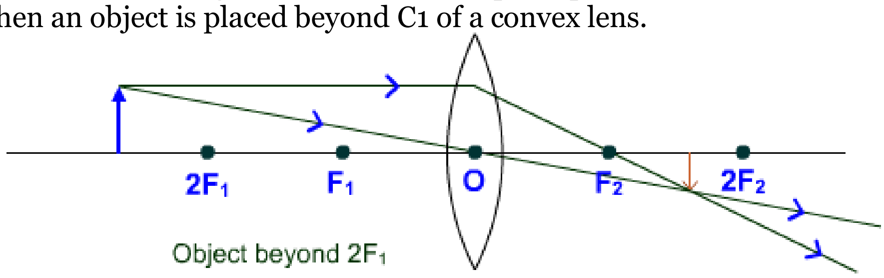
A same sized, real and inverted image is formed at centre of curvature, C2 when object is placed at centre of curvature, C1 of a convex lens.



Position of image: At 2F2
Nature of image: Real and inverted
Size of image: Same sized.

e) Object beyond centre of curvature, C1 or 2F1:-

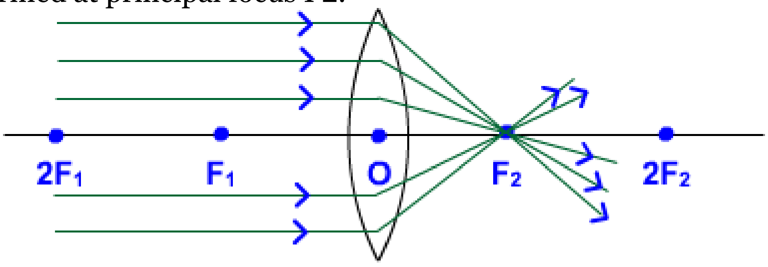
A diminished, real and inverted image is formed between principal focus, F2 and centre of curvature, C2 at the opposite side when an object is placed beyond C1 of a convex lens.



Position of image: Between 2F2 and F2
Nature of image: Real and inverted
Size of image: Diminished.

f) Object at infinity:-

Convex lens converge parallel rays coming from objet at infinity and a highly diminished – point sized, real and inverted image is formed at principal focus F2.



Object at infinity

Position of image: At F2
Nature of image: Real and inverted
Size of image: Point sized, highly diminished.

Rules for image formation by converging lenses.

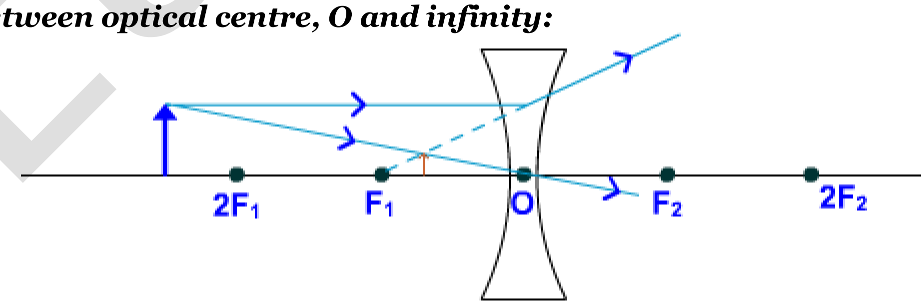
Position of the object	**Position of the image**	**Relative size of the image**	**Nature of the image**
At infinity	At focus F_2	Highly diminished, point-sized	Real and inverted
Beyond $2F_1$	Between F_2 and $2F_2$	Diminished	Real and inverted
At $2F_1$	At $2F_2$	Same size	Real and inverted
Between F_1 and $2F_1$	Beyond $2F_2$	Enlarged	Real and inverted
At focus F_1	At infinity	Infinitely large or highly enlarged	Real and inverted
Between focus $F_1$and optical centre O	On the same side of the lens as the object	Enlarged	Virtual and erect

The image formation by concave lens by placing the objects in the following positions:

(a) Object is between optical centre, O and infinity

(b) Object is at infinity

(a) *Object is between optical centre, O and infinity:*

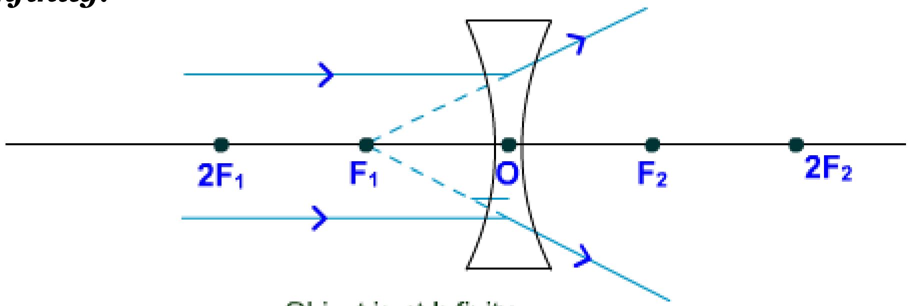


Object between Infinity and Optical centre

A diminished, virtual and erect image is formed between principal focus F1 and optical centre, O; when object is placed between optical centre and infinity of a concave lens.

Position of image:- Between F1 and O
Nature of image:- Virtual and erect
Size of image:- Diminished.

(b)Object is at infinity:-



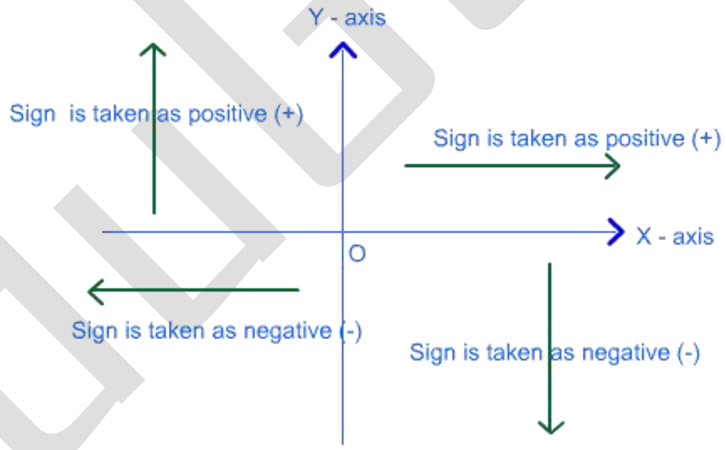
Object is at Infinity

A highly diminished point sized, virtual and erect image is formed when object is at infinity by a concave lens at principal focus F1.
Position of image:- At F1
Nature of image: Virtual and erect
Size of image: Point sized, highly diminished.

Rules for image formation by diverging lenses.

Position of the object	**Position of the image**	**Relative size of the image**	**Nature of the image**
At infinity	At focus F_1	Highly diminished, point-sized	Virtual and erect
Between infinity and optical centre O of the lens	Between focus F_1 and optical centre O	Diminished	Virtual and erect

Sign convention for lens:-



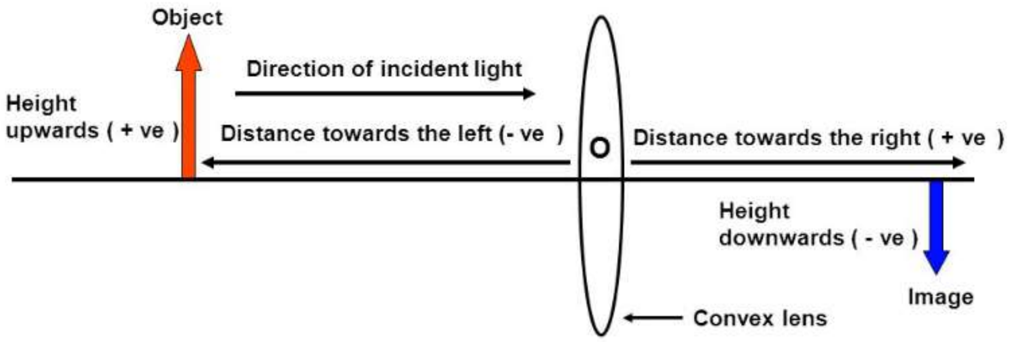
New Cartesian Sign Convention

Sign convention for lens is similar to that of spherical mirror.

Signs are taken left of the optical centre as negative, right of the optical centre as positive, above of the principal axis as positive and below of the principal axis as negative.

Sign Convention for spherical lenses

- The sign convention for spherical lenses is the same as in spherical mirrors except that the distances are measured from the optical centre (O)
- The focal length of a convex lens is the positive (+ve) and the focal length of a concave lens is negative (-ve)



i) All distances on the principal axis are measured from the optical center.
The distances measured in the direction of incident rays are positive and all the distances measured in the direction opposite to that of the incident rays are negative.
All distances measured above the principal axis are positive. Thus, height of an object and that of an erect image are positive and all distances measured below the principal axis are negative.

ii) The focal length of a convex lens is positive and the focal length of a concave lens is negative.
The new sign convention is known as New Cartesian Sign Convention. In this, sign is taken negative towards left and taken as positive towards right at X-axis from origin.

Practical application

Used in spectacles, camera, telescope, microscope etc.

Lens Formula and Magnification:

The relation between distance of object, distance of image and focal length for a lens is called lens formula.

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

Where, v is the distance of image, u is the distance of object, and f is the focal length of lens. Distance of object and image is measure from the optical centre of the lens. The sign for distance is given as per convention.
The lens formula is valid for all situations for spherical lens. By knowing any of the two the third can be calculated.

Magnification:

The ratio of height of image and that of object or ratio of distance of image and distance of object gives magnification. It is generally denoted by 'm'. If h is the height of the object and h′ is the height of the image given by a lens, then the magnification produced by the lens is given by,

$$(m) = \frac{Height\ of\ image\ (h')}{Height\ of\ object\ (h)}$$

$$= \frac{Distance\ of\ image\ (v)}{Distance\ of\ object\ (u)}$$

Magnification produced by a lens is also related to the object-distance u, and the image-distance v. This relationship is given by Magnification (m) = h′/h = v/u

$$(m) = \frac{Height\ of\ image\ (h')}{Height\ of\ object\ (h)}$$

$$= \frac{Distance\ of\ image\ (v)}{Distance\ of\ object\ (u)}$$

The positive (+) sign of magnification shows that image is erect and virtual while a negative (-) sign of magnification shows that image is real and inverted. A magnification of 2 means the image is twice the size of the object and a magnification of 1 indicates an image size being the same as the object size.

Power of a Lens

The degree of divergence or convergence of ray of light by a lens is expressed in terms of the power of lens. Degree of convergence and divergence depends upon the focal length of a lens. The power of a lens is denoted by 'P'. The power of a lens is reciprocal of the focal length.
P=1/f
The SI unit of Power of lens is dioptre and it is denoted by 'D'.
Power of a lens is expressed in dioptre when the focal length is expressed in metre. Thus, a lens having 1 metre of focal length has power equal to 1 dipotre.

$$Therefore, 1D = 1m^{-1}$$

A convex lens has power in positive and a concave lens has power in negative.