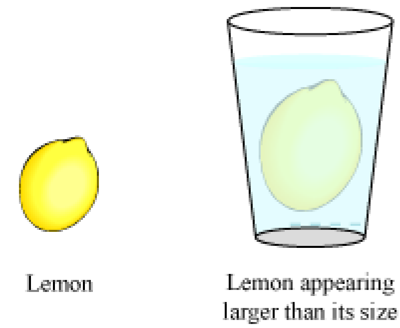
Light Energy

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?

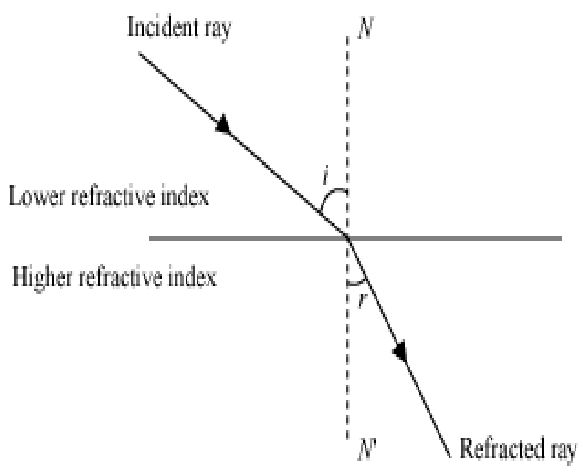


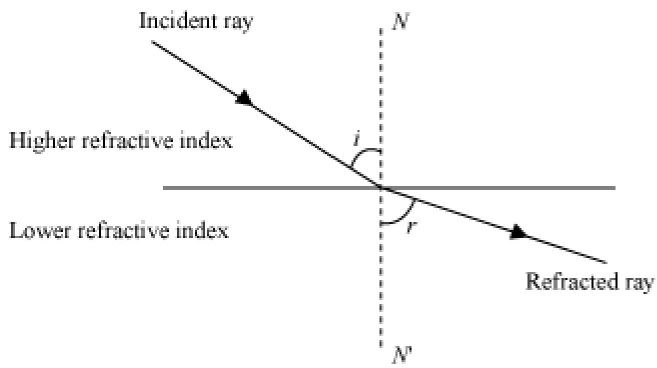
When a light ray travels from one transparent medium to another, it bends at the surface that separates the two media. Hence, the lemon appears larger than its actual size. This happens because different media have different optical densities.

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.

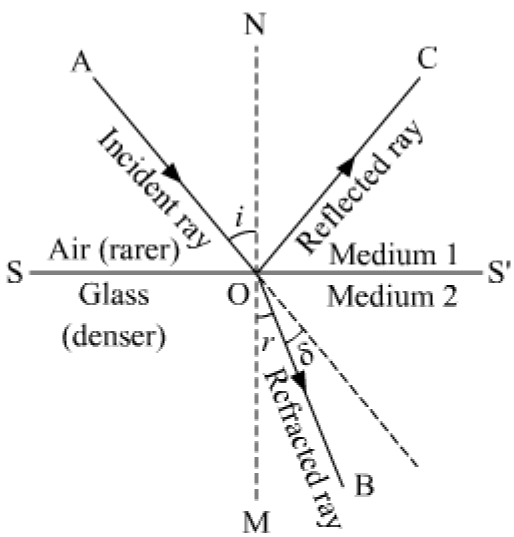
As a ray of light moves from an optically rarer medium to an optically denser medium, it bends towards the normal at the point of incidence. Therefore, the angle of incidence (*i*) is greater than the angle of refraction (*r*). Hence, ***i* > *r***.



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.


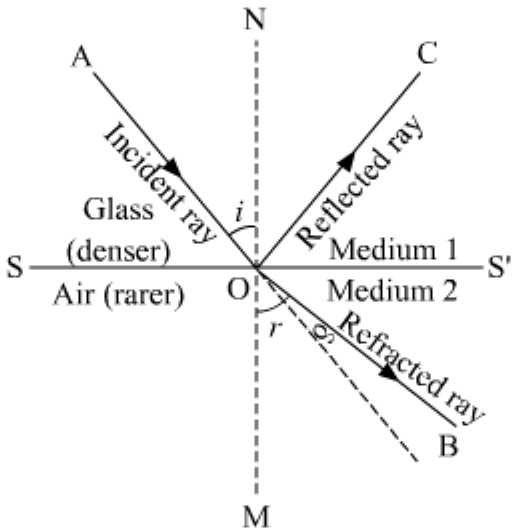
Partial reflection and refraction of light at the boundary of two medium

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

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.

Situation I

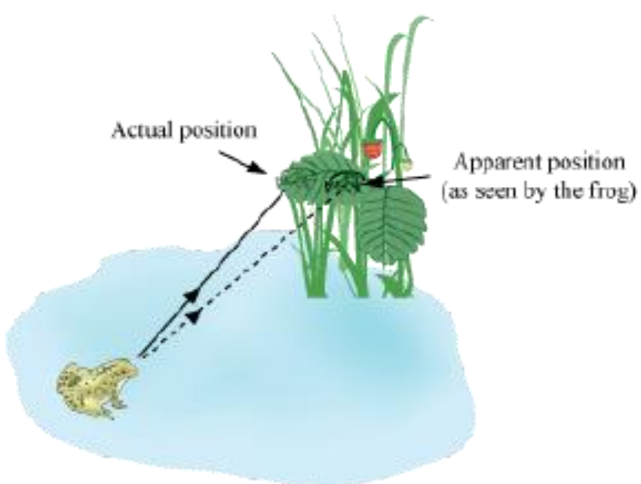
The grasshopper is looking towards the frog.

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.



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.

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.

Hence, when a light ray is incident on a rectangular glass slab, the light emerges parallel to the incident ray from the opposite side of the slab.

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

Example:

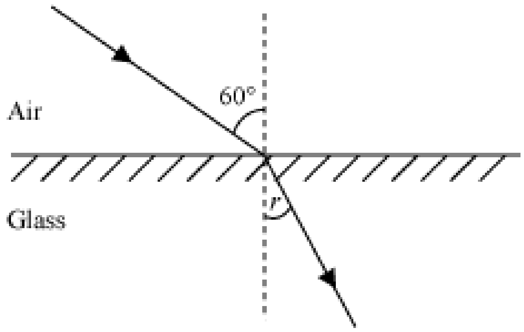
A ray of light is incident on a glass surface in such a way that it makes an angle of 60° with the normal (as shown in the given figure). **Determine the angle of refraction (**Given that the relative refractive index, μ = 1.34).

Solution:

Angle of incidence, $i = 60°$

Angle of refraction, $r =?$

Using Snell's law of refraction,



$$\frac{\sin i}{\sin r} = \text{constant}$$

$$\frac{\sin 60°}{\sin r} = 1.34$$

$$\sin r = \frac{\sqrt{3}}{2} \times \frac{1}{1.34} \qquad \left(\sin 60° = \frac{\sqrt{3}}{2}\right)$$

$$\sin r = 0.646$$

$$r = \sin^{-1}(0.646)$$

$$= 40°$$

Hence, the angle of refraction is approx. 40°.

Relation between refractive index of a medium and the speed of light

The refractive index of a medium (μ) and the speed of light in it are related as:

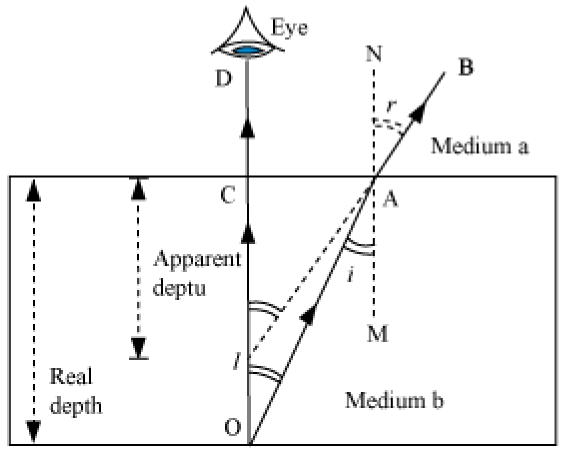
$$\mu = \frac{\text{Speed of light in the air}}{\text{Speed of light in the medium}} = \frac{c}{v}$$

This relation shows that the speed of light in a medium is inversely proportional to its refractive index, i.e., $v \propto = 1/\mu$.

Effects of Refraction

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

1. **Real and Apparent Depth**



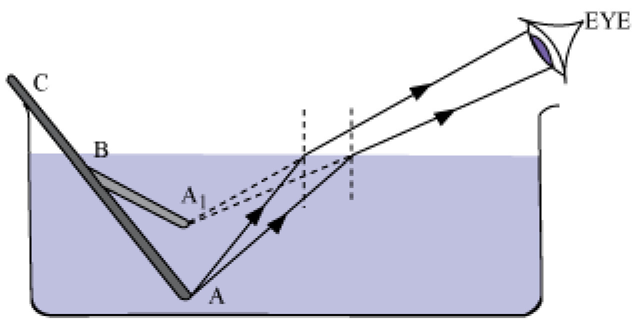
Real depth — the actual depth at which object is situated is called real depth.

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.

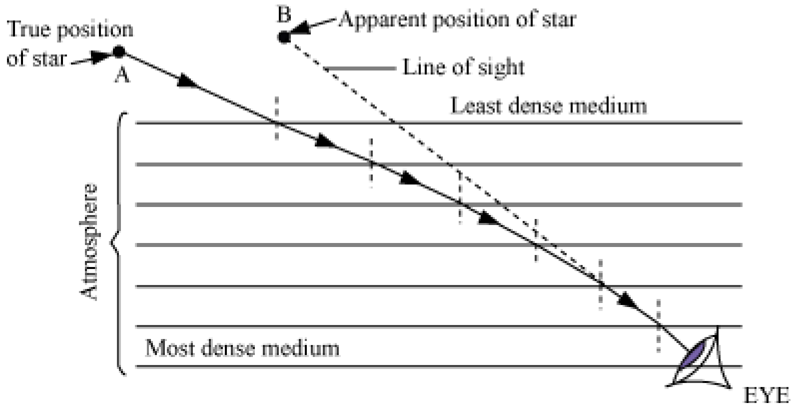
$$\text{Refractive index} = \frac{\text{Real depth}}{\text{Apparent depth}}$$

2. **Bending of Stick**



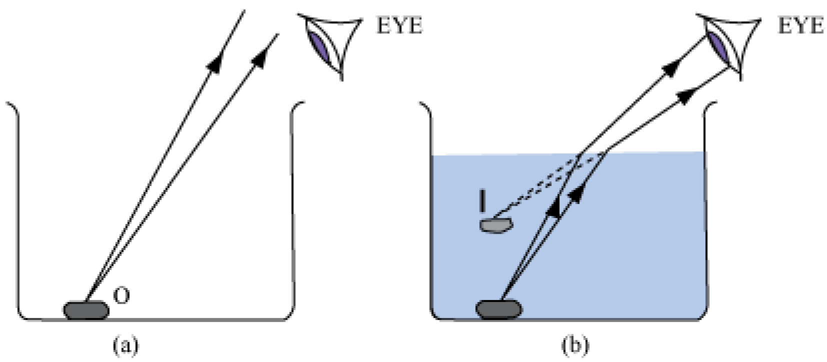
On the similar principle of refraction we see the stick bend and shorten when immersed in water.

3. **Twinkling of stars**



4. **Raised beaker bottom**

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

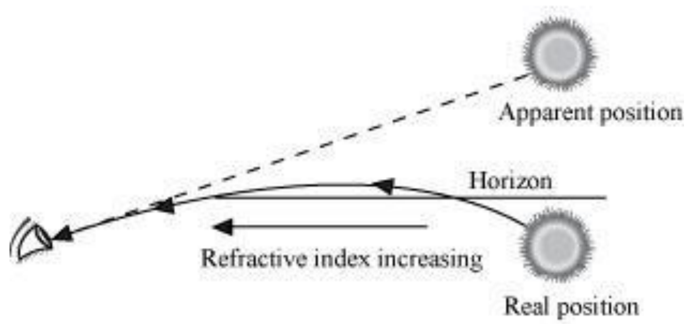


5. **Early sunrise and delay sunset**

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.



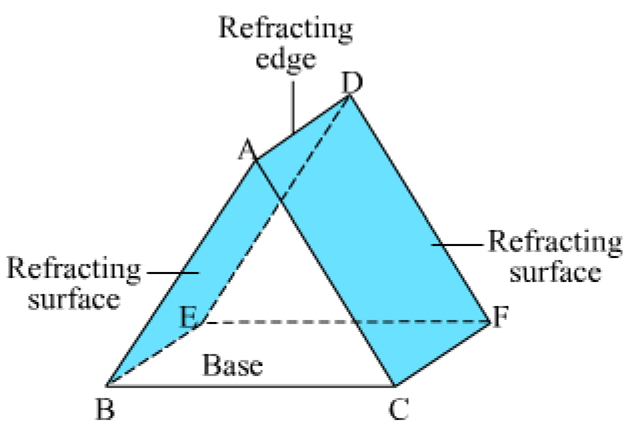
Dispersion of White Light in Prism

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.

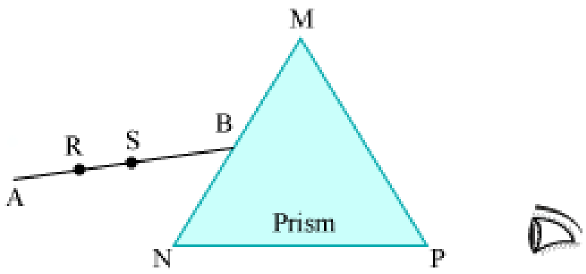


Refraction of light through a glass prism

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

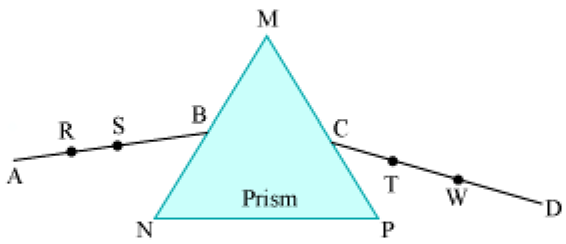
Take a triangular glass prism, paper sheet, and a few drawing pins. Fix the sheet on a drawing board with the help of drawing pins. Now, place the glass prism on the sheet and draw the outline **MNP** of the prism on the sheet (as shown in the figure).

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.

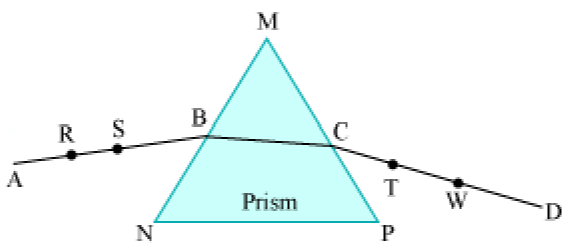


Now, observe the pins **R** and **S** through the other side of the prism. Move your head laterally to see the two pins **R** and **S** in a straight line. Fix a pin on the sheet near the prism on your side and mark it as **T**.

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

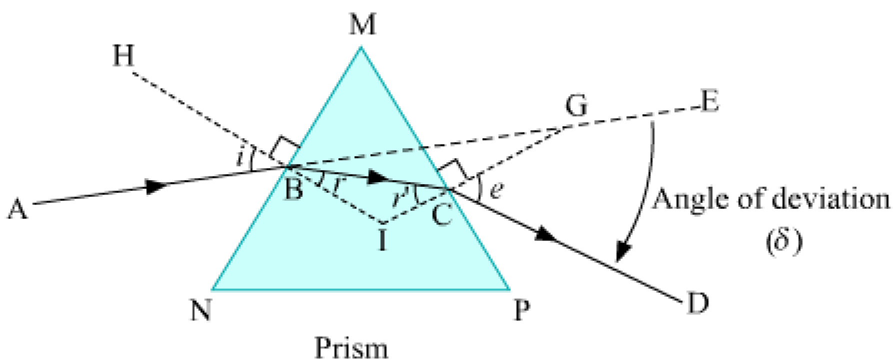
Line CD = Emergent ray

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 **).**

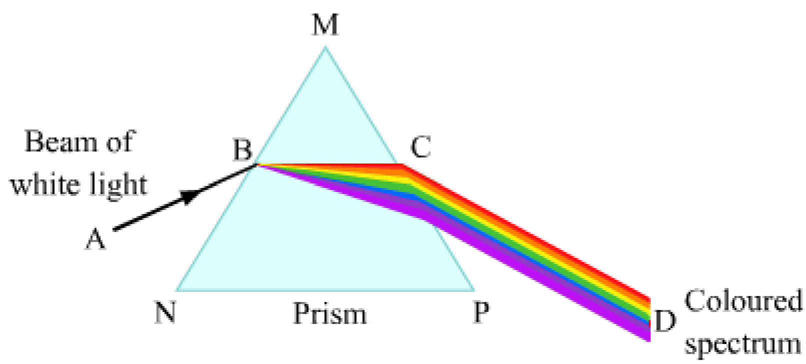
Do you know what happens when you take white light as incident ray instead of single ray?

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.

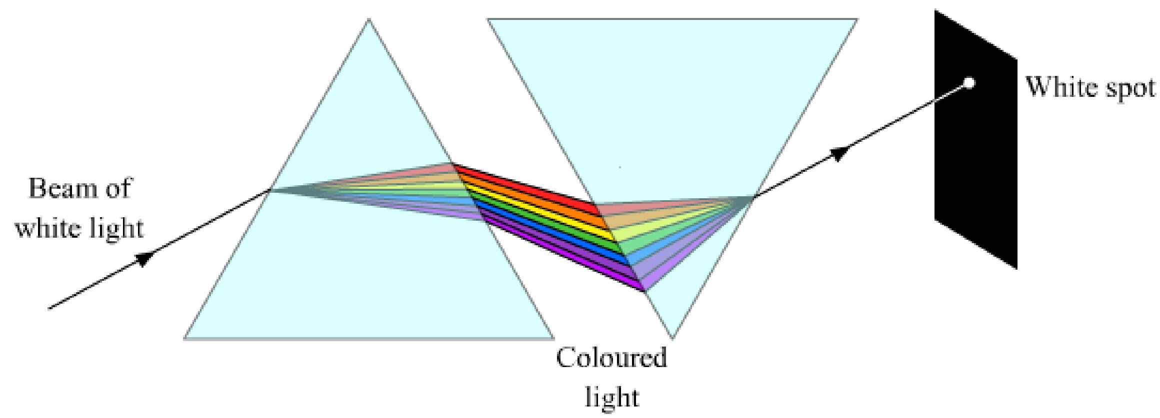
This splitting of the light rays occurs because of the different angles of bending for each colour. Hence, each colour while passing through the prism bends at different angles with respect to the incident beam. This gives rise to the formation of the colour spectrum.

Can you say which colour undergoes maximum deviation?

Violet light bends the most whereas red colour deviates least.

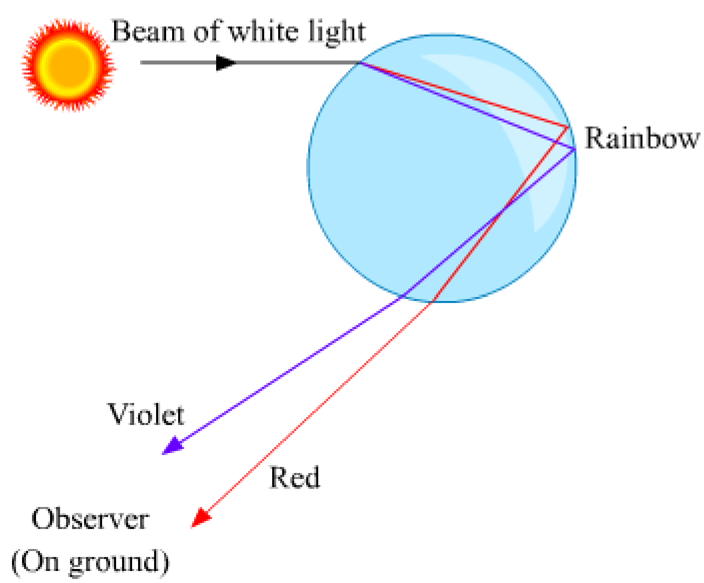
However, Newton did not stop at this point. He thought that if seven colours can be obtained from a white light beam, **is it possible to obtain white light back from the seven colours?**

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.



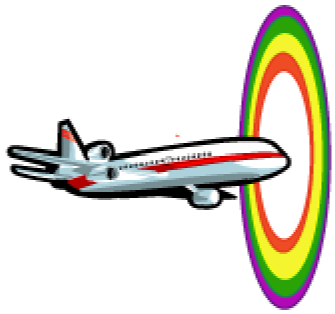
Let us see how a rainbow is actually formed.

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.



Reflection of Light by Spherical Mirrors

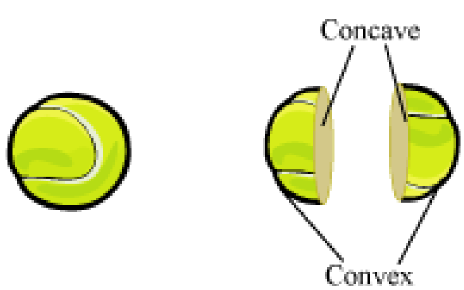
Light travels in a straight line and can change its direction when incident on a shiny surface.

Jatin looks inside a polished steel bowl and gets surprised to find his face appearing inverted inside the bowl. Furthermore, the image of his face changes its size as the bowl is moved towards or away from him. However, when he looks on the outer side of the same bowl, he finds his image to be erect.

Why does this happen? This happens because the curved surface of the bowl acts as special kind of mirror, known as a **spherical mirror**. A spherical mirror can be made from a spherical ball.

Take a tennis ball and cut it into two equal halves.

The inner surface of each half is known as the concave surface, while the outer surface is called the convex surface.

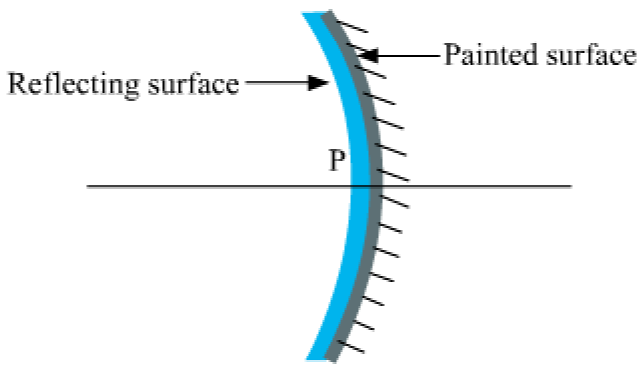


There are two types of spherical mirrors

i) Concave mirrors

ii) Convex mirrors

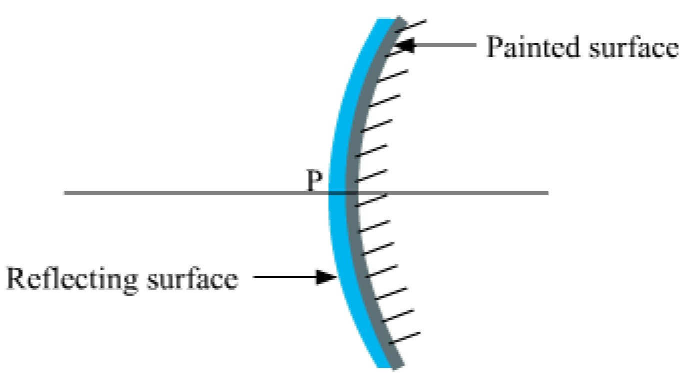
Concave mirrors



Concave mirror

A concave mirror is a spherical mirror whose reflecting surface is curved inwards. In a concave mirror, reflection of light takes place from the inner surface. This mirror resembles the shape of a '**cave**'. A Painted surface is a non-reflecting surface.

Convex mirrors



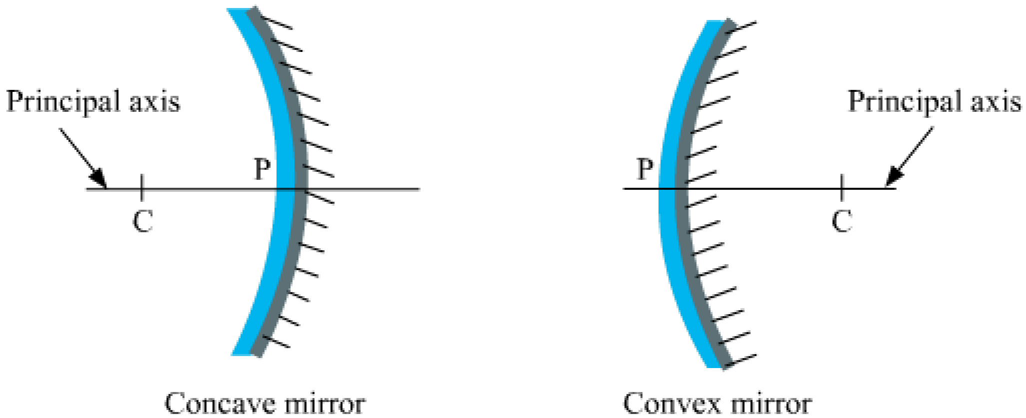
Convex mirror

A convex mirror is a spherical mirror whose reflecting surface is curved outwards. In a convex mirror, the reflection of light takes place from its outer surface. A Painted surface is a non-reflecting surface.

Hence, the inward surface of the steel bowl or a spoon acts as a concave mirror, while its outer surface acts as a convex mirror.

There are some definitions associated with spherical mirrors, which will prove helpful in the discussion of spherical mirrors. But, before going into the definitions, let us understand the terms clearly.

So, the definitions of the terminologies are as follows:

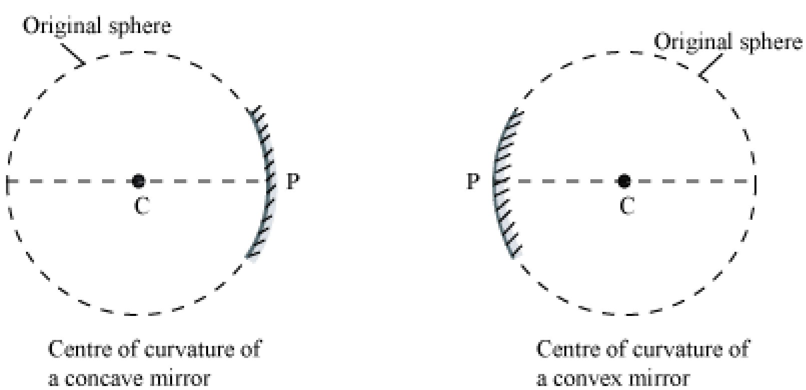


Pole of a spherical mirror

The central point of the reflecting surface of a spherical mirror is termed as the **pole**. It lies on the mirror and is denoted by the letter **(P)**.

Centre of curvature

The centre of curvature as the centre of a sphere from which the given spherical mirror (convex or concave) is obtained. It is denoted by the letter (**C)**.

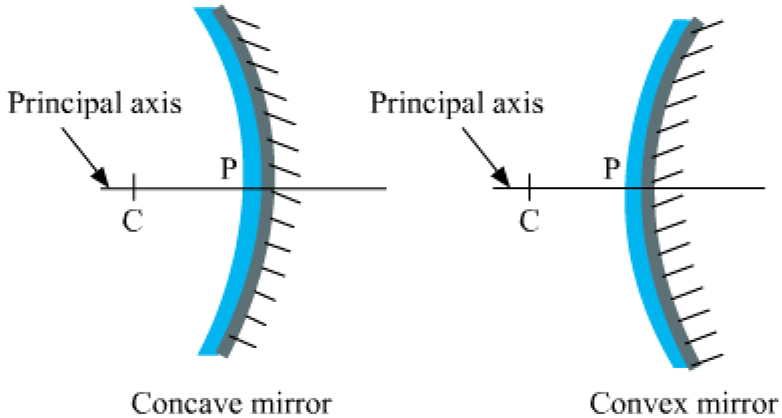


Radius of curvature

The distance between the centre of curvature and pole (**PC)** is known as the **radius of curvature**.

Principal axis of the spherical mirror

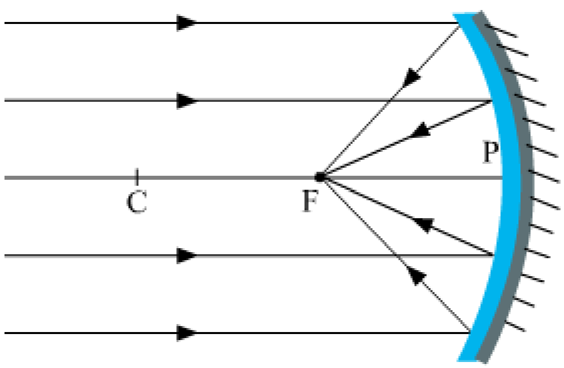
The imaginary straight line passing through the pole (P) and the centre of curvature (C) is termed as the principal axis.



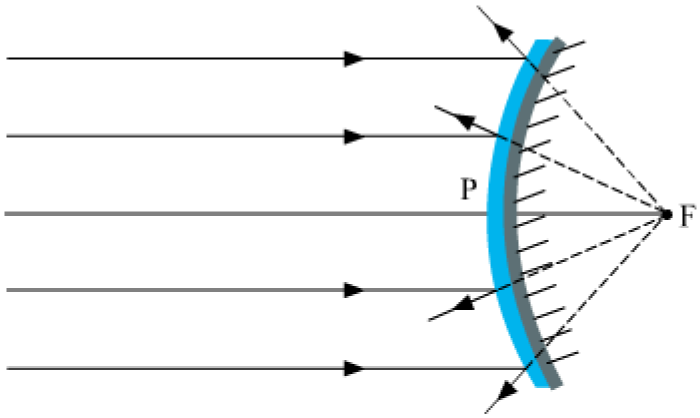
Focus

The focus **(F)** is the point on the principal axis of a spherical mirror where all the incident rays parallel to the principal axis meet or appear to diverge from after reflection.

For concave mirrors, the focus lies on the same side of the reflecting surface.



For convex mirrors, the focus is obtained on the opposite side of the reflecting surface by extrapolating the rays reflected from the mirror surface.



Radius of curvature **(*R*)** and the focal length **(*f*)** of a spherical mirror are related as

$R = 2f$

Where, ***R*** is the distance between the centre of curvature and the pole of the mirror, while ***f*** is the distance between the focus and the pole of the mirror.

The focus of a spherical mirror always lies between the pole (P) and the centre of curvature (C).

Reflection by spherical mirrors

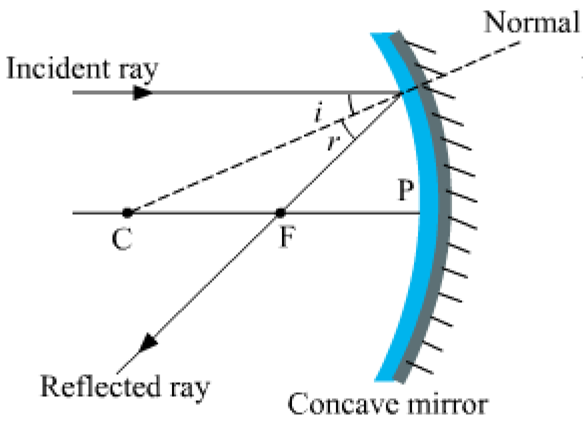
The laws of reflection are also followed by spherical mirrors, same as the plane mirrors. The laws of reflection are:

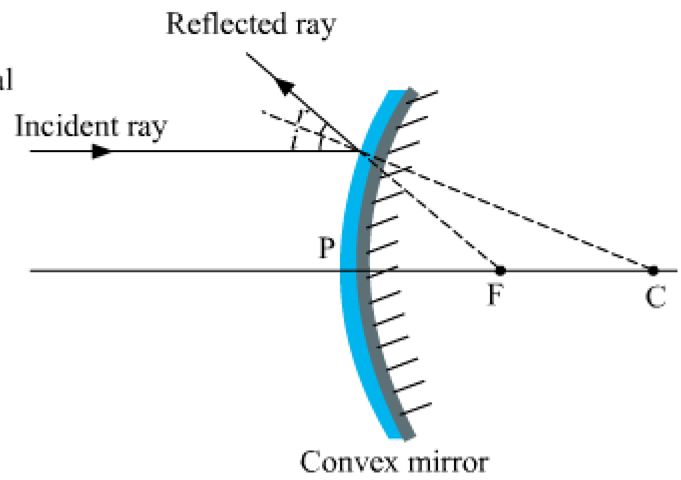
1) The angle of incidence of light is always equal to angle of reflection of light.
2) The incident ray, the normal and the reflected ray, all lie in the same plane.

The different ways in which a ray of light is reflected from a spherical mirror are:

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

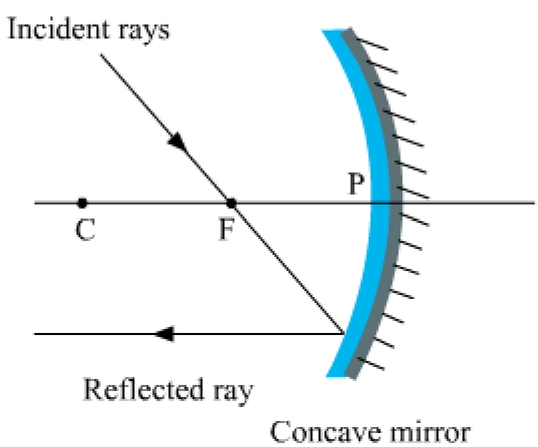
In this case, the reflected ray will pass through the focus of a concave mirror, or it appears to pass through the focus of a convex mirror.

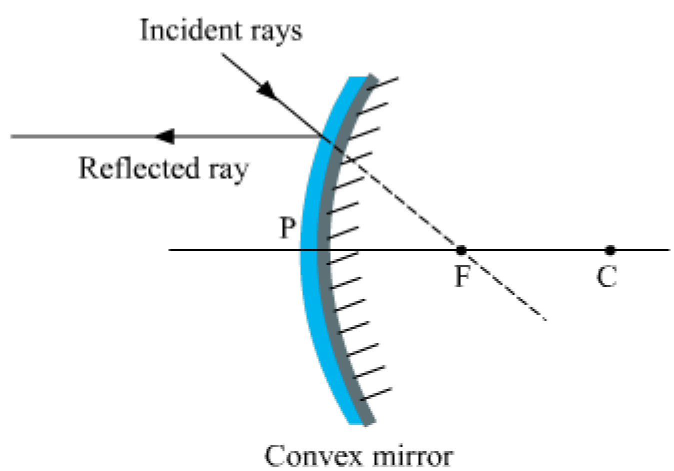




Case II: When the incident light ray passes through the focus of a concave mirror, or appears to pass through the focus of a convex mirror.

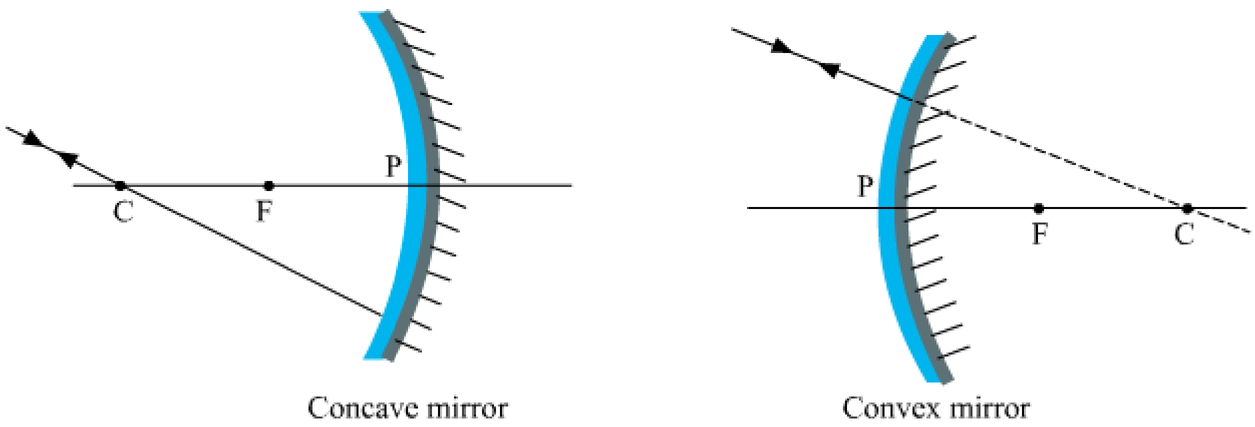
In this case, the reflected light will be parallel to the principal axis of the spherical mirror.





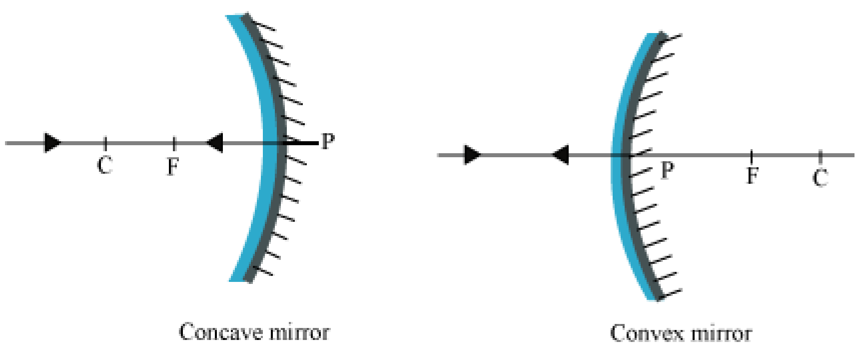
Case III: When the incident ray passes through or appears to pass through the centre of curvature.

In this case, light after reflecting from the spherical surface moves back in the same path. This happens because light is incident perpendicularly on the mirror surface.



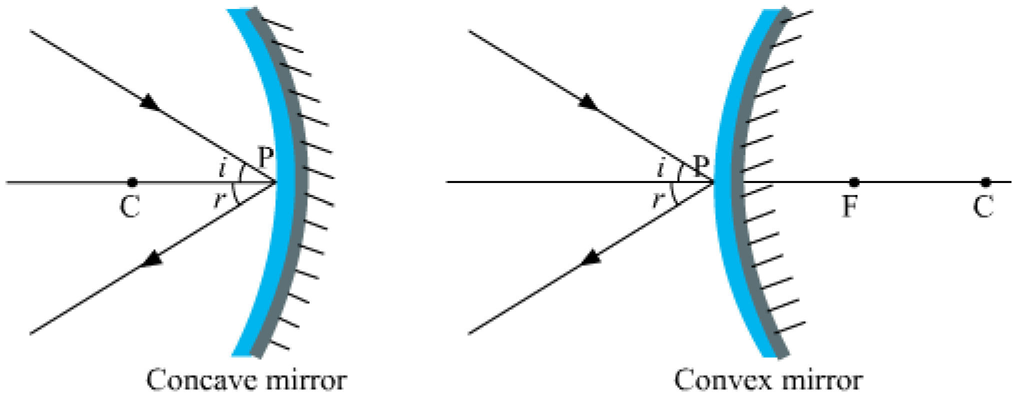
Case IV: When the incident ray is normal to the reflecting surface

In this case, the incident light ray will be reflected back by the reflecting surface of the spherical mirror, as in the case of plane mirror.



Case V: When the ray incident obliquely to the principal axis.

In this case, the incident ray will be reflected back by the reflecting surface of the spherical mirror obliquely. And making equal angles with the principal axis**.**

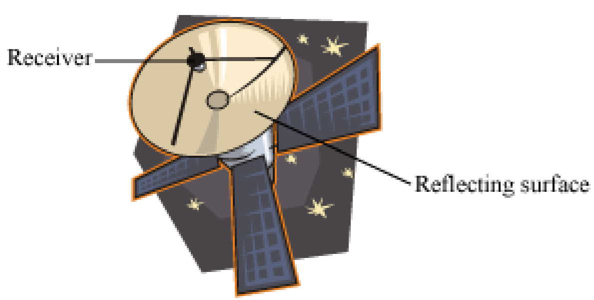


Four spherical mirrors of radius of curvature R_1, R_2, R_3, and R_4 ($R_1 > R_3 > R2 > R_4$) are placed against the sunlight. Try to obtain the bright spot on a paper sheet for each mirror. **Which mirror forms the brightest spot at a maximum distance from the pole of the mirror?** Explain.

Do You Know:

Radio telescope is a reflecting telescope that tends to reflect all parallel rays coming from distant stars, galaxies, deep space etc. to a single point. This is because the reflecting surface acts as a large concave mirror. The point where the reflected rays meet is its focus.

A receiver is placed at the focus, which receives light rays and sends these rays to a computer in the form of electrical signals. As a result, images of a light source can be obtained on the monitor.



Images formed by spherical mirrors

Spherical mirrors form images of an object that may be smaller, larger, or of the same size, erect or inverted, depending on their type and their distance from the object. In general, images formed by any type of mirrors can be classified in two types: real images and virtual images.

S. No.	Real Image	Virtual Image
1.	Can be obtained on a screen or wall	Cannot be obtained on a screen or wall
2.	Can be touched	Cannot be touched
3.	Formed in front of the mirror	Formed behind the mirror
4.	Formed by concave mirrors only	Formed by all types of mirrors i.e., plane, convex, and concave
5.	These images are always inverted	These images are always erect

Difference between a real image and a virtual image

You can distinguish between real and virtual images by checking the orientation (erect or inverted) of images and also by touching them.

Let us learn about the images formed by different spherical mirrors.

So, you have seen that

- the image formed by a convex mirror is **virtual**, **erect**, and of a **smaller size**.
- the image formed by a concave mirror is **virtual**, **erect** and of a **larger size** when placed near the surface of the mirror; and **inverted** and **may be smaller or larger than** the object when placed at a distance from the surface.

Concave mirrors form larger, smaller and of same size real images and also larger virtual images. On the other hand, convex mirrors always form smaller virtual images.

Take a concave mirror and a sharpener. Now, try to see the image of the sharpener in the mirror. Make sure that the sharpener is at a large distance from the concave mirror. Observe the size and the orientation of the image. Now, reduce the distance between the sharpener and the mirror and again notice the size and the orientation of the image. Repeat the observation by reducing the distance and try to complete the following table.

Distance between the sharpener and the concave mirror	Size of the image	Character of the image
20 cm	Smaller	Inverted
15 cm	Equal	
10 cm		
5 cm		

Replace the concave mirror with a convex mirror and follow the same steps. Make a similar table for the convex lens too.

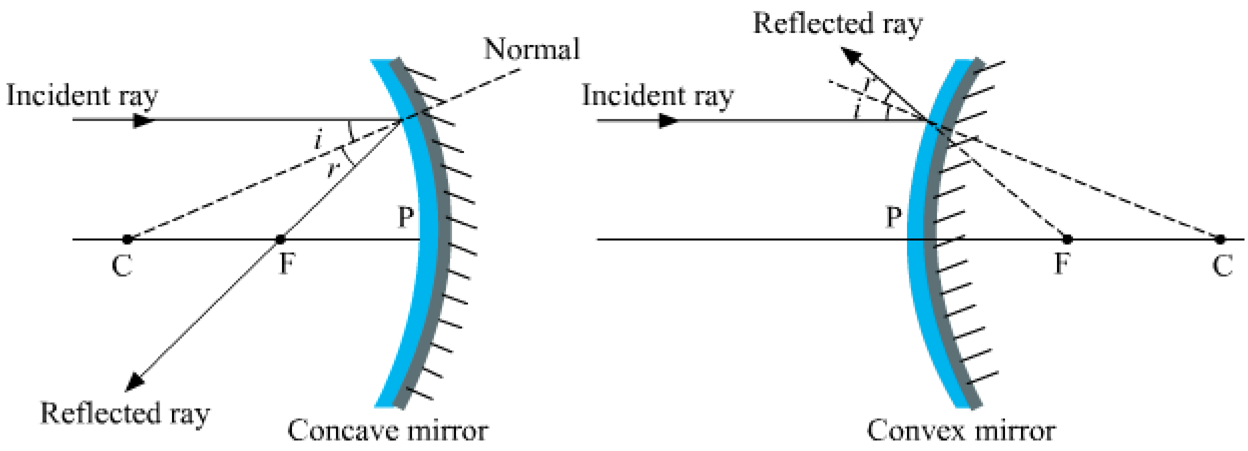
Collect some objects that have shiny surfaces and classify them as plane, convex, or concave mirrors.

Reflection by Spherical Mirrors

The different ways in which a ray of light is reflected from a spherical mirror are as follows:

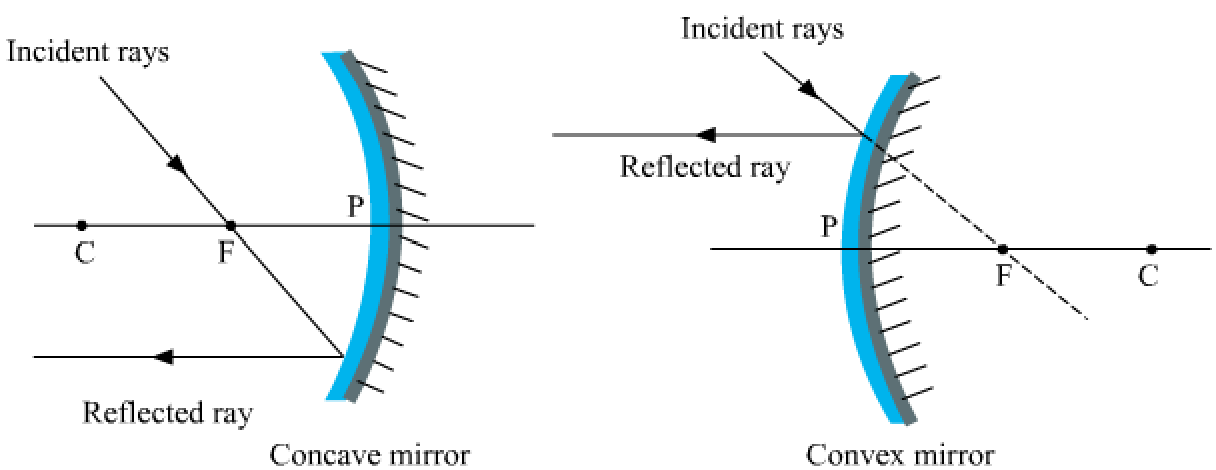
Case I: When the incident light ray is parallel to the principal axis

In this case, the reflected ray will pass through the focus of a concave mirror, or will appear to pass through the focus of a convex mirror.



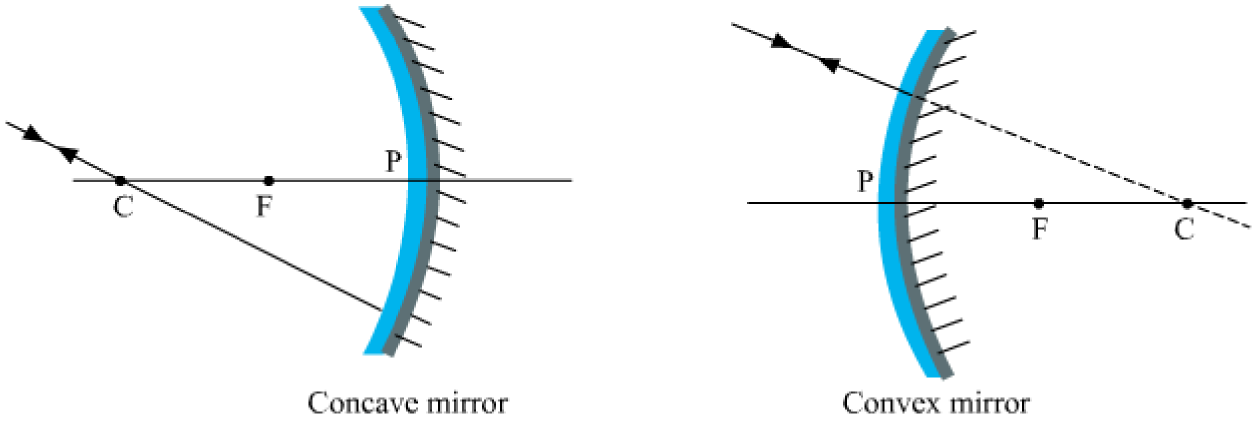
Case II: When the incident light ray passes through the focus of a concave mirror, or appears to pass through the focus of a convex mirror

In this case, the reflected light will be parallel to the principal axis of the spherical mirror.



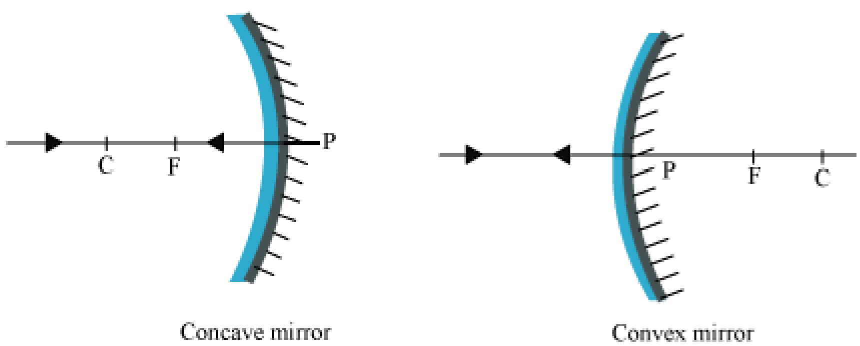
Case III: When the incident ray passes through or appears to pass through the centre of curvature

In this case, after reflecting from the spherical surface, light moves back in the same path. This happens because light is incident perpendicularly on the mirror surface.



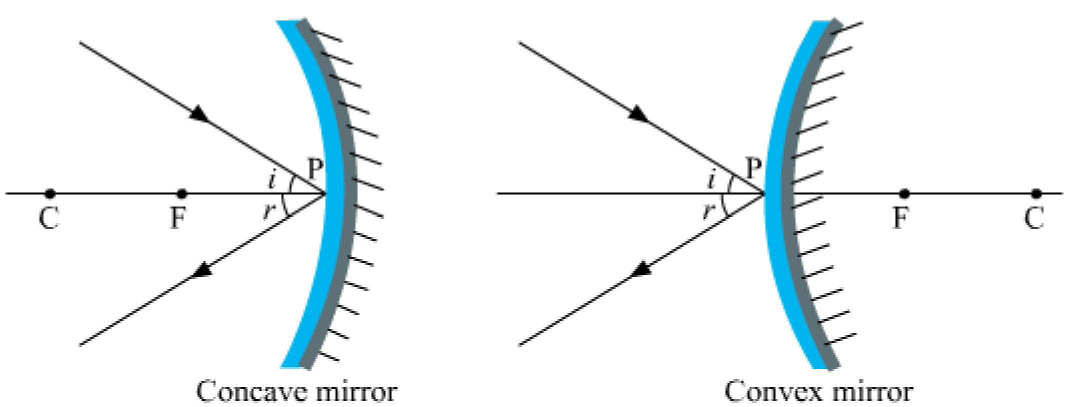
Case IV: When the incident ray is normal to the reflecting surface

In this case, the incident light ray will be reflected back by the reflecting surface of the spherical mirror, as in the case of a plane mirror.



Case V: When the ray incident obliquely to the principal axis.

In this case, the incident ray will be reflected back by the reflecting surface of the spherical mirror obliquely. And making equal angles with the principal axis**.**



Four spherical mirrors of radius of curvature R_1, R_2, R_3 and R_4 ($R_1 > R_3 > R2 > R_4$) are placed against sunlight. A bright spot is obtained on a paper sheet for each mirror. **Which mirror forms the brightest spot at a maximum distance from the pole of the mirror?** Explain.

Images formed by Concave Mirrors

A concave mirror can produce both real and virtual images. The nature of an image depends primarily on the distance of the object from the mirror.

Let us consider the following cases:

I. When the object is at infinity

II. When the object is behind the centre of curvature

III. When the object is at the centre of curvature

IV. When the object is between the centre of curvature and the focus

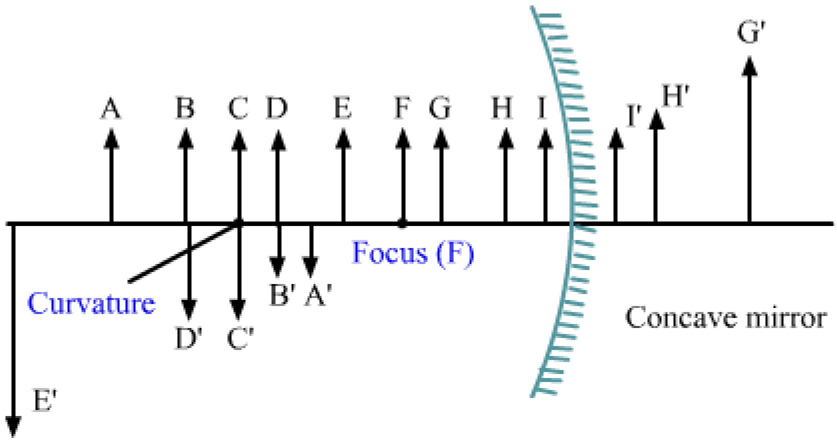
V. When the object is at the focus

VI. When the object is placed between the focus and the pole

The ray diagrams for all the six cases are as follows:

The discussion is summarised in the table given below.

Object position	Image position	Size of image	Nature of image
At infinity	At F	Point-sized	Real and inverted
Beyond C	Between F and C	Small	Real and inverted
At C	At C	Same as that of the object	Real and inverted
Between C and F	Behind C	Enlarged	Real and inverted
At F	At infinity	Highly enlarged	Real and inverted
Between F and P	Behind the mirror	Enlarged	Virtual and erect

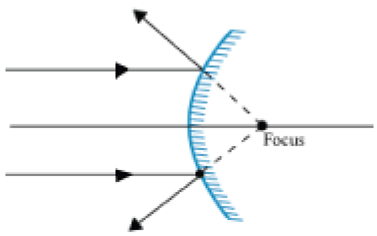


Images Formed by Convex Mirrors

A convex mirror always produces virtual and erect images of very small size. The images formed by a convex mirror are primarily classified in two ways.

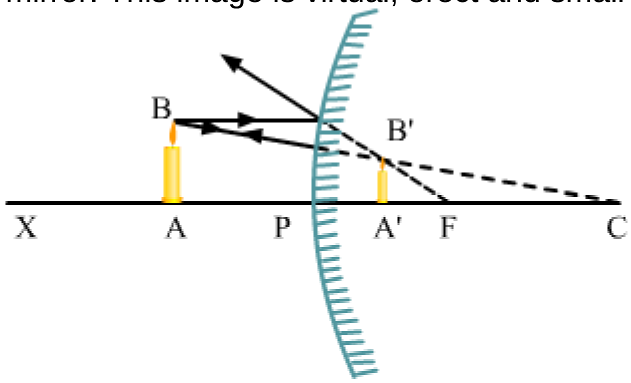
I. When the object is at infinity

In this case, the image appears to form at the focus. This image is virtual, erect and very small in size.



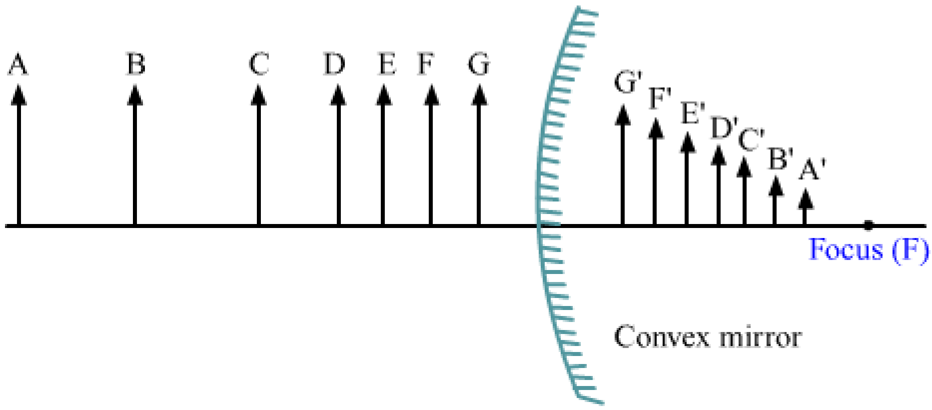
II. When the object is between the pole (P) and a point X (X lies beyond C)

In this case, the image is formed between the pole (P) and the focus (F), behind the mirror. This image is virtual, erect and small in size.



These results are summarised in the following table.

Object position	Image position	Size of image	Nature of image
At infinity	At F	Extremely small	Virtual and erect
Between P and X (X lies beyond C)	Between P and F	Small	Virtual and erect



Uses of Spherical Mirrors

Sanjay went to a dentist's clinic to get his decaying tooth examined. While sitting on the dentist's chair, he observed that the doctor was using a special type of mirror to examine his tooth. He wondered why the dentist had to use a different mirror for the examination.

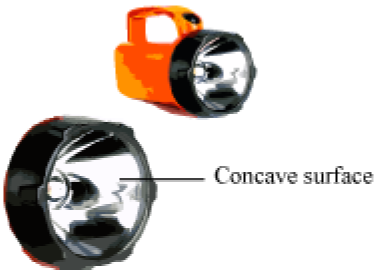
The special mirrors used by dentists are known as dentist's mirror. This mirror is actually a concave mirror and thus, capable of producing a larger image of an object (teeth, in this case). In this section, we will discuss the uses of the properties of concave and convex mirrors in our daily life.

1. Concave mirror

A concave mirror has the capability of forming images that can be smaller or larger in size and virtual or erect, depending on the position of the object.

These mirrors are used in various medical practices. For example, doctors use this mirror for obtaining a relatively larger image of teeth, ear, skin etc.

Concave mirrors are also used in reflectors for torches and headlights in vehicles. This is because these mirrors can reflect rays of light beams as very powerful light rays.



2. Convex mirror

A convex mirror always produces a smaller, virtual, and erect image of an object.

In convex mirror, the length of the image is shorter than that of the object. Hence, it is used as a side view mirror in vehicles because the viewed area must be larger than the surface area of the mirror. The convex mirror forms images of vehicles that are spread over a relatively larger area.

Vehicle mirror

Owing to this property, convex mirrors are also used in security mirrors that we often see in shops, malls, etc.