Refraction: When light travelling in a medium (such as air) enters another medium (such as water), it generally bends at the surface separating the two media. But once it is in the second medium, it moves along a straight line. **This phenomenon of bending of light at the surface separating two media is commonly known as refraction of light**. The surface separating the two media is also called the interface between them. Not the entire light incident on the interface between two media passes into the second medium after refraction; a small part of light gets reflected too. Effects of Refraction in Our Day to Day life:

1. A spoon dipped in water. The part of the spoon in air and water appears to be disjoint.
2. While standing in a clear pool of water, the bottom looks raised and our legs appear shorter.
3. The bottom of a glass tumbler filled with water appears raised when viewed from above.
4. If we put pins or coins in a tumbler filled with water and look from the side, their images appear enlarged.
5. Our ability to see also depends on refraction. Our eyes contain several transparent liquids. When light from an object enters our eyes, it is refracted at the surfaces of these liquids to produce an image.
6. Refraction is also responsible for such wonderful things as the twinkling of stars and the sparkling of diamonds.

Refractive Index: Light travels at different speeds in different materials. Therefore, when it travels from one medium to another, it either speeds up or slows down. The amount by which its speed changes determines the amount by which it changes its direction.

The speed of light in vaccum is 3×10^8 m/s. The speed of light in a transparent medium such as glass, water or clear plastic is less than this.

Refractive Index $\eta = c/v$,

where c = the speed of light in vacuum and v = the speed of light in the medium. In all material media the speed of light is less than c. Hence, the refractive index of a material medium is greater than 1. The speed of light in air at atmospheric pressure is very close to that in vacuum, and we generally take the refractive index of air as 1.The refractive index of water is about 1.33, and that of ordinary glass and diamond are about 1.50 and 2.42 respectively. Larger the refractive index of a medium, greater is the bending of light when it enters the medium from air obliquely. Thus light bends more when it enters a diamond than when it enters an imitation jewel made of glass.

Water	1.33
Kerosene	1.41
Benzene	1.50
Crown glass	1.52
Carbon disulphide	1.63
Flint glass	1.65
Diamond	2.42

Question 1: A ray of light enters a diamond from air. If the refractive index of diamond is 2.42, by what per cent does the speed of light reduce on entering the diamond?

Answer: $\eta = c/v$

$v = c/\eta = c/2.42 = 0.41c$

The speed of light in diamond is therefore 41% of its speed in air. In other words, in diamond, the speed reduces by 59%.

Laws of Refraction : The way a ray of light refracts when it is incident on the surface separating two media depends not only on the refractive indices of the media but also on the angle of incidence.

Let AB represent a plane surface separating two transparent media—Medium 1 and Medium 2. Let their refractive indices be η_1 and η_2 respectively. The two media can be any pair such as air and water, or air and glass. Suppose a ray of light P0 travelling in Medium 1 is incident on the surface AB at a point 0. Draw a normal N_1ON_2 to the surface at 0. ON_1 is in Medium 1 and ON_2 is in Medium 2. The angle i between the incident ray P0 and the normal ON_1 is called the angle of incidence

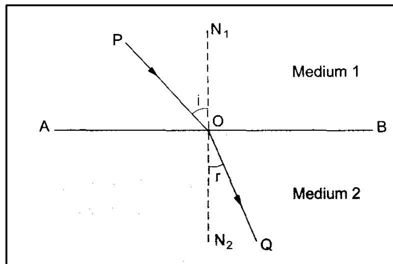


Fig. 2.2

The angle r between the refracted ray OQ and the normal ON_2 is called the angle of refraction. Two laws of refraction govern the refraction that takes place at a surface of separation such as AB.

1. The incident ray, the normal and the refracted ray to the refracting surface at the point of incidence lie in the same plane.
2. The angle of incidence and the angle of refraction satisfy the equation

$\sin i / \sin r = \eta_2 / \eta_1$

The second law given above is also called Snell's law.

If the first medium is air then $\eta_1 = 1$. Let the refractive index of the second medium be denoted by η then

$\sin i / \sin r = \eta$

The ration η_2 / η_1 is also called the refractive index of medium 2 with respect to medium 1 and is denoted by the symbol η_{21}. If v_1 and v_2 are the speeds of light in Medium 1 and Medium 2 respectively,

$\eta_{21} = \eta_2 / \eta_1 = (c/v_2) / (c/v_1)$

$\eta_{21} = v_1/v_2$

Similarly $\eta_{12} = v_2/v_1$

Thus $\eta_{21} = 1/\eta_{12}$

Question2: A ray of light travelling in air falls on the surface of a transparent slab. The ray makes an angle of 45° with the normal to the surface. Find the angle made by the refracted ray with the normal within the slab. Refractive index of the material of the slab =√2

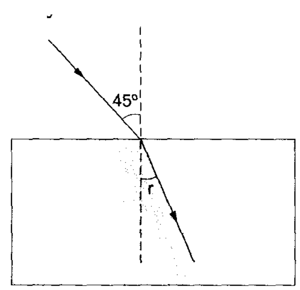
Answer:

We have, $\dfrac{\sin i}{\sin r} = n$

or $\dfrac{\sin 45°}{\sin r} = \sqrt{2}$

or $\sin r = \dfrac{1}{\sqrt{2}} \times \sin 45° = \dfrac{1}{\sqrt{2}} \times \dfrac{1}{\sqrt{2}} = \dfrac{1}{2}$.

This gives $r = 30°$.



If a ray falls perpendicularly on the refracting surface, it goes into the second medium without deviation. This is because in this case i = 0, and from Snell's law, sin r =(sin i)/n = 0,that is r=0

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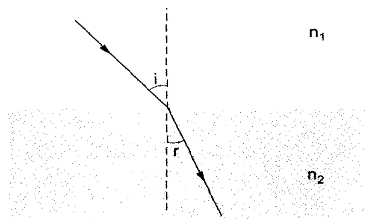
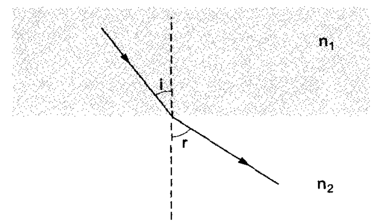
Even though there is no bending in the case of normal incidence, we say that light has refracted. You can associate refraction with change in the speed of light as the medium changes, and that occurs even if the rays fall normally and proceed without bending.

Optically Denser & Rarer Media: Of a pair of transparent media, the one that has the higher refractive index is called the optically denser medium of the two, while the one that has the lower refractive index is called the optically rarer medium. Thus water and glass are optically denser than air, water is optically rarer than glass, and so on.



Ray goes from rarer to denser medium ($n_1 < n_2$).

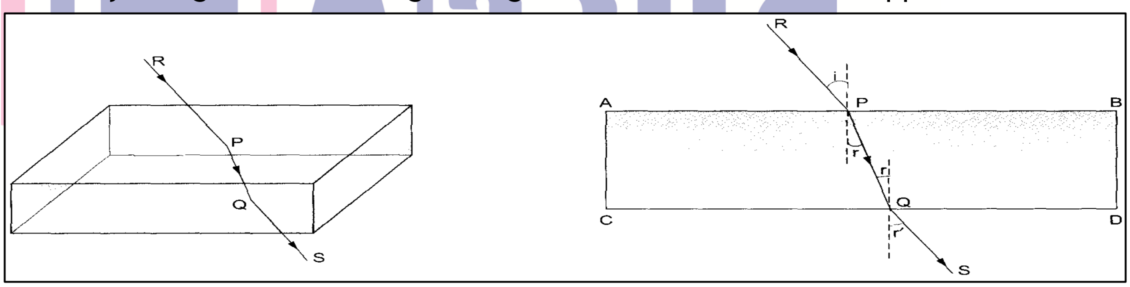


Ray goes from denser to rarer medium ($n_1 > n_2$).

Remember that optically denser does not mean greater mass density (mass per unit volume). For example, kerosene is lighter than water (it floats on water), but it has higher refractive index, that is, it is optically denser than water.

When light goes from the optically rarer medium to the optically denser medium, it slows down and bends towards the normal. And when it goes from the denser medium to the rarer medium, it speeds up and bends away from the normal.

Let a ray of light RP travelling through air be incident on the upper surface of a



transparent rectangular slab. This ray gets refracted at the upper surface and moves along PQ within the slab. When it reaches the lower surface, it gets refracted again as it re-enters air.

For the refraction at P. let the angle of incidence be i and the angle of refraction be r. If the refractive index of the material of the slab is n,

$$\frac{\sin i}{\sin r} = n.$$

sin i= n sin r

For the refraction at Q, PQ is the incident ray and QS is the refracted ray. Since AB and CD are parallel, the normals to them are also parallel. Hence, from geometry, the angle of incidence at Q is r. Let the angle of refraction be r'. Since for this refraction the slab is the first medium ($\eta_1 = \eta$) and air is the second medium ($\eta_2 =$ 1), we have from Snell's law

$$\frac{\sin r}{\sin r'} = \frac{1}{n} \qquad \sin r' = n \sin r.$$

But from (i), sin i = n sin r.

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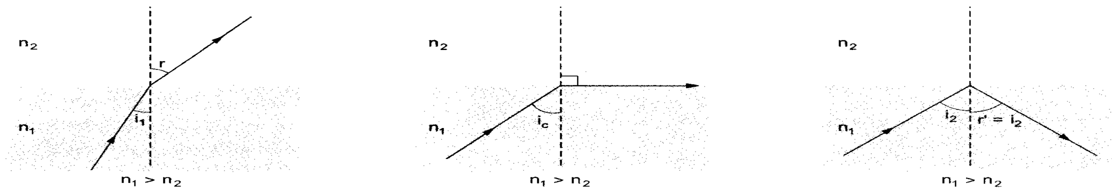
Therefore sin r'= sin i or r'=i.

This means that the ray QS is parallel to the ray RP. Thus, on passing through a transparent slab with parallel faces, a ray is displaced parallel to itself. That is, the ray is shifted laterally (sideways). The amount by which the ray is displaced is proportional to the thickness of the slab. Therefore, for a very thin slab (for example, a sheet of thin glass) the displacement is negligible.

Total Internal Reflection

Let a ray of light travel from a medium of higher refractive index (η_1) to a medium of lower refractive index (η_2) as sown in the figure below.



After refraction the ray of light bends away from the normal. Therefore, the angle of refraction is greater than the angle of incidence, i.e., r > i. Now, if the angle of incidence i increased the angle of refraction r increases. For a particular value of i, called the (i_c), the angle of refraction becomes 90º. The refracted ray then comes out parallel to the surface separating the two media. When the angle of incidence is greater than the critical angle, the angle of refraction will be more than 90°. This would bring the ray back into the first medium. But that would not be refraction. This means that for an angle of incidence greater than i_c, refraction is not possible. So, the ray reflects back into the first medium. This reflection obeys the laws of reflection, and therefore, $r' = i_2$. Such a reflection is called total internal reflection. Remember that total internal reflection takes place only for light travelling from a medium of higher refractive index to a medium of lower refractive index.

<u>The total reflection of light travelling in a medium of higher refractive index when it is incident on the boundary with another medium of lower refractive index at an angle greater than the critical angle is called total internal reflection.</u>

We say it as 'total' because we know that when light falls obliquely on the interface between two transparent media, a small part of the light is reflected into the first medium. But when the angle of incidence is greater than the critical angle, the whole of the light gets reflected. Hence, it is called total internal reflection.

For $i = i_c$ r= 90°. From Snell's law,

$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1} \quad \text{or} \quad \frac{\sin i_c}{\sin 90°} = \frac{\sin i_c}{1} = \frac{n_2}{n_1}$$

The critical angle is different for different pairs of media. The higher the refractive index of the denser medium, the smaller is the critical angle for the pair.

<u>Sparkling of diamond</u>: The high refractive index (2.42) of diamond gives it a critical angle of only 24°. So, many rays trying to cross the diamond—air interface are incident

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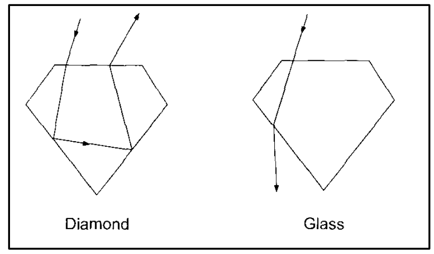
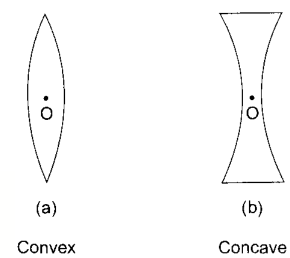
at angles greater than the critical angle. The faces of the diamond are cut in such a way that most rays inside the diamond undergo total internal reflection. For example, most rays entering from the top of a properly cut diamond undergo multiple total internal reflections and emerge from the top face. But if we take a similarly cut piece of glass, a large number of incident rays emerge on the other side of the glass. Thus, the diamond sparkles in comparison, because the eye receives much more light from the diamond than it does from the glass.



Thin Lenses: A transparent material bounded by two surfaces of which at least one is curved is called a lens. Most lenses used in spectacles, magnifying glasses, cameras and microscopes have at least one spherical surface. In some cases, cylindrical lenses are used in spectacles.

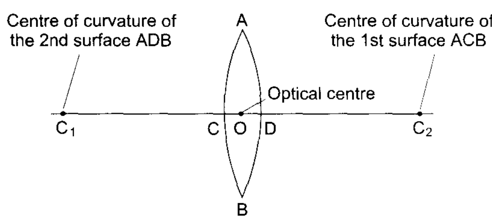
The cross sections of some lenses are shown in Figure. A lens that is thicker at the middle than at the edges is called a convex lens while a lens that is thicker at the edges is called a concave lens. If both the surfaces of a lens are convex, it is called a double-convex or biconvex lens. And the type of concave lens in which both the surfaces are concave is called a double-concave or biconcave lens.

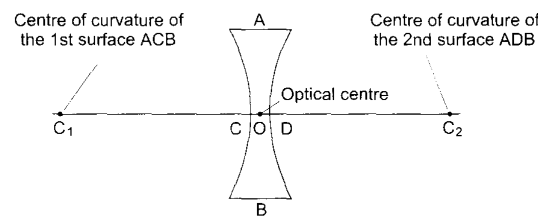


Terms:

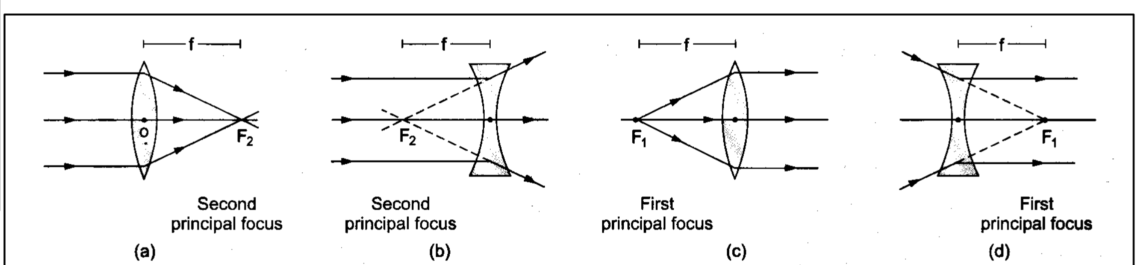
Optical centre: The central point 0 of the lens is called its optical centre. A ray incident towards the optical centre passes almost without any deviation through the lens.

Principal Axis: lens is bounded by two spherical surfaces, and therefore, has two centres of curvature—C_1 and C_2. The line C_1C_2 joining them is called the principal Axis of the lens.





Focus or Focal length: If a beam of light is incident parallel to the principal axis of a convex lens, it converges to a point F_2 on the principal axis on the other side of the lens. This point is called the second principal of the convex lens. In case of a concave lens, a beam of light incident parallel to the principal axis diverges after passing through the lens. If the transmitted rays are produced backwards, they meet at a point F_2 on the principal axis on the side of the incident rays. To an observer, the transmitted rays appear to come from this point. This point F_2 is



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called the second principal focus of the concave lens. A point object is kept at the point F_1 on the principal axis of a convex lens such that the rays starting from F_1 become parallel to the principal axis after transmission. Such a point is called the first principal focus axis of the convex lens. Rays converging towards a point F_1 fall on a concave lens such that they become parallel to the principal axis after transmission. Such a point is called the first principal focus of the concave lens.

In a thin lens, rays incident parallel to the principal axis after passing through the lens converge to or appear to diverge from a point on the principal axis. And, the rays coming from a point on the principal axis or rays going towards a point on it become parallel to the principal axis after passing through the lens. Each of these two points is called a focus of the thin lens, and the distance of the focus from the optical centre is called its focal length. Usually, when we say 'focus', we mean the second principal locus.

Since a parallel beam of light incident on a convex lens converges on the other side, a convex lens is also called a converging lens. On the other hand, a parallel beam of light incident on a concave lens diverges on the other side. A concave lens is therefore also called a diverging lens.

Power of a lens The power of a lens is defined as the reciprocal of its focal length.

$P = \frac{1}{f}$ If focal length is measured in metres, power will be in metre^{-1}. This unit (metre^{-1}) is also called dioptre and is represented by D. Thus, if the focal length of a lens is 25 cm (that is, 0.25 m), its power will be P= 1/0.25 = 4.0 D

Rays used for ray diagram of Image formation:

1. We choose the ray that is incident parallel to the principal axis. In case of a convex lens, the transmitted ray will pass through the focus, and in case of a concave lens, the transmitted ray's backward projection will pass through the focus.

2. We choose the ray that passes through the optical centre of the lens. This ray is transmitted without any deviation.

The point of intersection of these two transmitted rays is the image of the point object. While tracing the rays, we do not show the ray bending at each surface of the lens. Instead, we show the incident rays getting bent at the central, vertical line of the lens.

Sign Conventions:

Object Distance: From the optical centre to the foot of the perpendicular drawn from the point object to the principal axis. It is denoted by u

Image Distance: From the optical centre to the foot of the perpendicular drawn from the image of a point object to the principal axis. It is denoted by v.

Focal length: From the optical centre to the second principal focus. It is denoted by f.

Height of the object: h_o,

Height of the image: h_i

These values can be positive or negative.

The focal length of a convex lens is always positive and that of a concave lens is always negative in this convention.

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Lens Equation: The quantities u, v and f for a thin lens are related by the lens equation.

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

Q1: An object is placed 30 cm from a convex lens. A real image is formed 20 cm from the lens. Find the focal length of the lens. [12cm]

Q2: A ray of light travelling in air is incident on the plane surface of a transparent medium. The angle of incidence is 450 and the angle of refraction is 300. Find the refractive index of the medium. [√2]

Images Formed by a Convex Lens

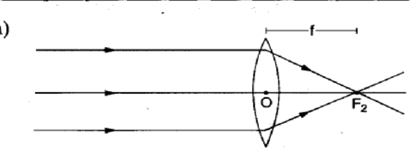
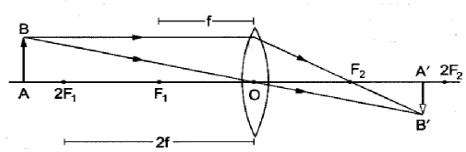
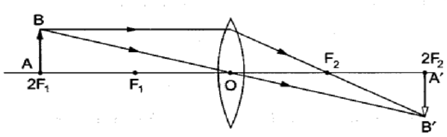
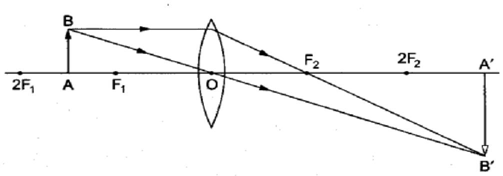
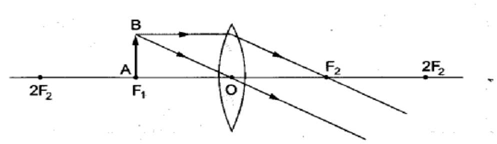
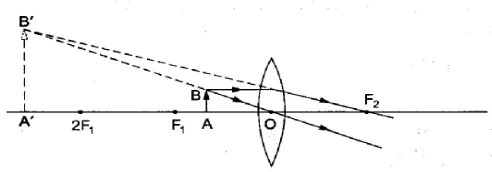
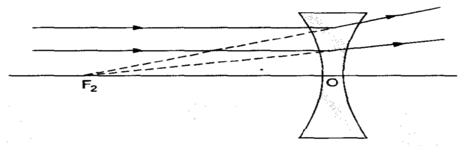
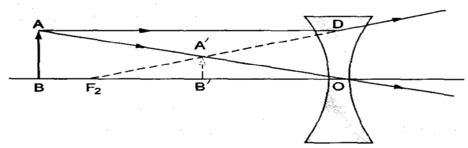
	Position of the object	Position of the image	Nature and size
(a) 	at infinity	at F_2	real, point-sized
(b) 	between infinity and $2F_1$	between F_2 and $2F_2$	real, smaller, inverted
(c) 	at $2F_1$	at $2F_2$	real, same-sized, inverted
(d) 	between $2F_1$ and F_1	between $2F_2$ and infinity	real, enlarged, inverted
*(e) 	at F_1	at infinity	real, infinitely large, inverted
(f) 	between F_1 and O	on the side of the object	virtual, larger, erect

Image formation of Concave Lens:

	Position of the object	Position of the image	Nature and size
	at infinity	at F_2	virtual, point-sized
	between infinity and O	between F_2 and O	virtual, erect and smaller

<u>Magnification</u>: The image formed by a lens can be larger or smaller than the object, or it can be of the same size. If h_0 and h_i denote the object-height and the image-height, the ratio h_i/h_0 is defined as the magnification. It is denoted by the symbol m. It is also defined as v/u.

If m is positive, h_i is also positive. This means, the image and the object are on the same side of the principal axis (erect image). If m is negative, they are on the opposite sides of the principal axis (inverted image). For a convex lens, the image can be erect or inverted. When the image is erect (and virtual) the magnification is positive, and when the image is inverted (and real) m is negative. For a concave lens m is always positive.

<u>Note</u> the difference of sign in the equations for the magnification by a spherical mirror and the magnification by a thin lens.

Question 2: A 2.0 cm long pin is placed perpendicular to the principal axis of a convex lens of focal length 12 cm. The distance of the pin from the lens is 15 cm. Find the size of the image. [-8.0 cm]

<u>Lenses in Contact</u>:

When two or more thin lenses are kept in contact with each other such that they have the same principal axis, the combination can be treated as a single thin lens. If the focal lengths of the individual lenses are f_1, f_2,.., the focal length F of the equivalent single lens is given by

$$\frac{1}{F}=\frac{1}{f_1}+\frac{1}{f_2}+\ldots$$

Power for the combination: $P = P_1 + P_2 + \ldots$

This equation is often used in deciding the power of the lens to be prescribed for a person suffering from a defect of vision. If by putting two lenses of powers +2.0 D and +0.50 D in contact the person can see clearly, a lens of power +2.50 D is prescribed for that person.

<u>Exercise</u>:

Q1. A ray of light travelling in air falls on the surface of a rectangular slab of a plastic material whose refractive index is 1.6. If the incident ray makes an angle of 53° with the normal, find the angle made by the refracted ray with the normal (sin 53° = 4/5). [30°]

Q2. Find the refractive index of glass with respect to water. The refractive indices of these with respect to air are 3/2 and 4/3 respectively. [9/8]

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Q3. A point object is placed at a distance of 12 cm from a convex lens on its principal axis. Its image is formed on the other side of the lens at a distance of 18 cm from the lens. Find the focal length of the lens. [7.2cm]

Q4. The image of an object formed by a convex lens is of the same size as the object. If the image is formed at a distance of 40 cm, find the focal length of the lens. Also, find the power of the lens. At what distance from the lens is the object placed? [40cm]

Q5. A convex lens of power 4 D is placed at a distance of 40 cm from a wall. At what distance from the lens should a candle be placed so that its image is formed on the wall? [200/3 cm]

Q6. A 4.0-cm-high object is placed at a distance of 60 cm from a concave lens of focal length 20 cm. Find the size of the image. [1cm high]

Q7. A convex lens of focal length 20 cm is placed in contact with a concave lens of focal length 12.5 cm in such a way that they have the same principal axis. Find the power of the combination. [-3D]

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