CHAPTER (23)

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CONCEPTS

- 23-1: The Ray Model of Light
- 23-4: Index of Refraction
- 23-5: Refraction: Snell's Law
- 23-6: Total Internal Reflection; Fiber Optics
- 23-7: Thin Lenses; Ray Tracing
- 23-8: The Thin Lens Equation

23–1 THE RAY MODEL OF LIGHT

- the ray model of light. This model assumes that light travels in straight-line paths called light rays in transparent media.
- When we see an object, according to the ray model, light reaches our eyes from each point on the object. Although light rays leave each point in many different directions, normally only a small bundle of these rays can enter the pupil of an observer's eye
- the ray model has been very successful in describing many aspects of light such as reflection, refraction, and the formation of images by mirrors and lenses. Because these explanations involve straight-line rays at various angles, this subject is referred to as geometric optics

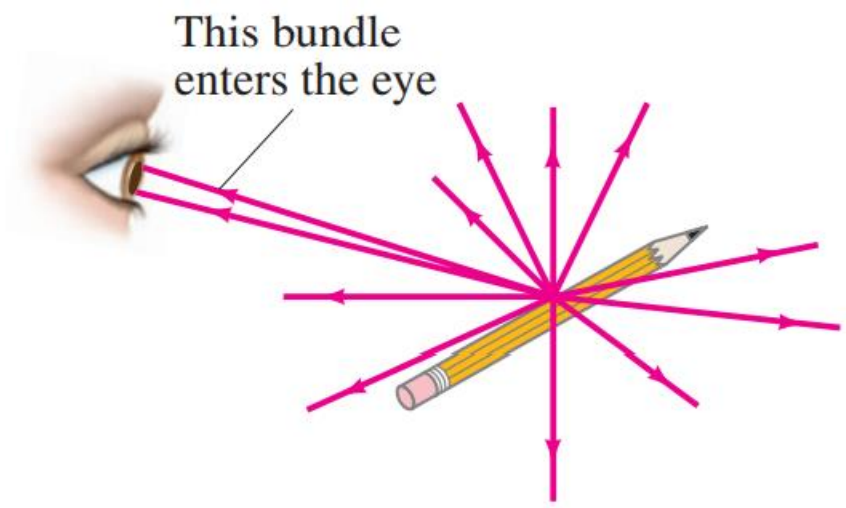


FIGURE 23–1 Light rays come from each single point on an object. A small bundle of rays leaving one point is shown entering a person's eye.

23–4 Index of Refraction

- the speed of light in vacuum = $3.00 \times 10^8\,\mathrm{m/s}$

In air, the speed is only slightly less. In other transparent materials, such as glass and water, the speed is always less than that in vacuum. For example, in water light travels at about $\frac{3}{4}c$. The ratio of the speed of light in vacuum to the speed v in a given material is called the **index of refraction**, n, of that material:

$$n = \frac{c}{v}. \qquad \textbf{(23–4)}$$

The index of refraction is never less than 1, and values for various materials are given in Table 23–1. For example, since $n = 1.33$ for water, the speed of light in water is

$$v = \frac{c}{n} = \frac{(3.00 \times 10^8\,\mathrm{m/s})}{1.33} = 2.26 \times 10^8\,\mathrm{m/s}.$$

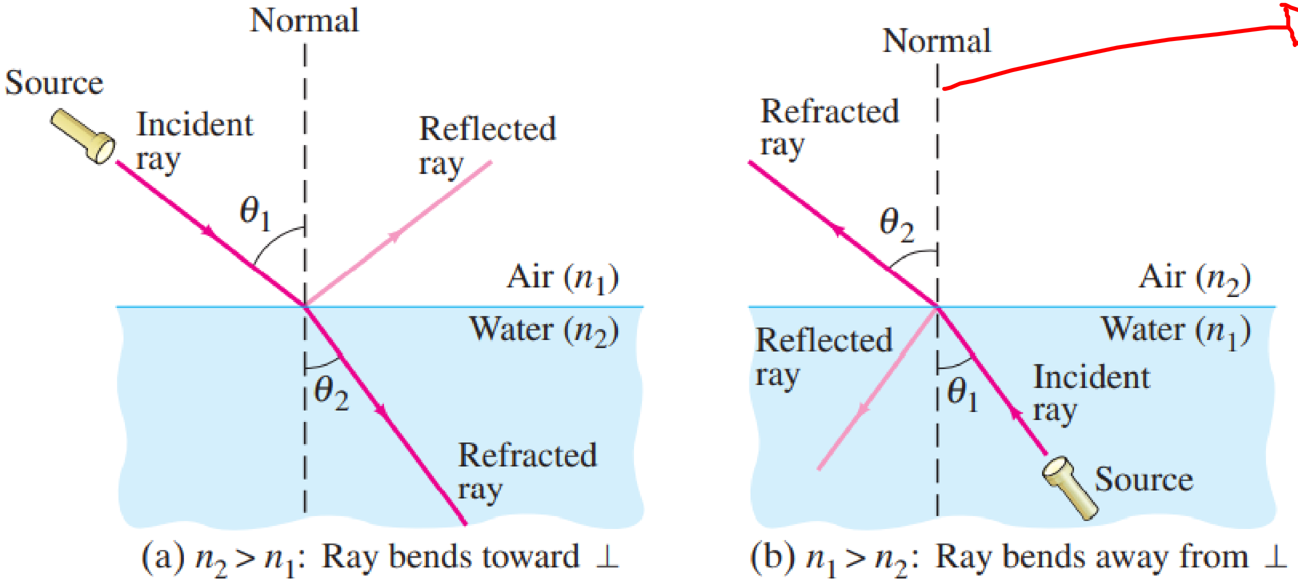
TABLE 23–1 Indices of Refraction†

Material	$n = \frac{c}{v}$
Vacuum	1.0000
Air (at STP)	1.0003
Water	1.33
Ethyl alcohol	1.36
Glass	
Fused quartz	1.46
Crown glass	1.52
Light flint	1.58
Plastic	
Acrylic, Lucite, CR-39	1.50
Polycarbonate	1.59
“High-index”	1.6–1.7
Sodium chloride	1.53
Diamond	2.42

† $\lambda = 589$ nm.

23–5 REFRACTION: SNELL'S LAW

- The change in light direction is called refraction



Perpendicular to the two media

FIGURE 23–21 Refraction. (a) Light refracted when passing from air (n_1) into water (n_2): $n_2 > n_1$. (b) Light refracted when passing from water (n_1) into air (n_2): $n_1 > n_2$.

θ_1 Angle of incidence

θ_2 Angle of refraction

- So we can conclude:
  Light bends toward the normal when we moves from lower density to higher density area
  Light bends away from the normal when we moves from higher density to lower density area

(a)

(b)

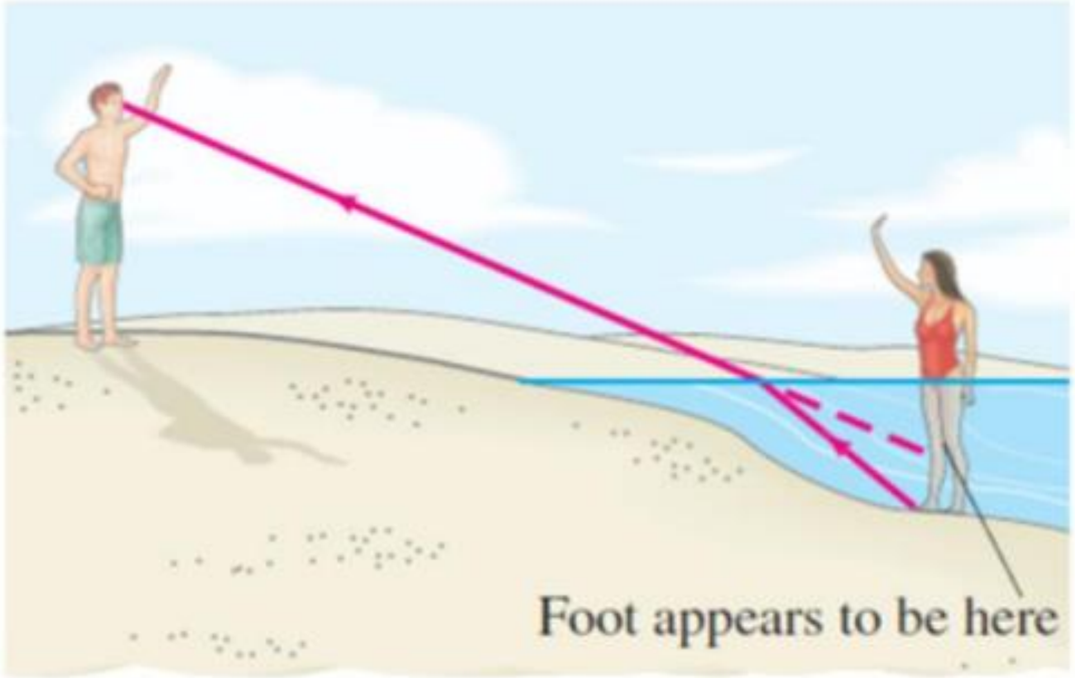
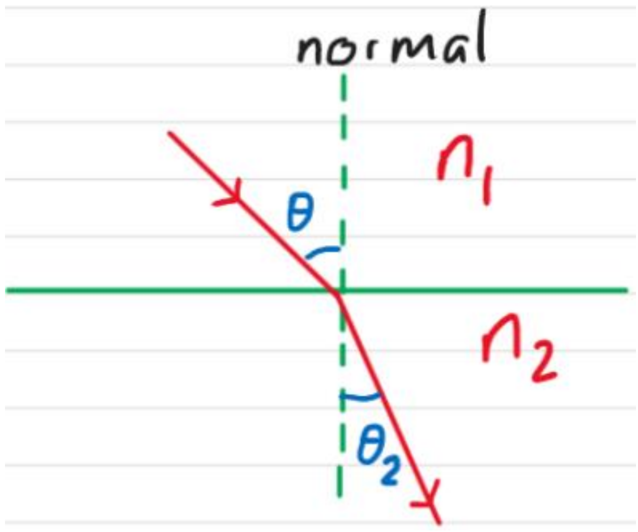


FIGURE 23–22 (a) Photograph, and (b) ray diagram showing why a person's legs look shorter standing in water: a ray from the bather's foot to the observer's eye bends at the water's surface, and our brain interprets the light as traveling in a straight line, from higher up (dashed line).

23–5 REFRACTION: SNELL'S LAW

- Snell's law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$
- The incident and refracted rays lie in the same plane, which also includes the perpendicular to the surface. Snell's law is the law of refraction



EXERCISE C Light passes from a medium with $n = 1.3$ (water) into a medium with $n = 1.5$ (glass). Is the light bent toward or away from the perpendicular to the interface?

A: Towards Normal

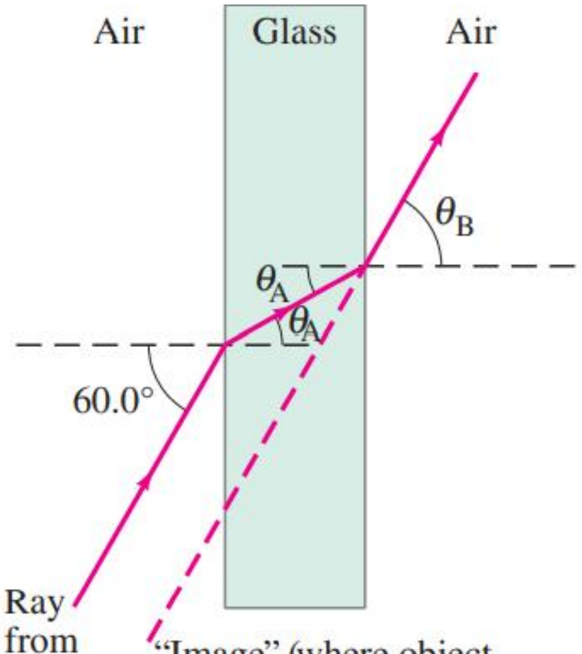


FIGURE 23–24 Light passing through a piece of glass (Example 23–8).

EXAMPLE 23–8 **Refraction through flat glass.** Light traveling in air strikes a flat piece of uniformly thick glass at an incident angle of 60.0°, as shown in Fig. 23–24. If the index of refraction of the glass is 1.50, (*a*) what is the angle of refraction θ_A in the glass; (*b*) what is the angle θ_B at which the ray emerges from the glass?

APPROACH We apply Snell's law twice: at the first surface, where the light enters the glass, and again at the second surface where it leaves the glass and enters the air.

SOLUTION (*a*) The incident ray is in air, so $n_1 = 1.00$ and $n_2 = 1.50$. Applying Snell's law where the light enters the glass $(\theta_1 = 60.0°,\ \theta_2 = \theta_A)$ gives

$$(1.00)\sin 60.0° = (1.50)\sin\theta_A$$

or

$$\sin\theta_A = \frac{1.00}{1.50}\sin 60.0° = 0.5774,$$

and $\theta_A = 35.3°$.

(*b*) Since the faces of the glass are parallel, the incident angle at the second surface is also θ_A (geometry), so $\sin\theta_A = 0.5774$. At this second interface, $n_1 = 1.50$ and $n_2 = 1.00$. Thus the ray re-enters the air at an angle θ_B given by

$$\sin\theta_B = \frac{1.50}{1.00}\sin\theta_A = 0.866,$$

and $\theta_B = 60.0°$. The direction of a light ray is thus unchanged by passing through a flat piece of glass of uniform thickness.

NOTE This result is valid for any angle of incidence. The ray is displaced slightly to one side, however. You can observe this by looking through a piece of glass (near its edge) at some object and then moving your head to the side slightly so that you see the object directly. It "jumps."

28. (I) A flashlight beam strikes the surface of a pane of glass ($n = 1.56$) at a 67° angle to the normal. What is the angle of refraction?

32. (II) An aquarium filled with water has flat glass sides whose index of refraction is 1.54. A beam of light from outside the aquarium strikes the glass at a 43.5° angle to the perpendicular (Fig. 23–56). What is the angle of this light ray when it enters (*a*) the glass, and then (*b*) the water? (*c*) What would be the refracted angle if the ray entered the water directly?

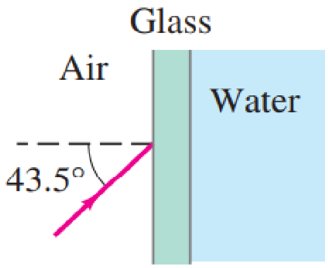


FIGURE 23–56 Problem 32.

34. (II) In searching the bottom of a pool at night, a watchman shines a narrow beam of light from his flashlight, 1.3 m above the water level, onto the surface of the water at a point 2.5 m from his foot at the edge of the pool (Fig. 23–57). Where does the spot of light hit the bottom of the 2.1-m-deep pool? Measure from the bottom of the wall beneath his foot.

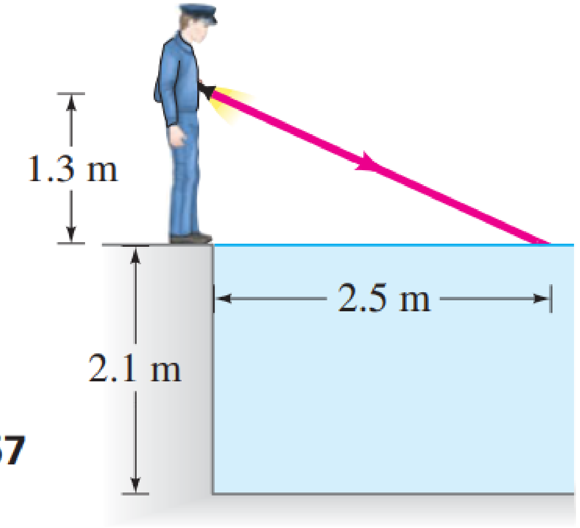
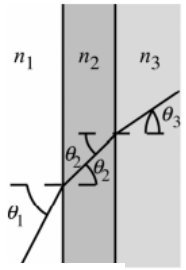


FIGURE 23–57 Problem 34.

28. Find the angle of refraction from Snell's law.

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \rightarrow \theta_2 = \sin^{-1}\left(\frac{n_1}{n_2}\sin\theta_1\right) = \sin^{-1}\left(\frac{1.00}{1.56}\sin 67°\right) = \boxed{36°}$$

32. (*a*) We use Eq. 23–5 to calculate the refracted angle as the light enters the glass ($n = 1.56$) from the air ($n = 1.00$).



$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \rightarrow$$

$$\theta_2 = \sin^{-1}\left[\frac{n_1}{n_2}\sin\theta_1\right] = \sin^{-1}\left[\frac{1.00}{1.54}\sin 43.5°\right] = 26.55° \approx \boxed{26.6°}$$

(*b*) We again use Eq. 23–5 using the refracted angle in the glass and the indices of refraction of the glass and water.

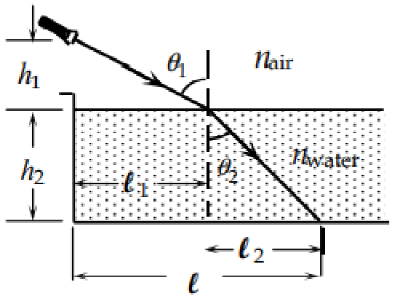
$$\theta_3 = \sin^{-1}\left[\frac{n_2}{n_3}\sin\theta_2\right] = \sin^{-1}\left[\frac{1.54}{1.33}\sin 26.55°\right] = 31.17° \approx \boxed{31.2°}$$

(*c*) We repeat the same calculation as in part (*a*) but using the index of refraction of water.

$$\theta_3 = \sin^{-1}\left[\frac{n_1}{n_3}\sin\theta_1\right] = \sin^{-1}\left[\frac{1.00}{1.33}\sin 43.5°\right] = 31.17° \approx \boxed{31.2°}$$

As expected, the refracted angle in the water is the same whether the light beam first passes through the glass or passes directly into the water.

34. We find the angle of incidence from the distances.



$$\tan\theta_1 = \frac{\ell_1}{h_1} = \frac{(2.5\text{ m})}{(1.3\text{ m})} = 1.9231 \rightarrow \theta_1 = 62.526°$$

Use Snell's law to find the angle in the water.

$$n_{air}\sin\theta_1 = n_{water}\sin\theta_2;$$

$$(1.00)\sin 62.526° = (1.33)\sin\theta_2 \rightarrow \theta_2 = 41.842°$$

Find the horizontal distance from the edge of the pool.

$$\ell = \ell_1 + \ell_2 = \ell_1 + h_2\tan\theta_2$$

$$= 2.5\text{ m} + (2.1\text{ m})\tan 41.842° = 4.38\text{ m} \approx \boxed{4.4\text{ m}}$$

23–6 TOTAL INTERNAL REFLECTION; FIBER OPTICS

When light passes from one material into a second material where the index of refraction is less (say, from water into air), the refracted light ray bends away from the normal, as for rays I and J in Fig. 23–26. At a particular incident angle, the angle of refraction will be 90°, and the refracted ray would skim the surface (ray K).

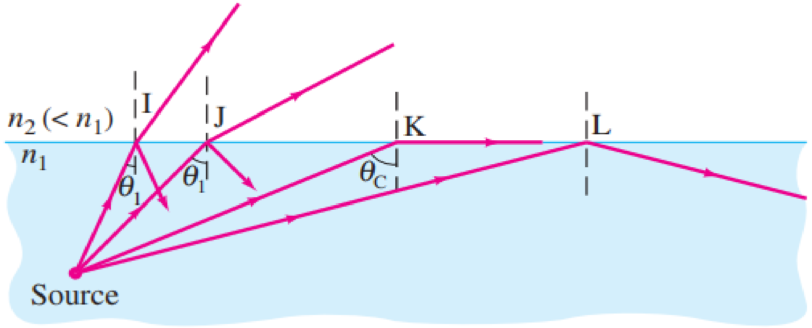


FIGURE 23–26 Since $n_2 < n_1$, light rays are totally internally reflected if the incident angle $\theta_1 > \theta_C$, as for ray L. If $\theta_1 < \theta_C$, as for rays I and J, only a part of the light is reflected, and the rest is refracted.

The incident angle at which this occurs is called the **critical angle**, θ_C. From Snell's law, θ_C is given by

$$\sin\theta_C = \frac{n_2}{n_1}\sin 90° = \frac{n_2}{n_1}. \qquad \textbf{(23–6)}$$

For any incident angle less than θ_C, there will be a refracted ray, although part of the light will also be reflected at the boundary. However, for incident angles θ_1 greater than θ_C, Snell's law would tell us that $\sin\theta_2$ ($= n_1 \sin\theta_1 / n_2$) would be greater than 1.00 when $n_2 < n_1$. Yet the sine of an angle can never be greater than 1.00. In this case there is no refracted ray at all, and *all of the light is reflected*, as for ray L in Fig. 23–26. This effect is called **total internal reflection**. Total internal reflection occurs only when light strikes a boundary where the medium beyond has a *lower* index of refraction.

CAUTION

Total internal reflection (occurs only if refractive index is smaller beyond boundary)

36. (I) The critical angle for a certain liquid–air surface is 47.2°. What is the index of refraction of the liquid?

36. Use Eq. 23–6.

$$\sin\theta_C = \frac{n_{air}}{n_{liquid}} \rightarrow n_{liquid} = \frac{n_{air}}{\sin\theta_1} = \frac{1.00}{\sin 47.2°} = \boxed{1.36}$$

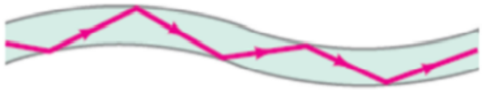
Fibre Optics; Medical Instruments

Total internal reflection is the principle underlying the use of fibre optics.

Glass and plastic fibres as thin as few micrometers are used to manufacture optic fibres.

A bundle of such transparant fibres is called a fibre-optic cable or light pipe.

FIGURE 23–29 Light reflected totally at the interior surface of a glass or transparent plastic fiber.



Fibre-optic cables are use in:

- communications: lead to very fast and larg transmission of data. fibres can support more than 100 separate wavelengths, each can carry more than 10 gigabits of data per second.

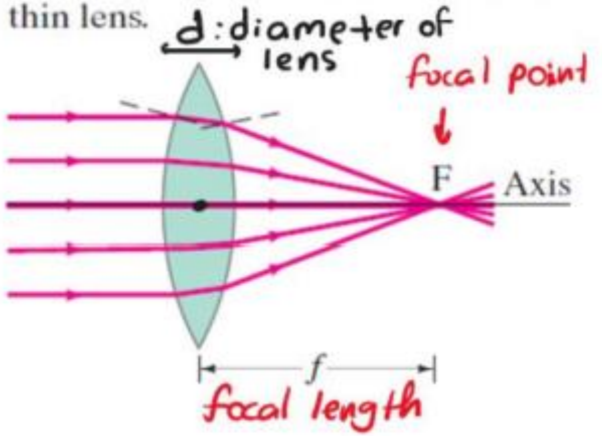
- medicine : Optic-fibres are used in medicine to provide clear pictures of human organs.

  bronchoscope: optic-fibre cable used to view the lungs.

  Colonoscope : optic-fibre cable used to view the colon.

23-7] Thin Lenses; Ray Tracing

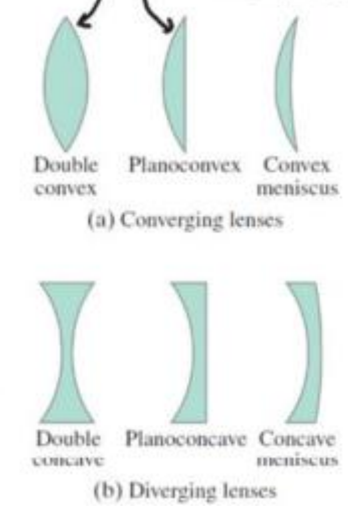
FIGURE 23–33 Parallel rays are brought to a focus by a converging thin lens.



parts of spherical surfaces

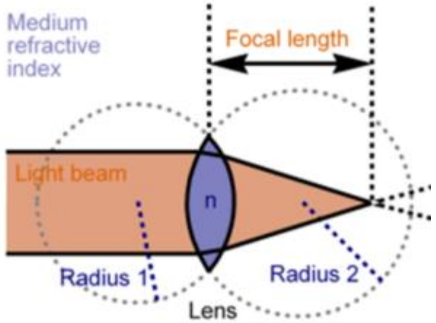
converging lenses →

diverging lenses →



When diameter of lens (d) << radius of curvature
⇒ lens is called a thin lens.

Radius 1: radius of curvature of right hand side of spherical surface of the lens.

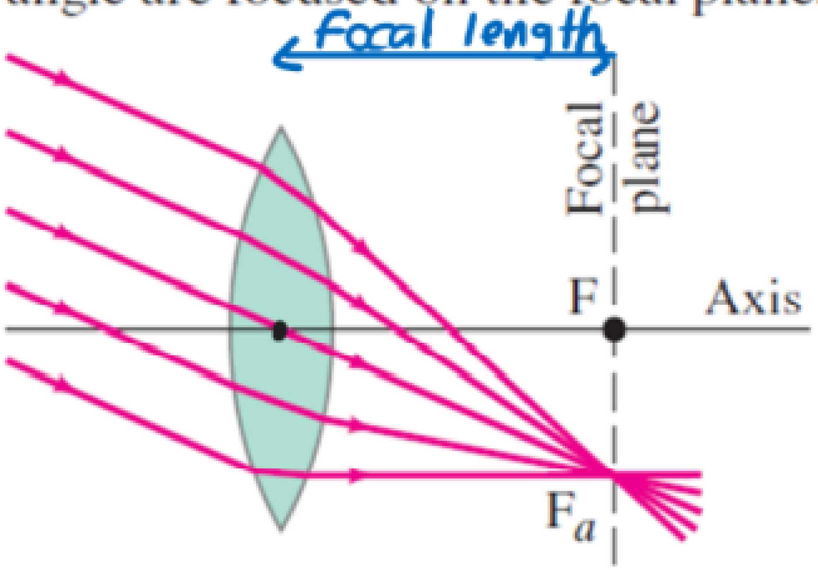


Radius2: radius of curvature of left hand side spherical surface of the lens.

Rays that are parallel to the principal axis refract passing through the focal point ⇒ converging lens.

Parallel rays falling on the lens at an angle are focused on a point F_a that lies on the focal plane.

FIGURE 23–35 Parallel rays at an angle are focused on the focal plane.

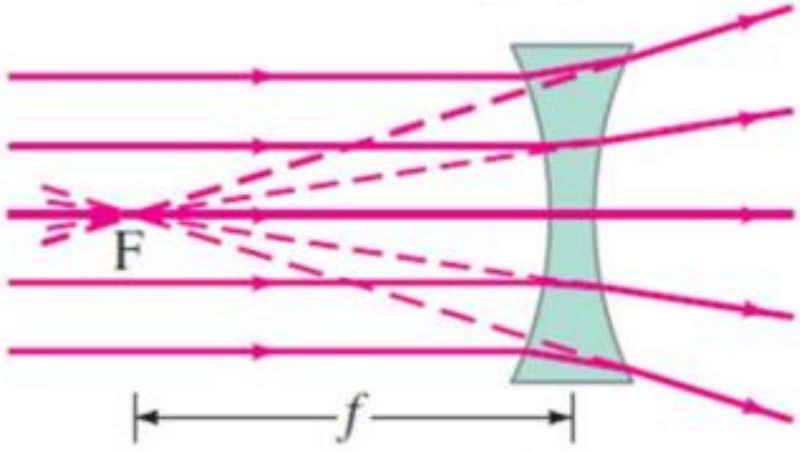


• center of the lens.

Diverging lens: it diverges the parallel rays falling on it.

Refracted rays seem to originate from the focal point F.

FIGURE 23–36 Diverging lens.



focal length

Lens Power

Optometrists and Opthalmologists define the lens power as

$$P = \frac{1}{f} \quad , \quad f \text{ is the focal length}$$

A lens whose focal length $f = 20$ cm $= 0.2$ m has a lens power of

$$P = \frac{1}{0.2} = 5 \text{ m}^{-1} = 5 \text{ D}$$

diopter

So the unit used for lens power is diopter $D \equiv m^{-1}$

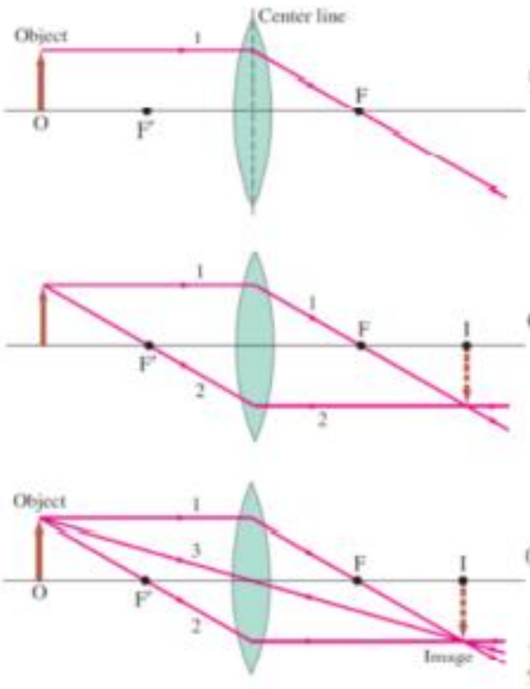
Determining the position of the image of an object

Need to draw three rays:

Ray ① falls parallel to the lens axis
is refracted through the focal point

Ray ② passes through the focal point
(F' in front of the lens) is refracted
parallel to the lens axis.

Ray ③ it passes through the center
of the thin lens as shown.



(a) Ray 1 leaves one point on object going parallel to the axis, then refracts through focal point behind the lens.

(b) Ray 2 passes through F' in front of the lens; therefore it is parallel to the axis behind the lens.

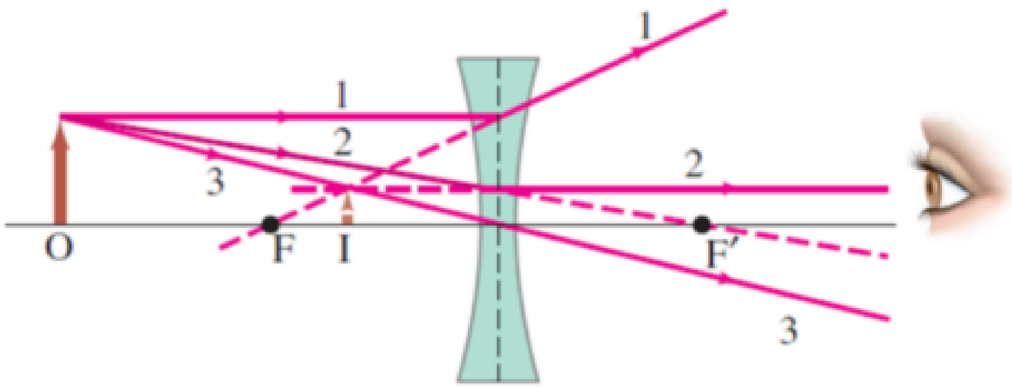
(c) Ray 3 passes straight through the center of the lens (assumed very thin).

The image of the tip of the of the arrow is at the position of intersection of the three rays. The same technique can be applied to all points of the object ⇒ leading to the image shown in the figure.

The image is a result of intersection of the actual rays and can be observed on a screen ⇒ Real Image.

Diverging Lens

It diverges the refracted rays as shown.



The refracted rays appear as if they originate from the focal point (F) infront of the lens.

To determine the position of the image, we need three rays as shown.

Ray 1 : Incident parallel to the lens axis. It is refracted such that it extrapolation passes through the focal point (F).

Ray 2 : It falls on the lens such that its extrapolation passes through the focal point (F'). This ray is refracted parallel to the lens axis.

Ray 3 : It passes through the center of the lens and passes through the thin lens along the same direction.

The same can be done to find the position of the image corresponding to all the other points on the object

All refracted rays seem as if they originate from a point on the left of the lens, which is the position of the image. This is a virtual image since it is NOT formed at the point of intersection of the rays.