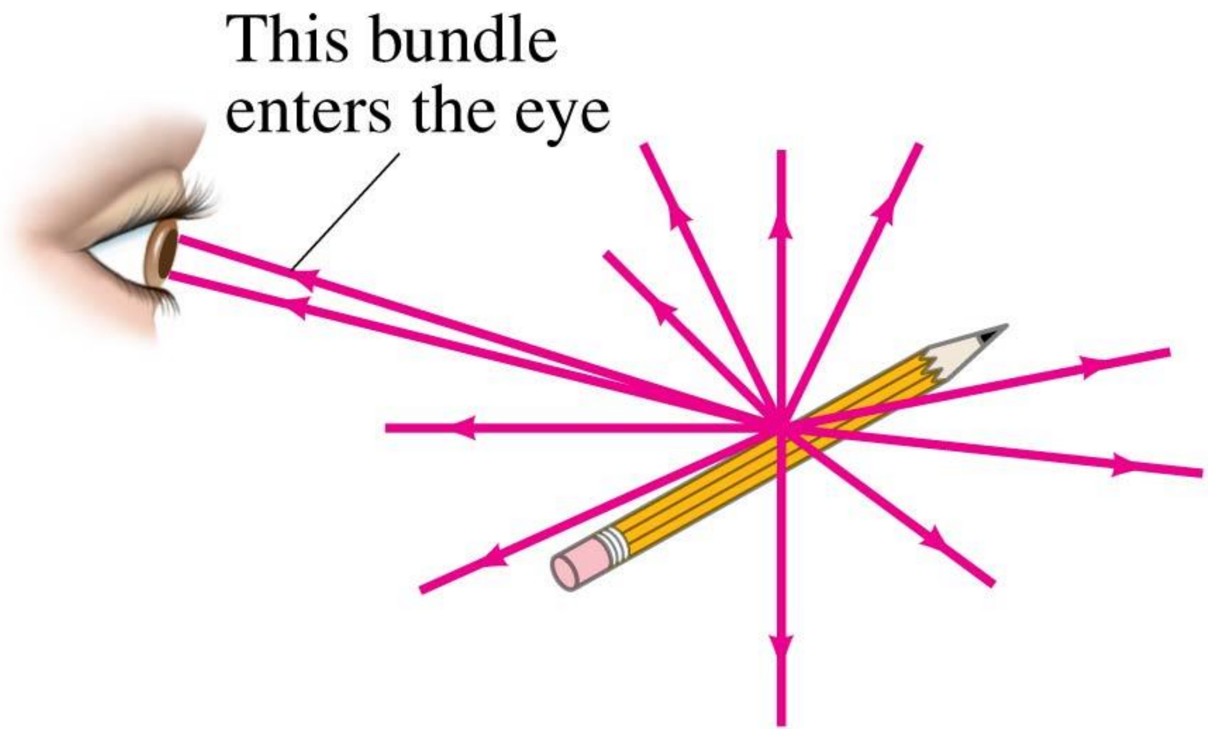
Chapter 23
Light: Geometric Optics

23-1 The Ray Model of Light

Light very often travels in straight lines. We represent light using rays, which are straight lines emanating from an object. This is an idealization, but is very useful for geometric optics.



23-4 Index of Refraction

In general, light slows somewhat when traveling through a medium. The index of refraction of the medium is the ratio of the speed of light in vacuum to the speed of light in the medium:

$$n = \frac{c}{v}. \qquad (23\text{-}4)$$

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.

25. (I) What is the speed of light in (*a*) ethyl alcohol, (*b*) lucite, (*c*) crown glass?

a) $V = \frac{3\times10^8}{1.36}$ m/s

b) $V = \frac{c}{1.5}$

c) $v = \frac{c}{1.52}$

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Plastic	
Acrylic, Lucite, CR-39	1.50
Polycarbonate	1.59
“High-index”	1.6–1.7
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Diamond	2.42

†λ = 589 nm.

26. (II) The speed of light in a certain substance is 82% of its value in water. What is the index of refraction of that substance?

n

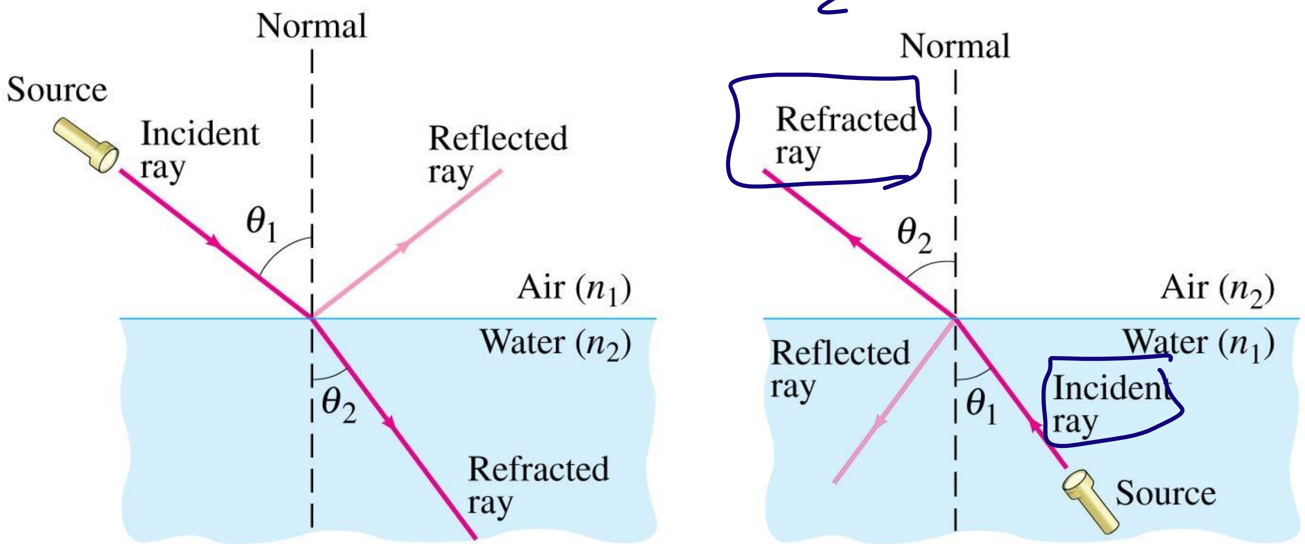
$$v_x = 0.82 \times v_w = 0.82 \times \frac{c}{n_w}$$

$$n_x = \frac{c}{v_x} = \frac{c}{0.82 \times \frac{c}{n_w}} = \frac{n_w}{0.82} = \frac{1.33}{0.82}$$

$$n_x = 1.62$$

23-5 Refraction: Snell's Law

Light changes direction when crossing a boundary from one medium to another. This is called refraction, and the angle the outgoing ray makes with the normal is called the angle of refraction.

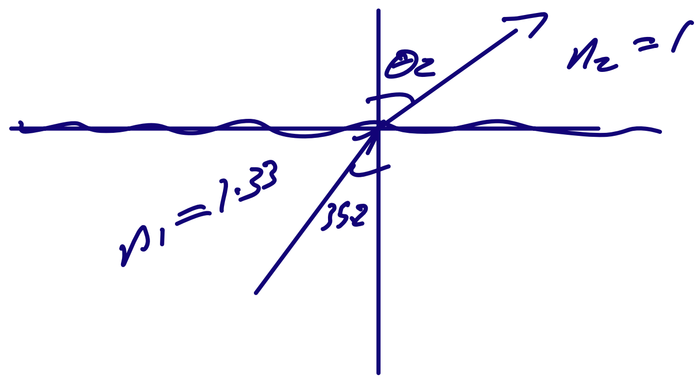


(a) $n_2 > n_1$: Ray bends toward ⊥ (b) $n_1 > n_2$: Ray bends away from ⊥

The angle of refraction depends on the indices of refraction, and is given by Snell's law:

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

28. (I) A diver shines a flashlight upward from beneath the water at a 35.2° angle to the vertical. At what angle does the light leave the water?



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

$$\frac{1.33 \times \sin(35.2)}{1} = \sin\theta_2$$

$$\theta_2 = \sin^{-1}(1.3 \times \sin(35.2))$$

$$\theta_2 = 50.1^\circ$$

Light traveling in air strikes a flat piece of uniformly thick glass at an incident angle of 60.0°. If the index of refraction of the glass is 1.50,
(a) what is the angle of refraction in the glass;
(b) what is the angle at which the ray emerges from the glass?

$n_1 = 1$, θ_1

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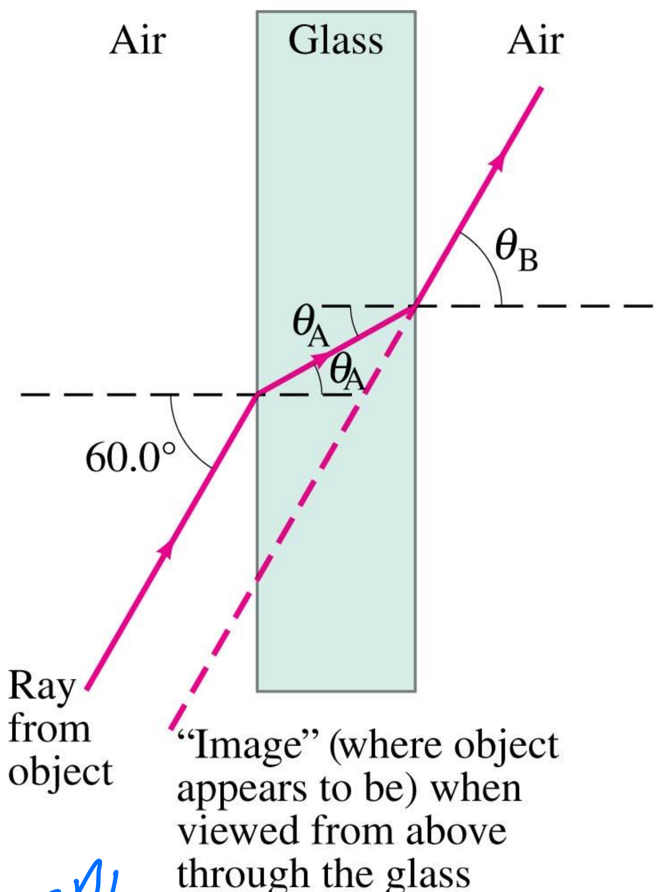
a) $\theta_1 = 60$

$1 \times \sin 60 = 1.5 \sin \theta_2$

$\theta_2 = \sin^{-1}\left(\frac{\sin 60}{1.5}\right)$

$= 35.26$



b) it will be the same as the incident angle that light passes with through the glass at first because:

$n_1 \sin\theta_1 = n_2 \sin\theta_2 = n_3 \sin\theta_3$

$n_3 = n_1$

$n_1 \sin\theta_1 = n_3 \sin\theta_3 \rightarrow \sin\theta_1 = \sin\theta_3$

$\theta_1 = \theta_3$ ✓

31. (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?

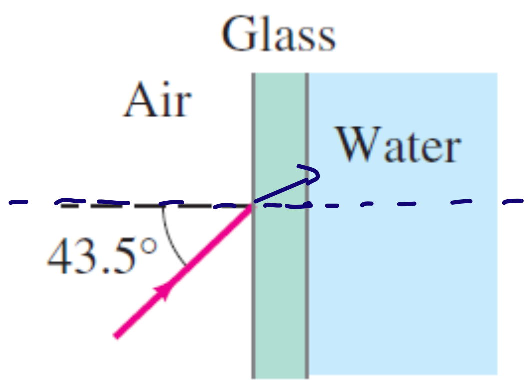


FIGURE 23–56
Problem 31.

a) $n_1 = 1$ $n_2 = 1.54$

$\theta_1 = 43.5$

$\theta_2 = \sin^{-1}\left(\frac{\sin(43.5)}{1.54}\right)$

$\theta_2 \approx 26.6^0$

b) $\theta_3 = \sin^{-1}\left(\frac{\sin(43.5)}{1.33}\right)$

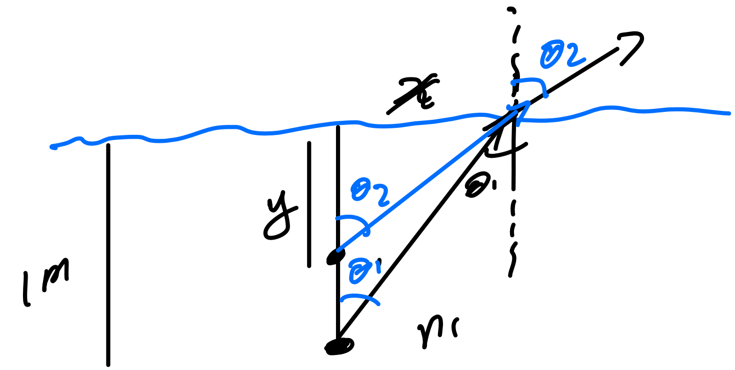
$\theta_3 \approx 31.2^0$

c) $\theta = 31.2$ nothing will change

EXAMPLE 23–9 **Apparent depth of a pool.** A swimmer has dropped her goggles to the bottom of a pool at the shallow end, marked as 1.0 m deep. But the goggles don't look that deep. Why? How deep do the goggles appear to be when you look straight down into the water?

$\tan\theta_1 = \frac{x}{1\,m}$

$\tan\theta_2 = \frac{x}{y}$



$n_1 \tan\theta_1 = \tan\theta_2$

$1.3 \times \frac{x}{1} = \frac{x}{y}$

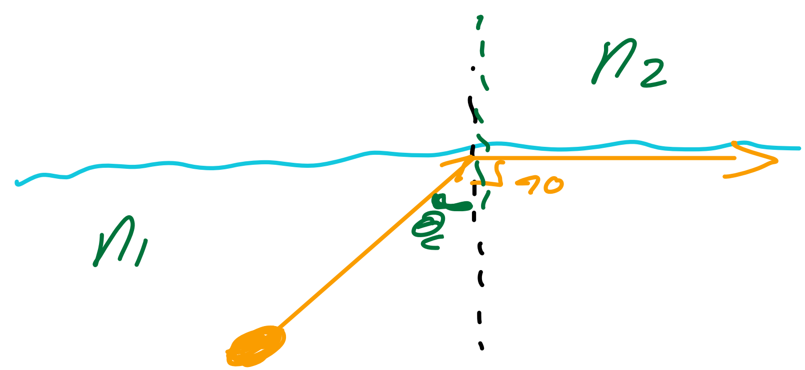
$y = \frac{1}{1.33} = 0.75$

23-6 Total Internal Reflection; Fiber Optics

it occurs just when $n_1 > n_2$

If light passes into a medium with a smaller index of refraction, the angle of refraction is larger. There is an angle of incidence for which the angle of refraction will be 90°; this is called the critical angle:

$$\sin\theta_C = \frac{n_2}{n_1}\sin 90^\circ = \frac{n_2}{n_1}. \qquad (23\text{-}6)$$

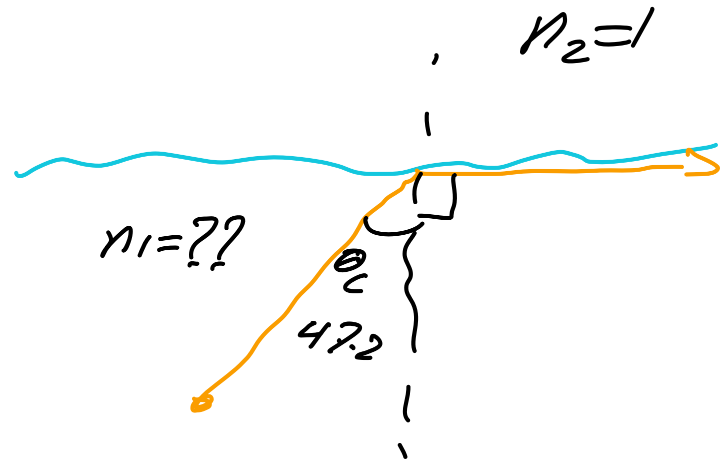


34. (I) The critical angle for a certain liquid–air surface is 47.2°. What is the index of refraction of the liquid?

$$n_1 \sin\theta_c = n_2 \sin 90$$

$$n_1 \sin 47.2 = 1 \times 1$$

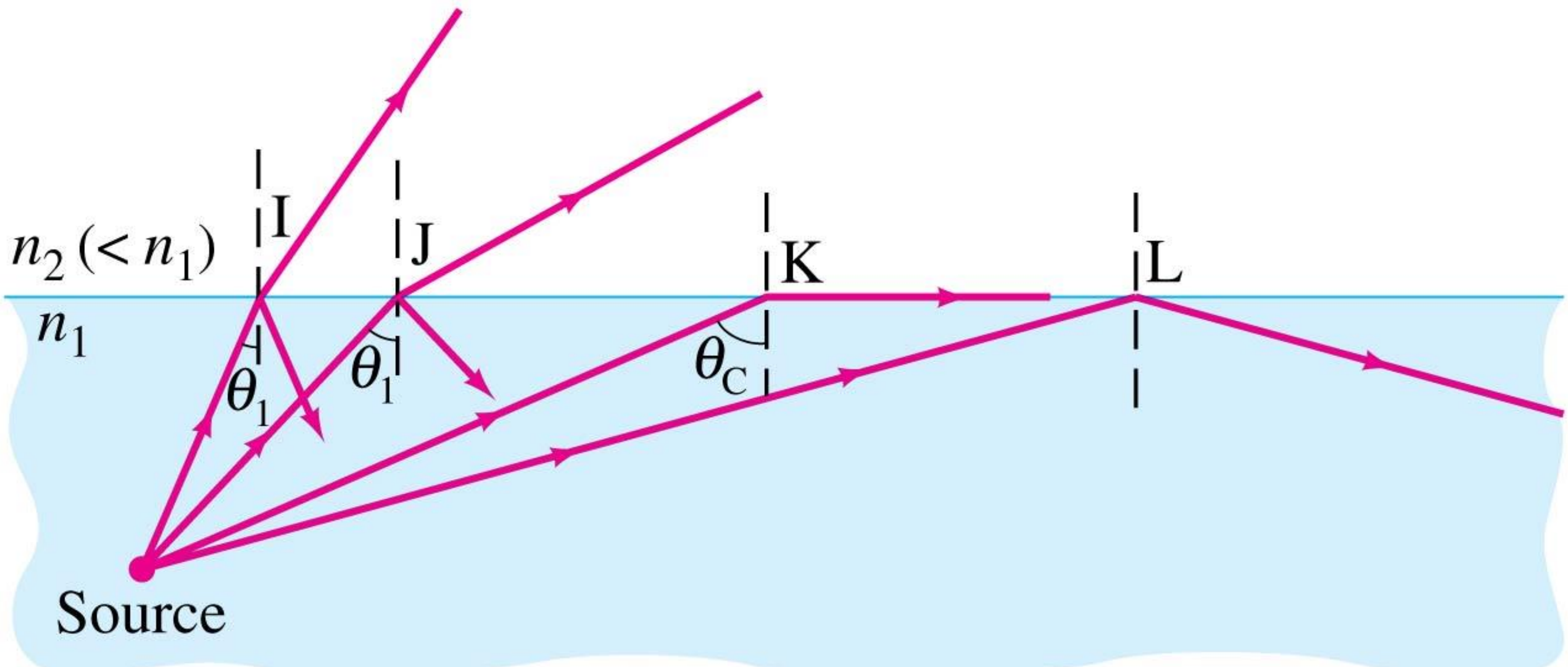
$$n_1 = \frac{1}{\sin 47.2} = 1.36$$



23-6 Total Internal Reflection; Fiber Optics

If the angle of incidence is larger than this, no transmission occurs. This is called total internal reflection.

when $\theta_1 > \theta_c$

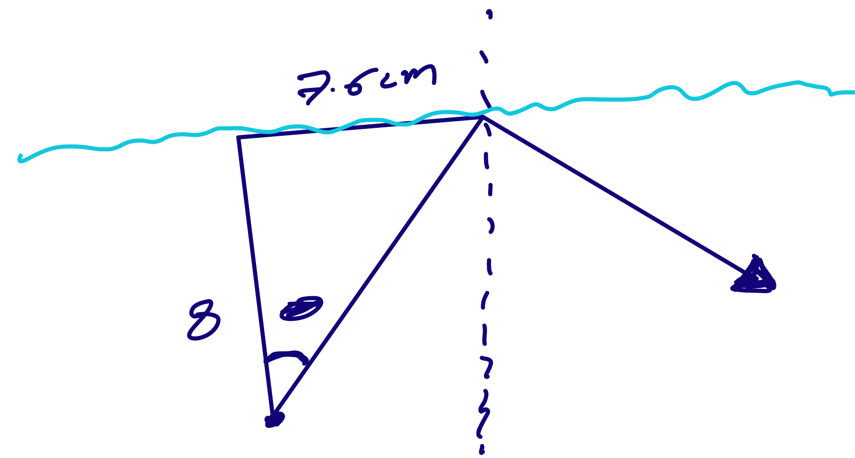


36. (II) A beam of light is emitted 8.0 cm beneath the surface of a liquid and strikes the air surface 7.6 cm from the point directly above the source. If total internal reflection occurs, what can you say about the index of refraction of the liquid?

$n_1 > n_2$

$\theta_1 > \theta_c$

$n_2 = 1$



$$\theta_1 = \tan^{-1}\left(\frac{7.6}{8}\right) = 43.5^\circ$$

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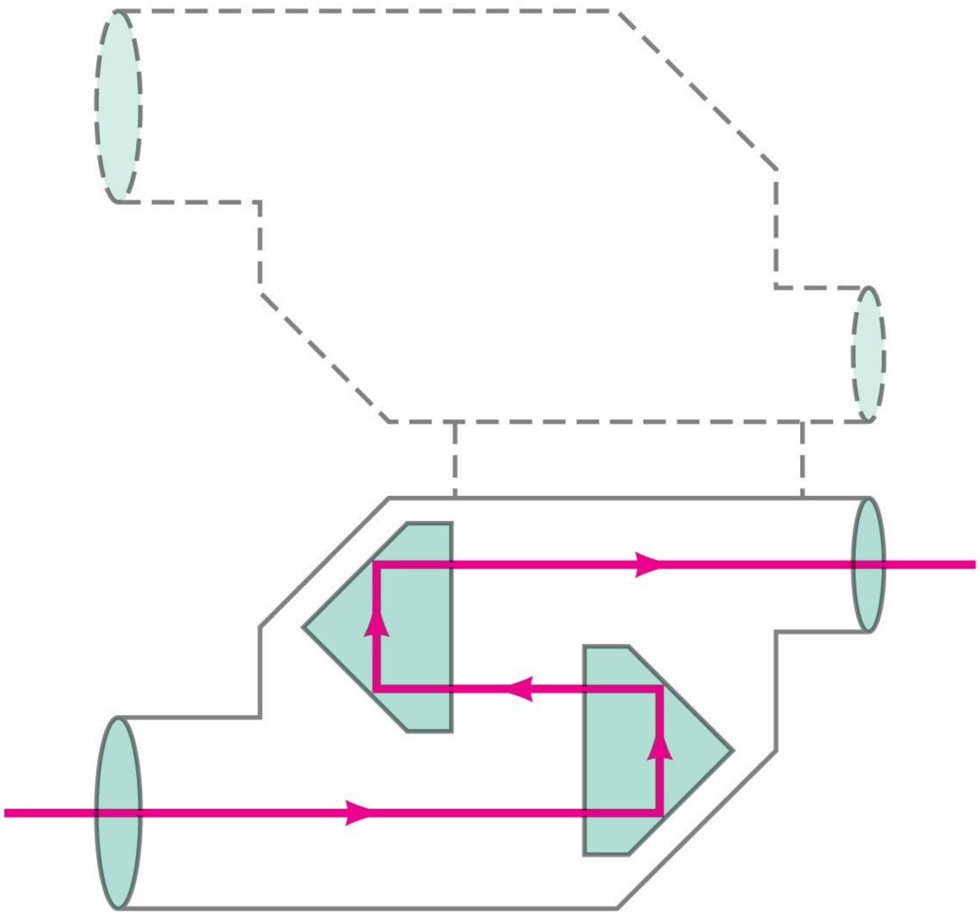
$n_1 > n_2$

$43.5 > \theta_c$

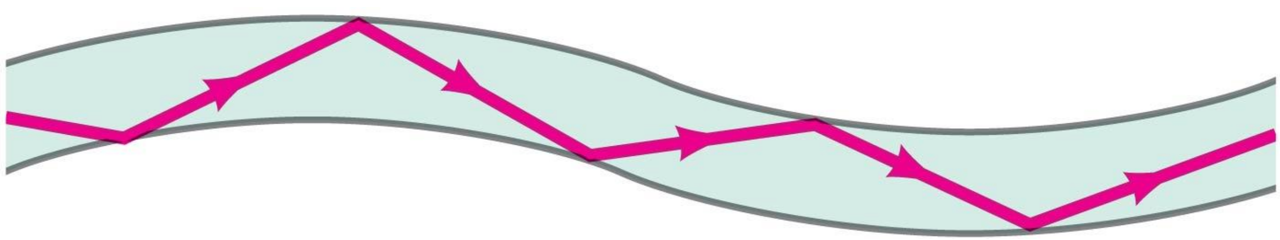
23-6 Total Internal Reflection; Fiber Optics

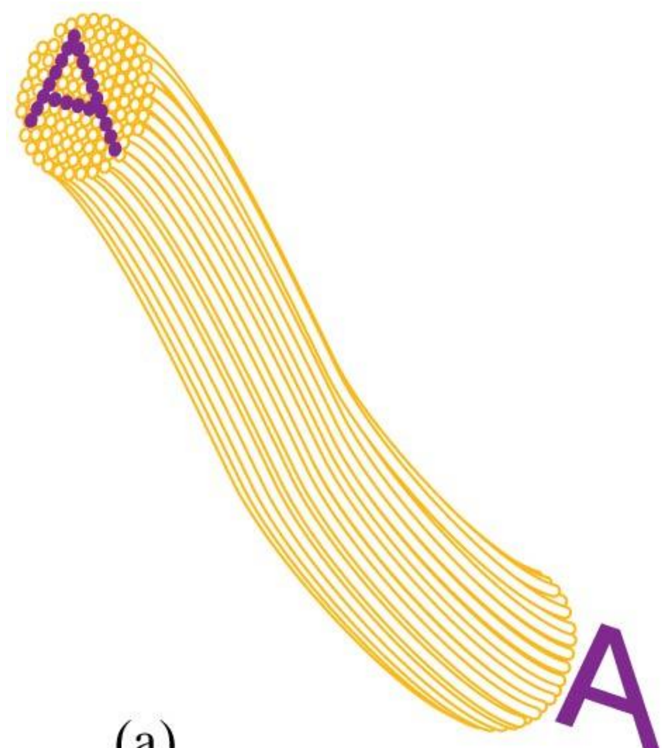
Binoculars often use total internal reflection; this gives true 100% reflection, which even the best mirror cannot do.



23-6 Total Internal Reflection; Fiber Optics

Total internal reflection is also the principle behind fiber optics. Light will be transmitted along the fiber even if it is not straight. An image can be formed using multiple small fibers.

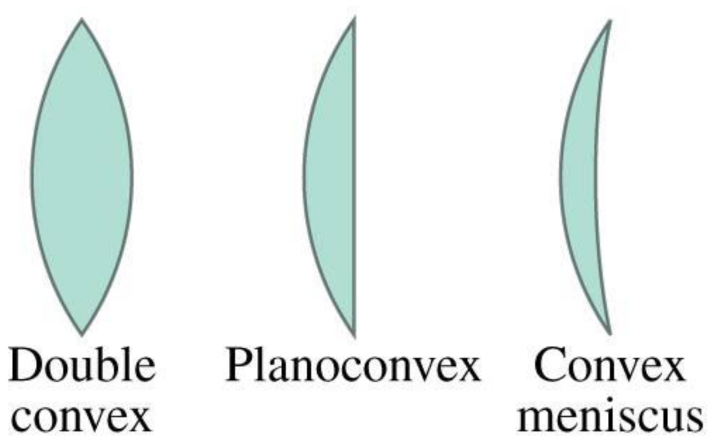




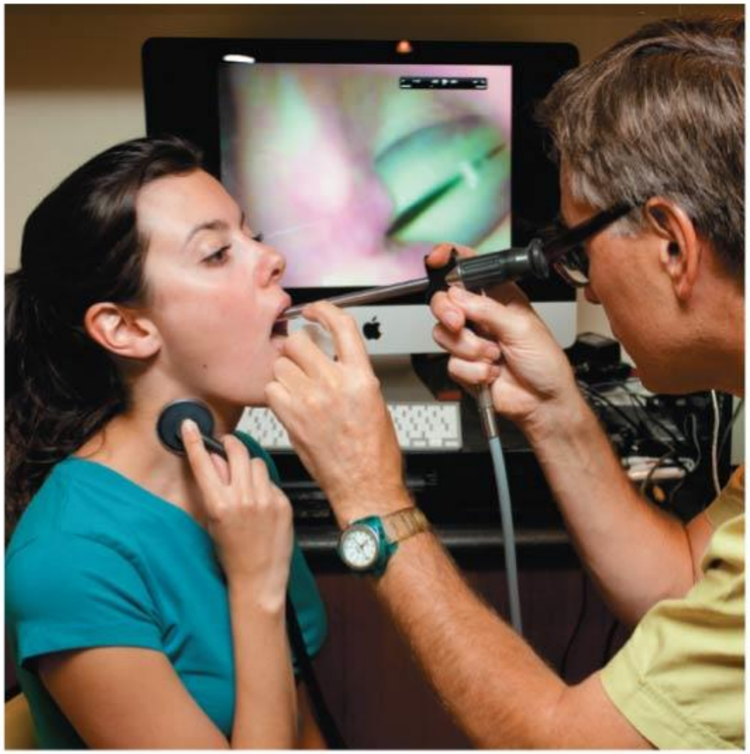
(a)

23-7 Thin Lenses; Ray Tracing

Thin lenses are those whose thickness is small compared to their radius of curvature. They may be either converging (a) or diverging (b).



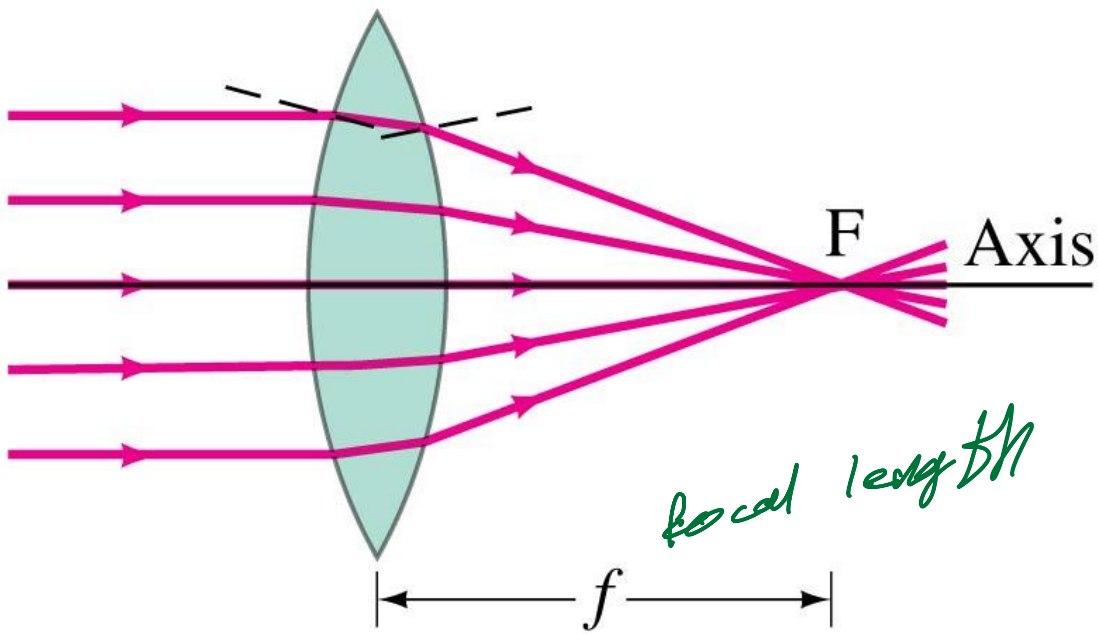
(a) Converging lenses



(b)

23-7 Thin Lenses; Ray Tracing

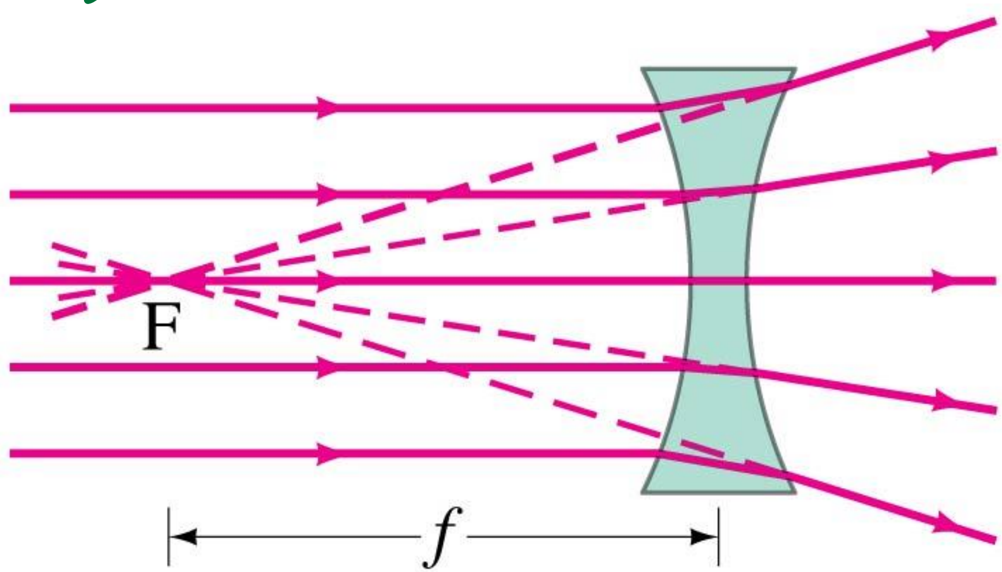
Parallel rays are brought to a focus by a converging lens (one that is thicker in the center than it is at the edge).



23-7 Thin Lenses; Ray Tracing

A diverging lens (thicker at the edge than in the center) make parallel light diverge; the focal point is that point where the diverging rays would converge if projected back.

always di is negative for diverging lens or concave



23-7 Thin Lenses; Ray Tracing

The power of a lens is the inverse of its focal length.

$$P = \frac{1}{f}. \qquad (23\text{-}7)$$

Lens power is measured in diopters, D.

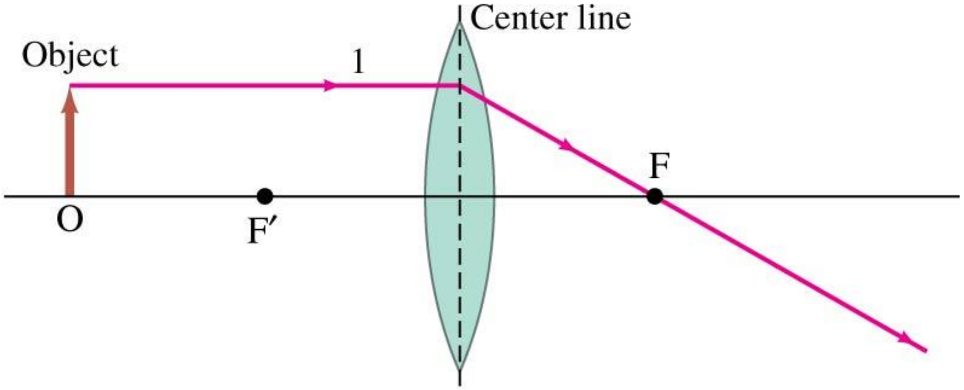
$$1\ \mathrm{D} = 1\ \mathrm{m}^{-1}$$

23-7 Thin Lenses; Ray Tracing

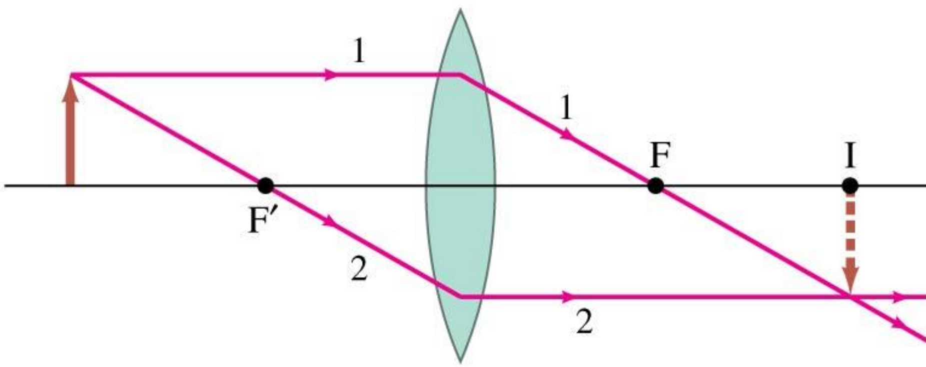
Ray tracing for thin lenses is similar to that for mirrors. We have three key rays:

1. This ray comes in parallel to the axis and exits through the focal point.
2. This ray comes in through the focal point and exits parallel to the axis.
3. This ray goes through the center of the lens and is undeflected.

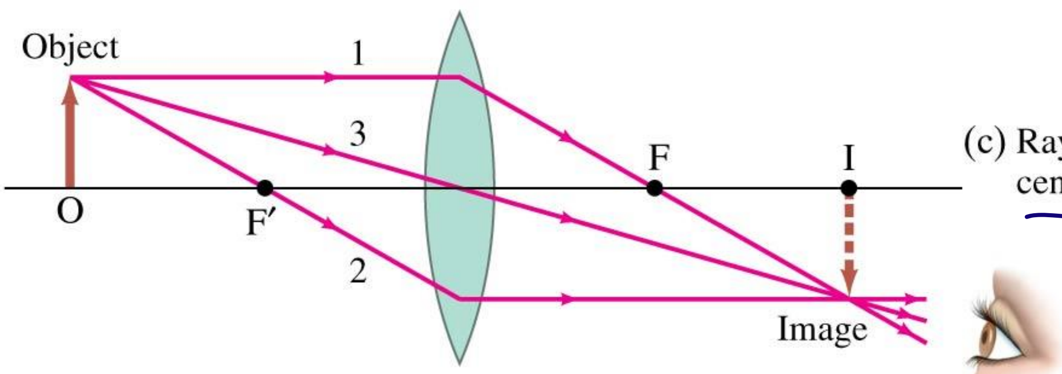
23-7 Thin Lenses; Ray Tracing



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



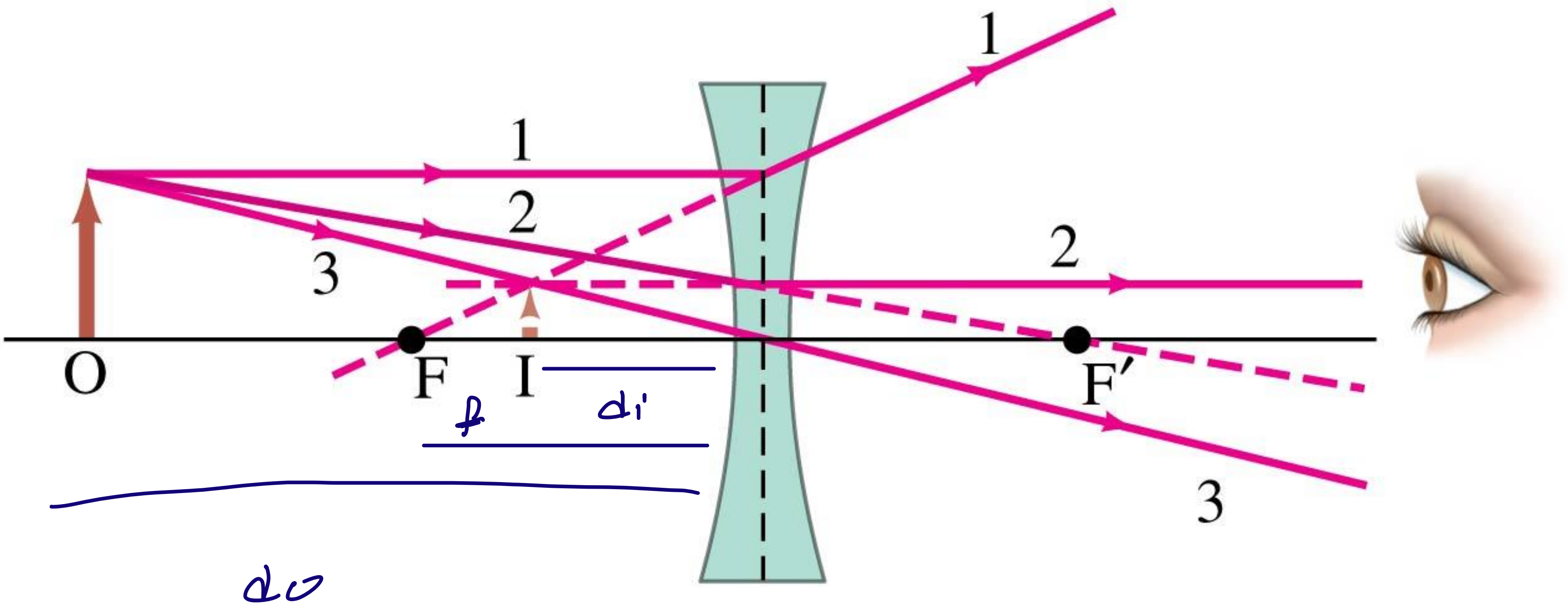
(b) Ray 2 passes through F′ in front of the lens; therefore it is parallel to the axis behind the lens.



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

23-7 Thin Lenses; Ray Tracing

For a diverging lens, we can use the same three rays; the image is upright and virtual.



23-8 The Thin Lens Equation

The thin lens

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}.$$

f → focal length

d_o → object

d_i → image

convergin → convex ⟹ f +

divergin → concave ⟹ f −

23-8 The Thin Lens Equation

The sign conventions :

1. The focal length is positive for converging lenses and negative for diverging.

2. The object distance is positive when the object is on the same side as the light entering the lens (not an issue except in compound systems); otherwise it is negative.

3. The image distance is positive if the image is on the opposite side from the light entering the lens; otherwise it is negative.

4. The height of the image is positive if the image is upright and negative otherwise.

23-8 The Thin Lens Equation

The magnification formula is also the same as that for a mirror:

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}. \qquad (23\text{-}9)$$

The power of a lens is positive if it is converging and negative if it is diverging.

P

converging ال (+) يكون focal length ال

diverging ال (−) يكون focal length ال

important

magnification sign

m(−) ⟶ real/inverted

m(+) ⟶ upright/virtual

|m| < 1 : reduced

|m| > 1 : enlarged

|m| = 1 : same size

40. (I) Sunlight is observed to focus at a point 16.5 cm behind a lens. (*a*) What kind of lens is it? (*b*) What is its power in diopters?

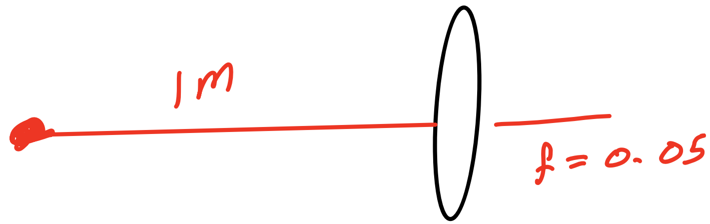
a) converging or convex lens

$D = m^{-1}$

b) $P = \frac{1}{f} = \frac{1}{0.165\,m} = 6.1\,D$

EXAMPLE 23–12 **Image formed by converging lens.** What is (*a*) the position, and (*b*) the size, of the image of a 7.6-cm-high leaf placed 1.00 m from a +50.0-mm-focal-length camera lens?

$h_i = 7.6 \times 10^{-2}$ m



a) $\frac{1}{0.05} = \frac{1}{1} + \frac{1}{d_i} \rightarrow d_i = 0.053$ m

$d_i = 5.3$ cm

b) $m = -\frac{5.3}{100} = -0.053 \rightarrow$ inverted

$-0.053 = \frac{h_i}{7.6} \rightarrow h_i = -0.4$ cm

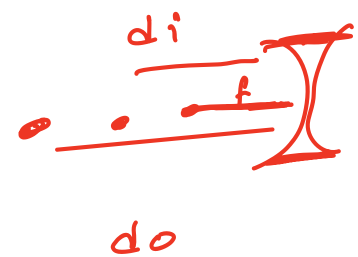
that means the image is real or inverted

EXAMPLE 23–14 Diverging lens. Where must a small insect be placed if a 25-cm-focal-length diverging lens is to form a virtual image 20 cm from the lens, on the same side as the object?

d_o

$d_i = -20$

$$-\frac{1}{f} = \frac{1}{d_o} - \frac{1}{d_i}$$



$$\frac{1}{-25} = \frac{1}{d_o} - \frac{1}{20} \rightarrow d_o = 1m$$

d_o

42. (II) A certain lens focuses light from an object 1.55 m away as an image 48.3 cm on the other side of the lens. What type of lens is it and what is its focal length? Is the image real or virtual?

d_i

1) because of that the image is on the other side of the lens the image is converging

$d_o = 155$ cm $d_i = 48.3$ cm

$$\frac{1}{f} = \frac{1}{155} + \frac{1}{48.3} \longrightarrow f = 36.8 \text{ cm}$$

2) $$m = -\frac{48.3}{155} = -0.312$$

because the magnification is negative the image is real (or inverted)

45. (II) A stamp collector uses a converging lens with focal length 28 cm to view a stamp 16 cm in front of the lens. (*a*) Where is the image located? (*b*) What is the magnification?

+f

d_o

d_i

a) $\frac{1}{28} = \frac{1}{16} + \frac{1}{d_i} \longrightarrow d_i = -37.33\text{ cm} \rightarrow$ negative sign means that the image located at the same side where object located

b $m = -\frac{(-37.33)}{16} = 2.33 \rightarrow$ virtual or upright

48. (II) (*a*) How far from a 50.0-mm-focal-length lens must an object be placed if its image is to be magnified 2.50× and be real? (*b*) What if the image is to be virtual and magnified 2.50×?

a) $m = -2.5 = \frac{-d_i}{d_o} \rightarrow d_i = 2.5\, d_o$

$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$

$\frac{1}{0.05} = \frac{1}{d_o} + \frac{1}{2.5 d_o} \rightarrow \frac{1}{0.05} = \frac{3.5}{2.5 d_o} \rightarrow d_o = 0.07\,m = 7\,cm$

b) $m = +2.5 = \frac{-d_i}{d_o} \rightarrow d_i = -2.5\, d_o$

$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$

$\frac{1}{0.05} = \frac{1}{d_o} - \frac{1}{2.5 d_o} \rightarrow \frac{1}{0.05} = \frac{1.5}{2.5 d_o} \rightarrow d_o = 3\,cm$

50. (II) How far from a converging lens with a focal length of 32 cm should an object be placed to produce a real image which is the same size as the object?

f

−m

$m = 1$

real image → $m = -1$

$-1 = \frac{-d_i}{d_o} \rightarrow d_i = d_o$

$\frac{1}{32} = \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{d_o} + \frac{1}{d_o}$

$\frac{1}{32} = \frac{2}{d_o} \rightarrow d_o = 64 \text{ cm}$

53. (III) How far apart are an object and an image formed by an 85-cm-focal-length converging lens if the image is 3.25× larger than the object and is real?

$d_i = ??$

$d_o = ??$

$-m$

real image → $m = -3.25 = \dfrac{-d_i}{d_o}$ → $d_i = 3.25\, d_o$

$$\frac{1}{85} = \frac{1}{d_o} + \frac{1}{3.25\, d_o}$$

→ $\dfrac{1}{85} = \dfrac{4.25}{3.25\, d_o}$ → $d_o = 111.2\ \text{cm}$

→ $d_i = 3.25\,(111.2\ \text{cm})$

$d_i = 361.3\ \text{cm}$

distance between d_i and d_o = $d_i + d_o = d$

→ $d \approx 472.4\ \text{cm}$

77. How large is the image of the Sun on a camera sensor with (*a*) a 35-mm-focal-length lens, (*b*) a 50-mm-focal-length lens, and (*c*) a 105-mm-focal-length lens? The Sun has diameter 1.4×10^6 km, and it is 1.5×10^8 km away.

infinity
$d_o \approx$ zero

d d_o

too small value

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

$d_i \approx f$

هون مش طالب ال magnification
طالب حجم الشمس بالكاميرا هيك بنضرب بـ d
(هيك فهمت)

a) $\text{Image size} = d \times m = 1.4 \times 10^6 \text{ km} \dfrac{(35 \text{ mm})}{1.5 \times 10^8 \text{ km}} = 0.33 \text{ mm}$

b) ----

c) ----