PHYSICS APPLIED
Convex rearview mirror

FIGURE 23–20 Example 23–7.

EXAMPLE 23–7 **Convex rearview mirror.** An external rearview car mirror is convex with a radius of curvature of 16.0 m (Fig. 23–20). Determine the location of the image and its magnification for an object 10.0 m from the mirror.

APPROACH We follow the steps of the Problem Solving Strategy explicitly.

SOLUTION

1. **Draw a ray diagram.** The ray diagram will be like Fig. 23–19b, but the large object distance $(d_o = 10.0\,\mathrm{m})$ makes a precise drawing difficult. We have a convex mirror, so r is negative by convention.
2. **Mirror and magnification equations.** The center of curvature of a convex mirror is behind the mirror, as is its focal point, so we set $r = -16.0\,\mathrm{m}$ so that the focal length is $f = r/2 = -8.0\,\mathrm{m}$. The object is in front of the mirror, $d_o = 10.0\,\mathrm{m}$. Solving the mirror equation, Eq. 23–2, for $1/d_i$ gives
$$\frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o} = \frac{1}{-8.0\,\mathrm{m}} - \frac{1}{10.0\,\mathrm{m}} = \frac{-10.0 - 8.0}{80.0\,\mathrm{m}} = -\frac{18}{80.0\,\mathrm{m}}.$$
Thus $d_i = -80.0\,\mathrm{m}/18 = -4.4\,\mathrm{m}$. Equation 23–3 gives the magnification
$$m = -\frac{d_i}{d_o} = -\frac{(-4.4\,\mathrm{m})}{(10.0\,\mathrm{m})} = +0.44.$$
3. **Sign conventions.** The image distance is negative, $-4.4\,\mathrm{m}$, so the image is *behind* the mirror. The magnification is $m = +0.44$, so the image is *upright* (same orientation as object, which is useful) and about half what it would be in a plane mirror.
4. **Check.** Our results are consistent with Fig. 23–19b.

Convex rearview mirrors on vehicles sometimes come with a warning that objects are closer than they appear in the mirror. The fact that d_i may be smaller than d_o (as in Example 23–7) seems to contradict this observation. The real reason the object seems farther away is that its image in the convex mirror is *smaller* than it would be in a plane mirror, and we judge distance of ordinary objects such as other cars mostly by their size.

23–4 Index of Refraction

We saw in Chapter 22 that the speed of light in vacuum (like other EM waves) is
$$c = 2.99792458 \times 10^8\,\mathrm{m/s},$$
which is usually rounded off to
$$3.00 \times 10^8\,\mathrm{m/s}$$
when extremely precise results are not required.

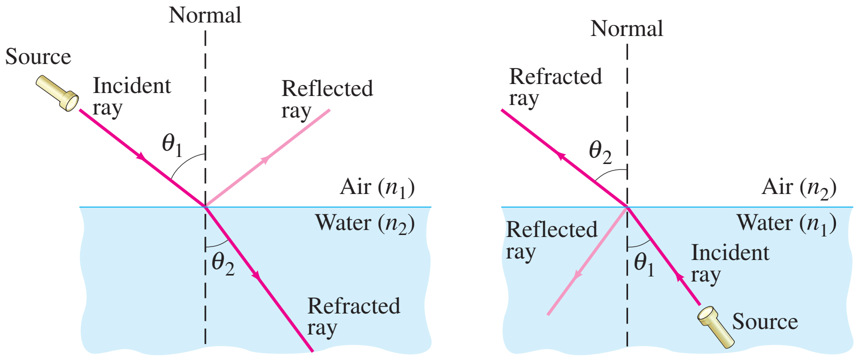
In air, the speed is only slightly less. In other transparent materials, such as glass and water, the speed is always less than that in vacuum. For example, in water light travels at about $\frac{3}{4}c$. The ratio of the speed of light in vacuum to the speed v in a given material is called the **index 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
$$v = \frac{c}{n} = \frac{(3.00 \times 10^8\,\mathrm{m/s})}{1.33} = 2.26 \times 10^8\,\mathrm{m/s}.$$
As we shall see later, n varies somewhat with the wavelength of the light—except in vacuum—so a particular wavelength is specified in Table 23–1, that of yellow light with wavelength $\lambda = 589\,\mathrm{nm}$.

That light travels more slowly in matter than in vacuum can be explained at the atomic level as being due to the absorption and reemission of light by atoms and molecules of the material.

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

† $\lambda = 589\,\mathrm{nm}$.



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

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): $n_1 > n_2$.

23–5 Refraction: Snell's Law

When light passes from one transparent medium into another with a different index of refraction, some or all of the incident light is reflected at the boundary. The rest passes into the new medium. If a ray of light is incident at an angle to the surface (other than perpendicular), the ray changes direction as it enters the new medium. This change in direction, or bending, of the light ray is called **refraction**.

Figure 23–21a shows a ray passing from air into water. Angle θ_1 is the angle the incident ray makes with the normal (perpendicular) to the surface and is called the **angle of incidence**. Angle θ_2 is the **angle of refraction**, the angle the refracted ray makes with the normal to the surface. Notice that the ray bends toward the normal when entering the water. This is always the case when the ray enters a medium where the speed of light is *less* (and the index of refraction is greater, Eq. 23–4). If light travels from one medium into a second where its speed is *greater*, the ray bends away from the normal; this is shown in Fig. 23–21b for a ray traveling from water to air.

CAUTION
Angles of incidence and refraction are measured from the perpendicular, not from the surface

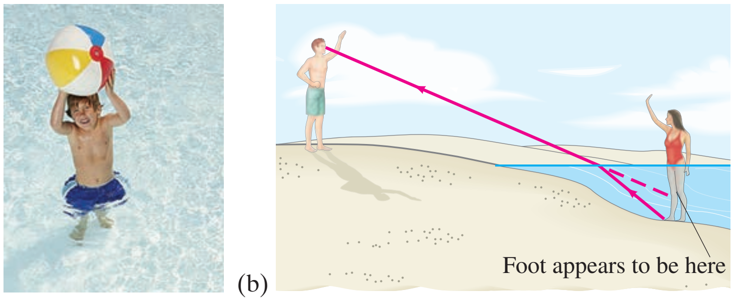
(a) (b)


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).

Refraction is responsible for a number of common optical illusions. For example, a person standing in waist-deep water appears to have shortened legs (Fig. 23–22). The rays leaving the person's foot are bent at the surface. The observer's brain assumes the rays to have traveled a straight-line path (dashed red line), and so the feet appear to be higher than they really are. Similarly, when you put a straw in water, it appears to be bent (Fig. 23–23). This also means that water is deeper than it appears.

FIGURE 23–23 A straw in water looks bent even when it isn't.

Snell's Law

The angle of refraction depends on the speed of light in the two media and on the incident angle. An analytic relation between θ_1 and θ_2 in Fig. 23–21 was arrived at experimentally about 1621 by Willebrord Snell (1591–1626). Known as **Snell's law**, it is written:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2. \qquad \textbf{(23–5)}$$

SNELL'S LAW (LAW OF REFRACTION)

θ_1 is the angle of incidence and θ_2 is the angle of refraction; n_1 and n_2 are the respective indices of refraction in the materials. See Fig. 23–21. 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**. (Snell's law was derived in Section 11–13 for water waves where Eq. 11–20 is just a combination of Eqs. 23–5 and 23–4, and we derive it again in Chapter 24 using the wave theory of light.)

Snell's law shows that if $n_2 > n_1$, then $\theta_2 < \theta_1$. Thus, if light enters a medium where n is greater (and its speed is less), the ray is bent toward the normal. And if $n_2 < n_1$, then $\theta_2 > \theta_1$, so the ray bends away from the normal. See Fig. 23–21.

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?

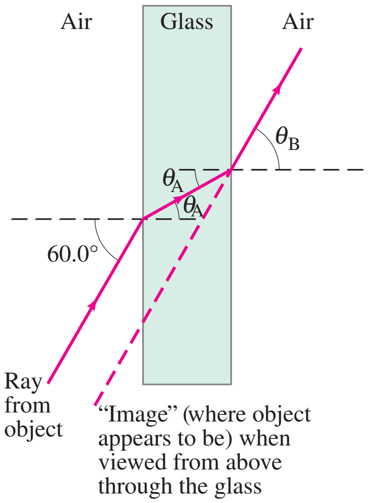


FIGURE 23–24 Light passing through a piece of glass (Example 23–8).

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 $\left(\theta_1 = 60.0°,\ \theta_2 = \theta_A\right)$ 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.

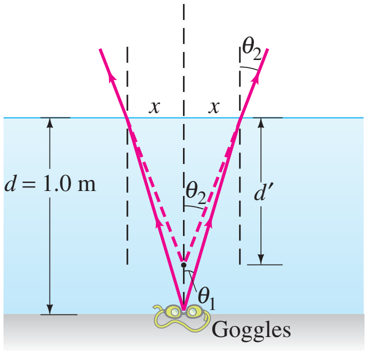
NOTE This result is valid for any angle of incidence. The ray is displaced slightly to one side, however. You can observe this by looking through a piece of glass (near its edge) at some object and then moving your head to the side slightly so that you see the object directly. It "jumps."

CAUTION (real life)
Water is deeper than it looks

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?

APPROACH We draw a ray diagram showing two rays going upward from a point on the goggles at a small angle, and being refracted at the water's (flat) surface, Fig. 23–25. The two rays traveling upward from the goggles are refracted *away* from the normal as they exit the water, and so appear to be diverging from a point above the goggles (dashed lines), which is why the water seems less deep than it actually is. We are looking straight down, so all angles are small (but exaggerated in Fig. 23–25 for clarity).

FIGURE 23–25 Example 23–9.



SOLUTION To calculate the apparent depth d' (Fig. 23–25), given a real depth $d = 1.0$ m, we use Snell's law with $n_1 = 1.33$ for water and $n_2 = 1.0$ for air:

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

We are considering only small angles, so $\sin\theta \approx \tan\theta \approx \theta$, with θ in radians. So Snell's law becomes

$$\theta_2 \approx n_1\theta_1 .$$

From Fig. 23–25, we see that $\theta_2 \approx \tan\theta_2 = x/d'$ and $\theta_1 \approx \tan\theta_1 = x/d$. Putting these into Snell's law, $\theta_2 \approx n_1\theta_1$, we get

$$\frac{x}{d'} \approx n_1\frac{x}{d}$$

or

$$d' \approx \frac{d}{n_1} = \frac{1.0\ \text{m}}{1.33} = 0.75\ \text{m}.$$

The pool seems only three-fourths as deep as it actually is.

NOTE Water in general is deeper than it looks—a useful safety guideline.