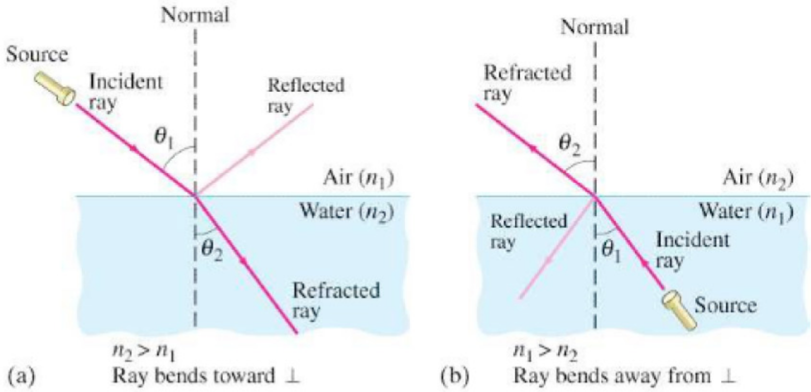

FIGURE 23–19 Refraction. (a) Light refracted when passing from air (n_1) into water (n_2): $n_2 > n_1$. (b) Light refracted when passing from water (n_1) into air (n_2): $n_1 > n_2$.

Figure 23–19a 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 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. 23–19b for a ray traveling from water to air.

Angle of refraction

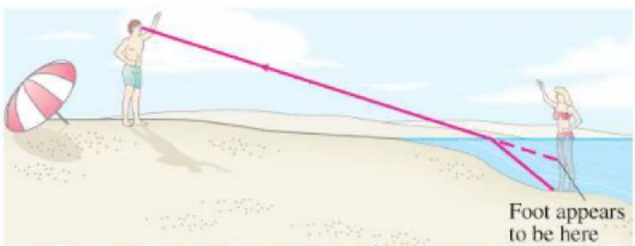

FIGURE 23–20 Ray diagram showing why a person's legs look shorter when standing in waist-deep water: the path of light traveling from the bather's foot to the observer's eye bends at the water's surface, and our brain interprets the light as having traveled in a straight line, from higher up (dashed line).

FIGURE 23–21 A pencil in water looks bent even when it isn't.

Refraction is responsible for a number of common optical illusions. For example, a person standing in waist-deep water appears to have shortened legs. As shown in Fig. 23–20, 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 pencil in water, it appears to be bent (Fig. 23–21).

PHYSICS APPLIED
Optical illusions

Snell's Law

The angle of refraction depends on the speed of light in the two media and on the incident angle. An analytical relation between θ_1 and θ_2 was arrived at experimentally about 1621 by Willebrord Snell (1591–1626). It is known as **Snell's law** and 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. 23–19. The incident and refracted rays lie in the same plane, which also includes the perpendicular to the surface. Snell's law is the basic **law of refraction**. (Snell's law was derived in Section 11–14 where Eq. 11–20 is just a combination of Eqs. 23–5 and 23–4.)

CAUTION
Angles θ_1 and θ_2 are measured from the perpendicular, not from surface

It is clear from Snell's law that if $n_2 > n_1$, then $\theta_2 < \theta_1$. That is, if light enters a medium where n is greater (and its speed less), then 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. This is what we saw in Fig. 23–19.