When light passes from one transparent medium into another, the rays bend or refract. The **law of refraction** (**Snell's law**) states that

$$n_1 \sin \theta_1 = n_2 \sin \theta_2, \quad \text{(23–5)}$$

where $n_1$ and $\theta_1$ are the index of refraction and angle with the normal to the surface for the incident ray, and $n_2$ and $\theta_2$ are for the refracted ray.

When light rays reach the boundary of a material where the index of refraction decreases, the rays will be **totally internally reflected** if the incident angle, $\theta_1$, is such that Snell's law would predict $\sin \theta_2 > 1$. This occurs if $\theta_1$ exceeds the critical angle $\theta_C$ given by

$$\sin \theta_C = \frac{n_2}{n_1}. \quad \text{(23–6)}$$

A lens uses refraction to produce a real or virtual image. Parallel rays of light are focused to a point, called the **focal point**, by a **converging** lens. The distance of the focal point from the lens is called the **focal length** $f$ of the lens.

After parallel rays pass through a **diverging** lens, they appear to diverge from a point, its focal point; and the corresponding focal length is considered negative.

The **power** $P$ of a lens, which is $P = 1/f$ (Eq. 23–7), is given in diopters, which are units of inverse meters $(\mathrm{m}^{-1})$.

For a given object, the position and size of the image formed by a lens can be found approximately by ray tracing. Algebraically, the relation between image and object distances, $d_i$ and $d_o$, and the focal length $f$, is given by the **thin lens equation**:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}. \quad \text{(23–8)}$$

The ratio of image height to object height, which equals the magnification $m$ for a lens, is

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

When using the various equations of geometrical optics, it is important to remember the **sign conventions** for all quantities involved: carefully review them (pages 641 and 651) when doing Problems.

[* When two (or more) thin lenses are used in combination to produce an image, the thin lens equation can be used for each lens in sequence. The image produced by the first lens acts as the object for the second lens. The **lensmaker's equation** relates the radii of curvature of the lens surfaces and the lens' index of refraction to the focal length of the lens.]

## Questions

**1.** What would be the appearance of the Moon if it had (*a*) a rough surface; (*b*) a polished mirrorlike surface?

**2.** Archimedes is said to have burned the whole Roman fleet in the harbor of Syracuse by focusing the rays of the Sun with a huge spherical mirror. Is this reasonable?

**3.** Although a plane mirror appears to reverse left and right, it doesn't reverse up and down. Explain.

**4.** If a concave mirror produces a real image, is the image necessarily inverted? Explain.

**5.** An object is placed along the principal axis of a spherical mirror. The magnification of the object is −3.0. Is the image real or virtual, inverted or upright? Is the mirror concave or convex? On which side of the mirror is the image located?

**6.** Using the rules for the three rays discussed with reference to Fig. 23–13, draw ray 2 for Fig. 23–17b.

**7.** What is the focal length of a plane mirror? What is the magnification of a plane mirror?

**8.** When you look at the Moon's reflection from a ripply sea, it appears elongated (Fig. 23–44). Explain.

**FIGURE 23–44** Question 8.

**9.** What is the angle of refraction when a light ray meets the boundary between two materials perpendicularly?

**10.** How might you determine the speed of light in a solid, rectangular, transparent object?

**11.** When you look down into a swimming pool or a lake, are you likely to underestimate or overestimate its depth? Explain. How does the apparent depth vary with the viewing angle? (Use ray diagrams.)

**12.** Draw a ray diagram to show why a stick looks bent when part of it is under water (Fig. 23–21).

**13.** Your eye looks into an aquarium and views a fish inside. One ray of light that emerges from the tank is shown in Fig. 23–45, as well as the apparent position of the fish. In the drawing, indicate the approximate position of the actual fish. Briefly justify your answer.

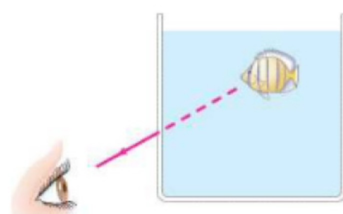

**FIGURE 23–45** Question 13.

**14.** How can you "see" a round drop of water on a table even though the water is transparent and colorless?

**15.** When you look up at an object in air from beneath the surface in a swimming pool, does the object appear to be the same size as when you see it directly in air? Explain.

**16.** How can a spherical mirror have a negative object distance?