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).

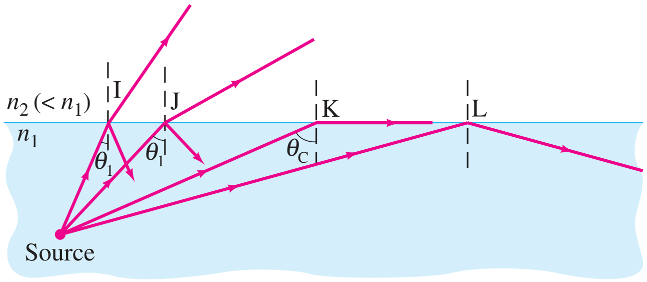


FIGURE 23–26 Since $n_2 < n_1$, light rays are totally internally reflected if the incident angle $\theta_1 > \theta_C$, as for ray L. If $\theta_1 < \theta_C$, as for rays I and J, only a part of the light is reflected, and the rest is refracted.

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

$$\sin\theta_C = \frac{n_2}{n_1}\sin 90° = \frac{n_2}{n_1}. \tag{23–6}$$

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)*

CONCEPTUAL EXAMPLE 23–10 **View up from under water.** Describe what a person would see who looked up at the world from beneath the perfectly smooth surface of a lake or swimming pool.

RESPONSE For an air–water interface, the critical angle is given by

$$\sin\theta_C = \frac{1.00}{1.33} = 0.750.$$

Therefore, $\theta_C = 49°$. Thus the person would see the outside world compressed into a circle whose edge makes a 49° angle with the vertical. Beyond this angle, the person would see reflections from the sides and bottom of the lake or pool (Fig. 23–27).

EXERCISE D Light traveling in air strikes a glass surface with $n = 1.48$. For what range of angles will total internal reflection occur?

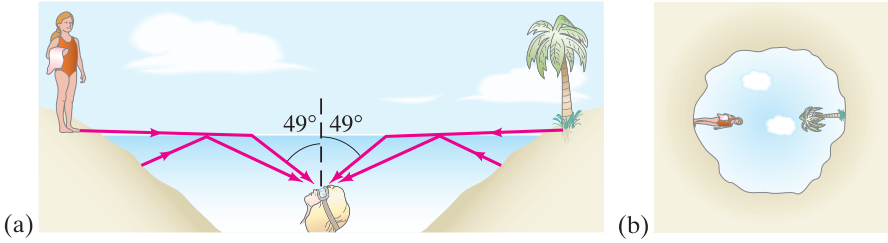


FIGURE 23–27 (a) Light rays entering submerged person's eye, and (b) view looking upward from beneath the water (the surface of the water must be very smooth). Example 23–10.

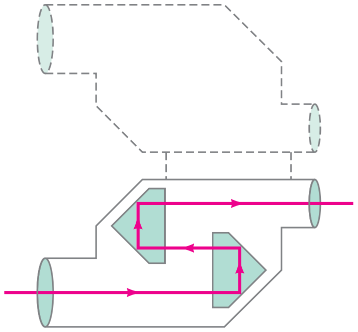
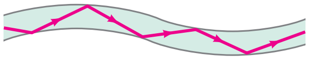


FIGURE 23–28 Total internal reflection of light by prisms in binoculars.

PHYSICS APPLIED
Fiber optics in communications and medicine—bronchoscopes, colonoscopes, endoscopes

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



Many optical instruments, such as binoculars, use total internal reflection within a prism to reflect light. The advantage is that very nearly 100% of the light is reflected, whereas even the best mirrors reflect somewhat less than 100%. Thus the image is brighter, especially after several reflections. For glass with $n = 1.50$, $\theta_C = 41.8°$. Therefore, 45° prisms will reflect all the light internally, if oriented as shown in the binoculars of Fig. 23–28.

EXERCISE E What would happen if we immersed the 45° glass prisms in Fig. 23–28 in water?

Fiber Optics; Medical Instruments

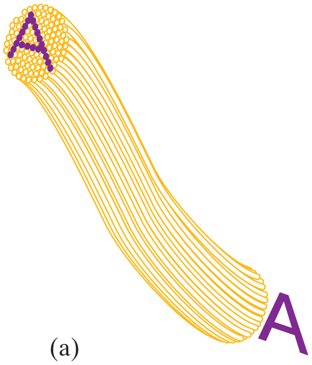
Total internal reflection is the principle behind **fiber optics**. Glass and plastic fibers as thin as a few micrometers in diameter are commonly used. A bundle of such slender transparent fibers is called a **light pipe** or **fiber-optic cable**. Light[†] can be transmitted along the fiber with almost no loss because of total internal reflection. Figure 23–29 shows how light traveling down a thin fiber makes only glancing collisions with the walls so that total internal reflection occurs. Even if the light pipe is bent gently into a complicated shape, the critical angle still won't be exceeded, so light is transmitted practically undiminished to the other end. Very small losses do occur, mainly by reflection at the ends and absorption within the fiber.

Important applications of fiber-optic cables are in communications and medicine. They are used in place of wire to carry telephone calls, video signals, and computer data. The signal is a modulated light beam (a light beam whose intensity can be varied) and data is transmitted at a much higher rate and with less loss and less interference than an electrical signal in a copper wire. Fibers have been developed that can support over one hundred separate wavelengths, each modulated to carry more than 10 gigabits $(10^{10}$ bits$)$ of information per second. That amounts to a terabit $(10^{12}$ bits$)$ per second for one hundred wavelengths.

The use of fiber optics to transmit a clear picture is particularly useful in medicine, Fig. 23–30. For example, a patient's lungs can be examined by inserting a fiber-optic cable known as a bronchoscope through the mouth and down the bronchial tube. Light is sent down an outer set of fibers to illuminate the lungs. The reflected light returns up a central core set of fibers. Light directly in front of each fiber travels up that fiber. At the opposite end, a viewer sees a series of bright and dark spots, much like a TV screen—that is, a picture of what lies at the opposite end. Lenses are used at each end of the cable. The image may be viewed directly or on a monitor screen or film. The fibers must be optically insulated from one another, usually by a thin coating of material with index of refraction less than that of the fiber. The more fibers there are, and the smaller they are, the more detailed the picture. Such instruments, including bronchoscopes, colonoscopes (for viewing the colon), and endoscopes (stomach or other organs), are extremely useful for examining hard-to-reach places.

[†]Fiber-optic devices use not only visible light but also infrared light, ultraviolet light, and microwaves.

FIGURE 23–30 (a) How a fiber-optic image is made. (b) Example of a fiber-optic device inserted through the mouth to view the vocal cords, with the image on screen.



(a)

(b)