Answer to Essential Question 24.1: Because all of these interfaces are parallel to one another, we can apply a rule-of-thumb that the smaller the angle between the normal and the beam, within a medium, the larger is that medium's index of refraction. Based on this rule-of-thumb, the ranking by index of refraction is 1 > 3 > 2.

24-2 Total Internal Reflection

Let's now explore an implication of Snell's Law that has practical applications. Under the right conditions, light incident on an interface between two media is entirely reflected back into the first medium. This phenomenon, that none of the light is transmitted into the second medium, is known as **total internal reflection**. Let's begin by examining light being transmitted from air to glass, a situation in which total internal reflection does not occur.

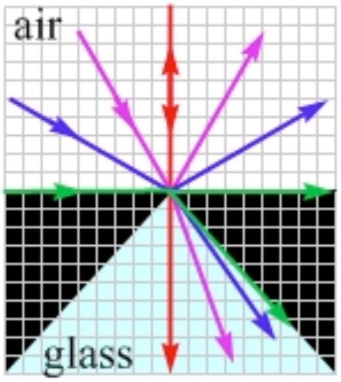

Figure 24.7: Four rays of light, incident on the same point on an air-glass interface. When the light strikes the interface, part of the beam is reflected back into the air, and part is refracted into the glass. The glass is rectangular, but the part of the glass that can not be reached by the light incident on this point has been shaded black.

Figure 24.7 shows various beams of light traveling in air and incident on the same point on an air-glass interface. The beams are shown in different colors to make it clear what path the reflected and transmitted beams follow. Four beams are shown, corresponding to angles of incidence of 0°, 30°, 60°, and almost 90°. As the angle of incidence increases, so does the refracted angle (the angle between the beam refracted into the glass and the normal). By choosing an appropriate angle of incidence, any point in the region shaded in blue in the glass can be illuminated by the light refracted into the glass from the air. Note, however, that no point in the region shaded in black in the glass can be illuminated by the light coming from the air, no matter what angle of incidence is used, if the beam of light is always incident on the same point on the interface.

Table 24.2 shows the angles of the refracted rays in the glass. These angles are determined by applying Snell's Law, using indices of refraction of 1.00 for air and 1.50 for glass.

Incident angle	Refracted angle
0°	0°
30.0°	19.5°
60.0°	35.3°
90.0°	41.8°

Table 24.2: The angles of the incident rays and the refracted rays in Figure 24.7.

EXPLORATION 24.2 – Total internal reflection

Let us now draw a similar picture to that in Figure 24.7, but the light will now travel through the glass before it is incident on the air-glass interface.

Step 1 – ***First, draw the rays in glass incident at angles of 0°, 19.5°, 35.3°, and 41.8°, the same values as the refracted angles in Table 24.2 . Show both the reflected rays and the rays that refract into the air.***

This figure is very similar to Figure 24.7, with the incident and refracted rays reversing directions. The values in Table 24.2 apply again, with the refracted angles in Table 24.2 now the incident angles, and vice versa.

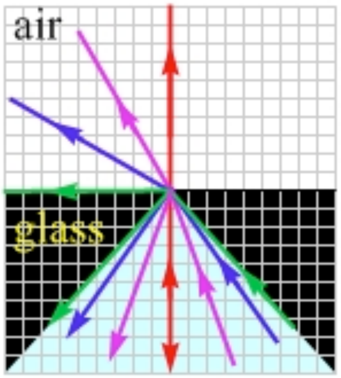

Figure 24.8: Four rays of light, incident on the same point on a glass-air interface. When the light strikes the interface, part of the beam is reflected back into the glass, and part is refracted into the air.

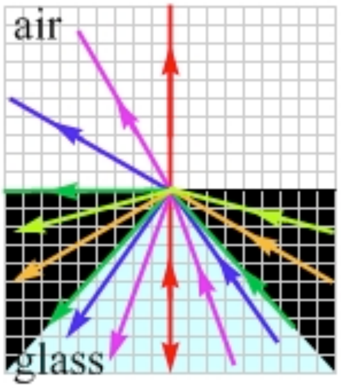

Figure 24.9: When the incident angle for light rays incident on the glass-air interface from the glass side exceed a particular critical angle (in the region colored black), 100% of the light reflects back into the glass. This is known as total internal reflection.

Step 2 – ***Now draw two additional rays, with angles of incidence of 60° and 75°, incident on the same point as the incident rays in Figure 24.8, and originally traveling in glass. What happens when you apply Snell's Law for these rays? What do these rays do when they encounter the interface?*** Let's apply Snell's Law to the situation of the 60° angle of incidence:

$$n_1 \sin(60°) = n_2 \sin\theta_2 .$$

$$\sin\theta_2 = \frac{n_{glass}\sin(60°)}{n_{air}} = \frac{1.5\times 0.866}{1.0} = 1.3 .$$

This equation cannot be solved, because the largest value that sin *θ* can be is 1. So, according to Snell's Law, there is no angle of refraction in the air for an angle of incidence of 60° in glass. A similar argument holds for all incident angles greater than 41.8° for rays traveling in glass and striking a glass-air interface. This is consistent with the forbidden region shaded in black in Figure 24.7. No light can refract into the glass from air at angles of refraction that exceed 41.8°, and so no refraction can occur in the opposite direction if the angle of incidence exceeds this critical angle of 41.8°. If the light does not refract into the air, it is entirely reflected back into the glass, obeying the law of reflection. This is known as **total internal reflection**.

Step 3 – ***In general, the critical angle of incidence beyond which total internal reflection occurs is the angle of incidence, in the higher-n medium, that results in a 90° angle of refraction in the lower-n medium. Apply Snell's Law to this situation to derive an equation for the critical angle, θ_c.*** Applying Snell's Law, and recognizing that sin(90°) = 1, gives:

$$n_1 \sin\theta_c = n_2 \sin(90°) = n_2 .$$

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right).$$ (Eq. 24.4: **The critical angle beyond which total internal reflection occurs**)

Key ideas: Total internal reflection can only occur when light in one medium strikes an interface separating that medium from a medium with a lower index of refraction. If the angle of incidence exceeds a particular critical angle, no light is transmitted into the second medium. Instead, all the light is reflected back into the first medium. **Related End-of-Chapter Exercises: 16 – 20.**

An important application of total internal reflection

Fiber optic cables, which are very important for communications, exploit total internal reflection. Data, as well as voice signals from telephone conversations, are sent through optical fibers by means of laser signals encoded to carry the information. The fibers can even bend around corners and, as long as the bend is not too abrupt, total internal reflection keeps the light inside the fiber.

Figure 24.10: A photograph of a collection of optical fibers. Photo credit: PhotoDisc/Getty Images.

Essential Question 24.2: Light traveling in medium 1 reaches the surface of the medium, which is surrounded by air (*n* = 1.00). The angle of incidence is 39°, and the light experiences total internal reflection. What can you say about the index of refraction of medium 1?