Consider in more detail what happens when light encounters the electrons in the atoms making up the very first layer of the medium's surface. When the light hits those electrons, oscillating electric and magnetic forces are exerted on them. As a result, the electrons begin oscillating at the same frequency at which the light wave oscillates. We know from Chapter 7 that an oscillating electron will emit light. These electrons, which are oscillating as a consequence of light striking them, emit some light of their own. This emitted light has the same frequency as the electron's oscillation, which is the same as the frequency of the incident light. This emitted light travels in the same direction as the incident light and adds to the original wave. From this, we conclude:

The frequency of a light wave is unchanged when it enters a transparent medium, although the speed of the wave changes.

Let us see what this fact implies about the light's wavelength. Recall that the wavelength equals the distance the wave travels in one period T (one full oscillation cycle). Let us introduce the symbol λ_n for the wavelength in the medium. The equation relating wavelength to speed and period is: *wavelength* = *speed* multiplied by *time between peaks*, or

$$\lambda_n = c_n \cdot T$$

The fact that the frequency remains unchanged when the wave enters the medium implies that the period also remains unchanged (because $f = 1/T$). The equation $\lambda_n = c_n \cdot T$ implies that the wavelength must change if the speed changes. The wavelength becomes shorter in a dense medium than it was in the surrounding vacuum (or air). This is because in a fixed time interval the wave travels a shorter distance in the medium than it would in vacuum. We conclude that the wavelength inside a medium equals the wavelength in vacuum divided by n. That is,

The wavelength of light inside a medium with refractive index equal to n is: $\lambda_n = \dfrac{\lambda}{n}$

We illustrate this behavior by drawing waves inside and outside of the medium, as in **Figure 13.3**. Here we consider a medium for which $n = 2$. The wave arrives from the left, travels to the right, and enters the medium. The wave speed slows for the light inside of the medium, then speeds up again when the wave exits the medium. Remember that the frequency is the same everywhere. From the relation $c_n = c/n$, we deduce that the speed inside the medium is one-half of the speed outside. In this case, the wavelength inside is one-half as long as the wavelength outside. As the wave moves from left to right, a crest outside of the medium travels a distance λ in the same time (T) that a crest on the inside travels a distance $\lambda/2$.

13.4 REFRACTION OF LIGHT AT A BOUNDARY

The wave nature of light produces an interesting effect: when light passes from one medium into another having a different refractive index, its direction of travel can change, depending on the angle at which the incoming wave travels. The bending of the wave fronts and propagation direction of a wave at a boundary between mediums of different refractive index is called ***refraction***. **Figure 13.4** illustrates this behavior, showing a "top view" of a light wave traveling from air into a dense medium, where its wave speed slows and its wavelength decreases. The direction of travel for each portion of the

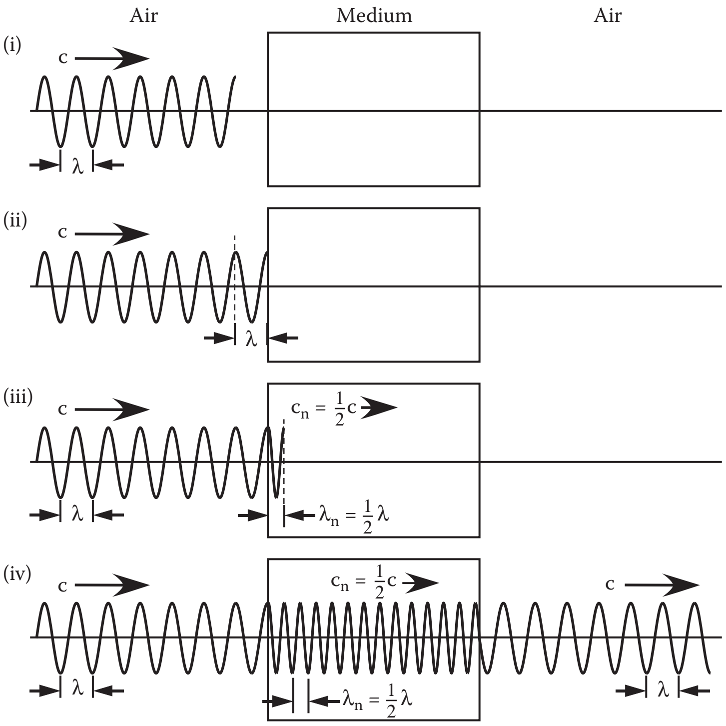

FIGURE 13.3 The first two frames show a light wave traveling from left to right in air with speed *c* and wavelength λ approaching a medium. The last two frames show the wave entering and passing through the medium, which has refractive index $n = 2$. In the medium, the wave travels with speed $c/2$, and its wavelength equals $\lambda/2$.

wave is shown as a bold arrow. Recall that a portion of a wave always travels in a direction perpendicular to its wave front. In the medium, each portion of the wave lags behind where it would be if it were not refracted. The wave fronts in the medium become angled relative to their original orientation. The angling of the wave fronts causes the upper and lower portions of the wave to travel in altered directions, as indicated by the arrows. As an analogy, think of a wave surfer who always travels in the direction of the steepest slope down the surface of a water wave; as the wave fronts bend, the surfer will change direction, following one of the paths of arrows shown in the figure.

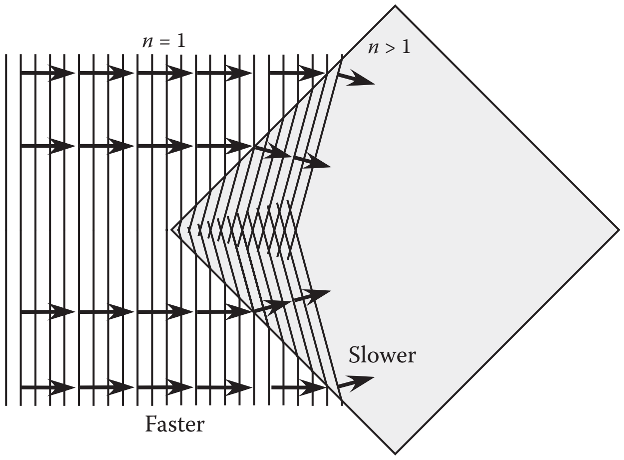

FIGURE 13.4 The shaded medium has higher refractive index than the air surrounding it. When the wave enters a higher-index medium, it refracts and the direction of travel bends relative to its original direction.

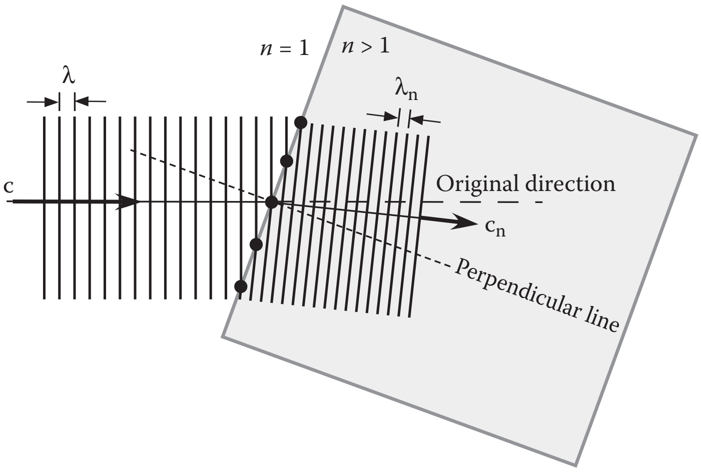

FIGURE 13.5 When the wave enters a higher-index medium from a lower-index one, the direction of travel bends toward the surface-perpendicular line relative to its original direction.

Figure 13.5 illustrates this behavior in detail, again showing a wave traveling from air into a denser medium, where its wave speed slows and its wavelength decreases. In the left side of the figure, a wave in a medium with refractive index $n = 1$ has a wavelength λ, and then enters a medium with higher index n. The wavelength λ_n in the higher-index medium is smaller than in the outside medium. The bold dots are drawn to indicate the points at the boundary where an outside wave front meets an inside wave front.

To understand how a wave behaves when it crosses the boundary between two media, we consider the following physical property: Wave fronts are continuous across the boundary between two media with different refractive indices. This is shown in the figure by the fact that every line representing a wave front outside of the denser medium meets a line representing a wave front inside the medium.

The consequence of this behavior is that inside of the medium, the wave fronts must tilt relative to their orientation outside of the medium, as shown. This means that the direction of travel tilts, or bends, when light enters a medium from another medium with a different refractive index. When a wave enters a higher-index medium from a lower-index one, the direction of travel bends toward the surface-perpendicular line, relative to its original direction.

A mechanical analogy can help to understand refraction. Consider a toy train made of a collection of rigid axles connected by compressible rods that can pivot at joints, as shown in **Figure 13.6**. The axles are initially a distance λ apart. Each axle supports two wheels, and each wheel rotates at a speed dependent on the properties of the surface below it. There are two types of surfaces—one on which wheels rotate rapidly, and one on which wheels rotate slower because of greater friction on a rolling wheel (e.g., sand.). When a wheel enters the shaded region, its rotation rate is slowed. Figure 13.6a of the figure shows such a "train" of axle segments moving in a straight line, approaching a surface on which wheels rotate slower. When the first lower wheel reaches the slower region, it slows, causing the first axle to turn. In Figure 13.6b the upper wheel of the first pair reaches the slow region, as the first axle moves in the new direction in the slow region. Because of deceleration, the connecting rod is compressed, making the distance (λ') between axles less. In successive frames of the animation, additional wheels and axles enter the slower region and turn in the angled direction. The axles in this picture are analogous to wave fronts.

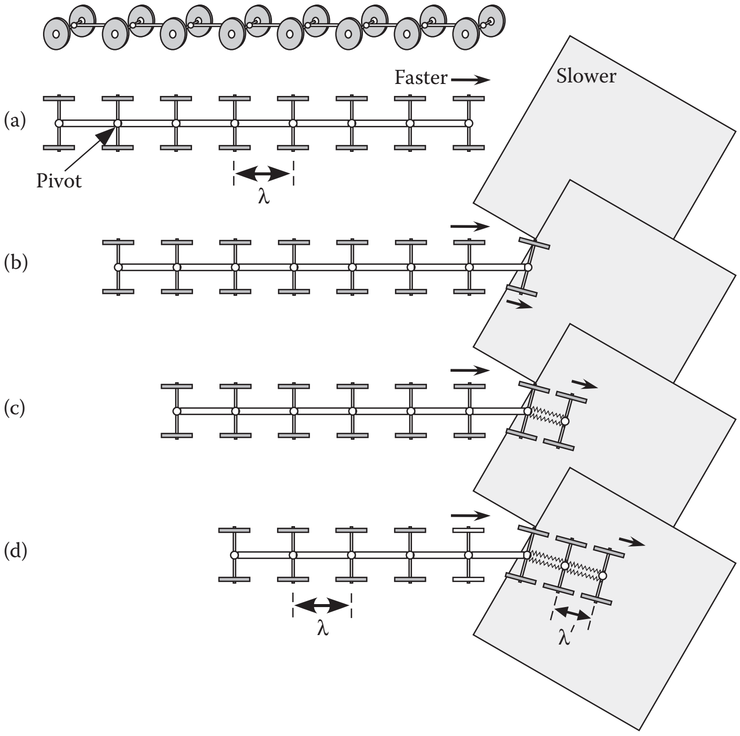

FIGURE 13.6 A "train" of wheel-and-axle segments enters a region where wheels rotate more slowly. The frames show the train at successive times.

On the other hand, if a wave leaves a higher-index medium and enters a lower-index medium, as in **Figure 13.7**, its wavelength increases and its speed increases. This causes the direction of travel to bend away from the surface-perpendicular line, relative to its original direction. This again results from the fact that the wave fronts are continuous when crossing the boundary, as indicated by the dark dots in Figure 13.7.

An example of refraction occurs when light enters water from the air. You are probably familiar with the way that objects seem to shift in their apparent position from their true position when you view an object that is under water. Try to explain to yourself how refraction causes this optical illusion.

QUICK QUESTION 13.1

Consider a transparent medium whose two surfaces are *parallel*, and which is surrounded on both sides by the same type of medium (e.g., air), as Figure 13.2a. When a light wave passes through the transparent medium and exits the other side, it travels *parallel* to the direction that it was initially traveling. This is because the refraction angle when exiting is equal but opposite to the refraction angle when entering. The amount of bending when entering and exiting depends on the ratio of the refractive indices inside and outside of the medium. Verify this conclusion by carefully drawing a continuation of the wave shown in Figure 13.5, being careful to make the wave fronts continuous at the surfaces.

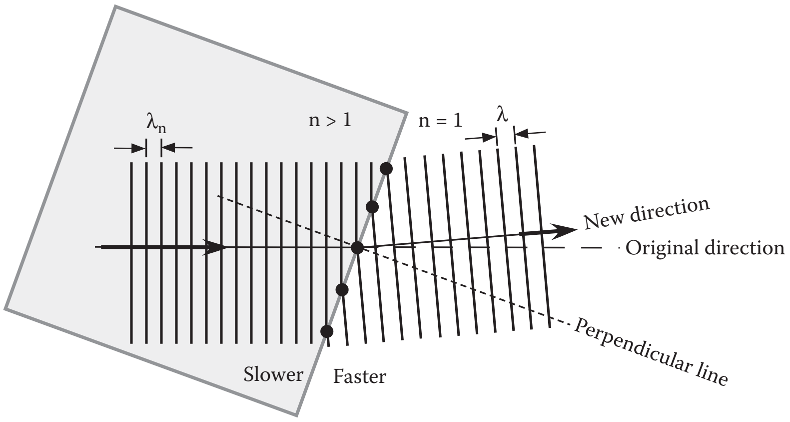

FIGURE 13.7 When a wave leaves a higher-index medium and enters a lower-index medium, the direction of travel bends away from the surface-perpendicular line, relative to its original direction.

We can summarize these observations by the following principle:

Principle of Wave Refraction:

Because wave fronts are continuous across the boundary between two media with different refractive indices, when a wave enters a higher-index medium, the direction of travel bends toward the surface-perpendicular line, relative to its original direction. If a wave enters a lower-index medium, the direction of travel bends away from the surface-perpendicular line, relative to its original direction.

THINK AGAIN

If a light wave is incident on a medium with its wave fronts parallel to the medium's surface, the direction of wave travel does not change, because this direction is already parallel to the surface-perpendicular line.

13.5 REFLECTION OF LIGHT AT A BOUNDARY

The reflection of light at a boundary between two mediums was illustrated in Figure 13.2. Here we will see why the reflected wave travels in the direction that it does. We defined propagation angles relative to a line drawn perpendicular to the medium's surface. **Figure 13.8** shows the incident and reflected wave fronts. Both waves have the same wavelength, because they are in the same medium. The bold straight lines indicate how one incident wave front joins up with a corresponding reflected wave front. Wave fronts must be continuous at the boundary, and this causes the reflected angle to equal the incident angle.

We state this behavior for reflection as a principle:

Principle of Reflection Angle:

Because wave fronts are continuous at a reflecting boundary, when a wave strikes a flat surface, the reflected wave travels with an angle from the surface-perpendicular line that is equal to that of the incident wave.

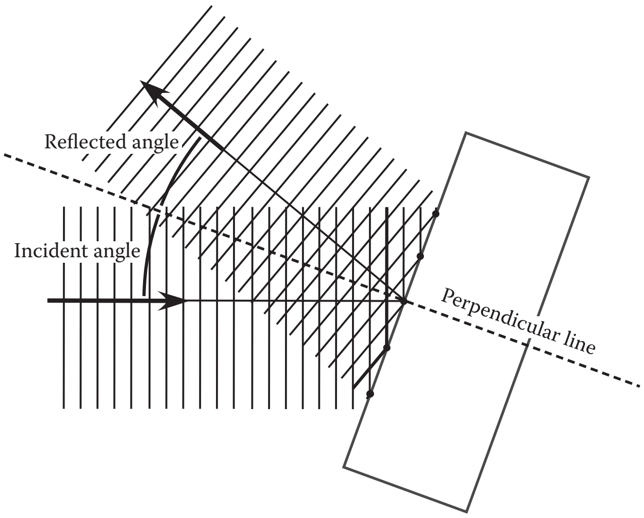

FIGURE 13.8 In reflection, the wave fronts are continuous, causing the reflected angle to equal the incident angle.