24-1 Refraction

To understand what happens when light passes from one medium to another, we again use a model that involves rays and wave fronts, as we did with reflection. Let's begin by creating a short pulse of light – say we have a laser pointer and we hold the switch down for just an instant. We shine this light onto the interface between two transparent media so that the beam of light is incident along the normal to the interface. For instance, Figure 24.1 shows a beam of light in air incident on a block of glass. Part of the beam is reflected straight back, and the rest is transmitted along the normal into the glass.

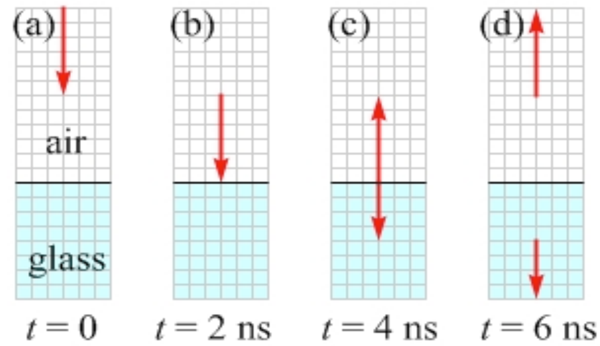

Figure 24.1: When a beam of light is incident along the normal to the interface between two transparent media, part of the beam is reflected straight back, while the rest is transmitted along the normal into the second medium. The squares on the grid measure 10 cm × 10 cm, and the images are shown at 2 ns intervals.

Figure 24.1 shows a sequence of images, showing the pulse of light at regular time intervals. Note that the light in the glass travels with an average speed that is about 2/3 of the average speed of the light in air. The average speed at which light travels through a medium depends on the medium. We can quantify this dependence of average speed on the medium by defining a unitless parameter known as the index of refraction, *n*.

$$n = \frac{c}{v},$$ (Equation 24.1: **Index of refraction**)

where $c = 3.00 \times 10^8$ m/s is the speed of light in vacuum. Table 24.1 gives indices of refraction for several media, and the corresponding speed of light in the media.

Medium	Index of refraction	Speed of light ($\times 10^8$ m/s)
Vacuum	**1.000**	**3.00**
Water	**1.33**	**2.25**
Glass	**1.5**	**2.0**
Diamond	**2.4**	**1.25**

Table 24.1: Typical indices of refraction for various media, and their corresponding speeds of light.

We can make sense of what happens in Figure 24.1 by looking at the wave fronts associated with the beam of light (see Figure 24.2). Because the wave slows down when it is transmitted into the glass, the wave fronts get closer together, shortening the distance from the front of the pulse to the end of the pulse. Going further, we can apply the wave equation (Equation 21.1, $v = f\lambda$) to re-write equation 24.1. The frequency of the wave in the two media is the same, so:

$$n = \frac{c}{v} = \frac{f\lambda}{f\lambda'} = \frac{\lambda}{\lambda'},$$

(Eq. 24.2: **Index of refraction, in terms of wavelength**)

where λ is the wavelength in vacuum, and λ' is the wavelength in the medium.

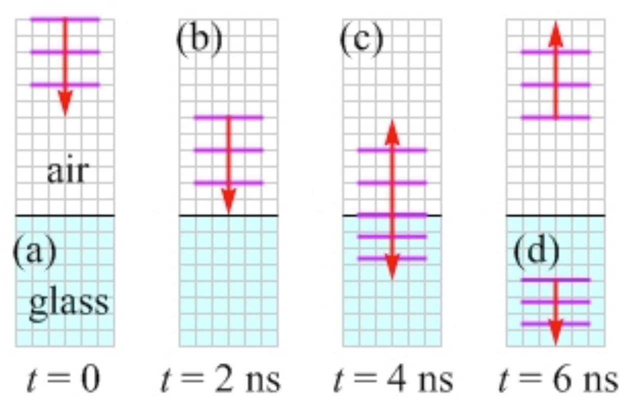

Figure 24.2: Looking at the wave fronts associated with the light as it passes from one medium to another, we can see that when the wave slows down, the wavelength decreases.

What happens when the beam of light is not incident along the normal? In this case, as shown in Figure 24.3, we observe that part of the wave is reflected from the interface, obeying the law of reflection, while the rest is transmitted into the second medium. However, the transmitted light travels in a different direction from the direction the incident light was traveling in the first medium. This change in direction experienced by light transmitted from one medium to another is known as **refraction**.

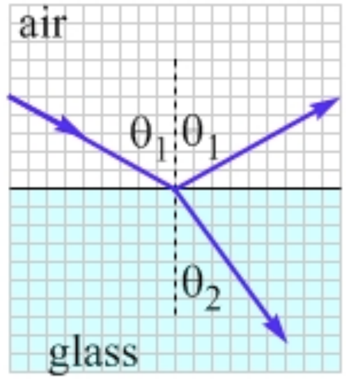

Figure 24.3: When light is not incident along the normal, the light changes direction when it is transmitted into the second medium, as long as the two media have different indices of refraction.

We can understand refraction by looking at the wave fronts as the beam of light passes from one medium to another, as shown in Figure 24.4. The part of the wave front that enters the glass first slows down, while the part still traveling in air maintains its speed. As can be seen, this causes the wave to change direction.

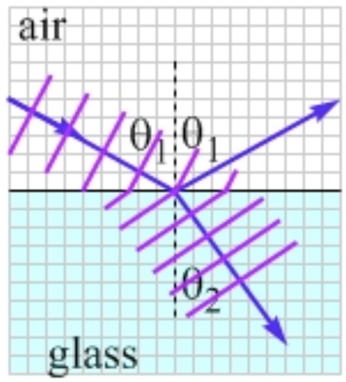

Figure 24.4: The part of the wave front that enters the slower medium (the glass) first slows down before the rest of the wave front, causing the ray to change direction. Wave fronts associated with the reflected wave have been omitted for clarity.

What happens if the light is traveling in the glass instead, and is then incident on the glass-air interface? The reflected ray is quite different from what we had above, but if the angle between the normal and the ray of light in the glass is the same in Figure 24.2 and Figure 24.4, the angle between the normal and the ray in air is also the same in the two cases. Snell's Law applies, no matter which direction the light is going.

When light is transmitted from one medium to another, the angle of incidence, θ_1, in the first medium is related to the angle of refraction, θ_2, in the second medium by:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$ (Equation 24.3: **Snell's Law**)

These angles are measured from the normal (perpendicular) to the surface. The n's represent the indices of refraction of the two media.

In general, when light is transmitted from one medium to a medium with a higher index of refraction, the light bends toward the normal (that is, the angle for the refracted ray is less than that for the incident ray). Conversely, the light bends away from the normal when light is transmitted from a higher-n medium to a lower-n medium.

Figure 24.5: The photograph shows a picture of a pencil in a glass of water. Refraction of the light leaving the water makes the pencil appear to bend. Photo credit: A. Duffy.

Related End-of-Chapter Exercises: 1, 2, 3 – 5.

Essential Question 24.1: Figure 24.6 shows a beam of light as it is transmitted from medium 1 to medium 3. Rank these media based on their index of refraction.

Figure 24.6: A beam of light passing through three media.