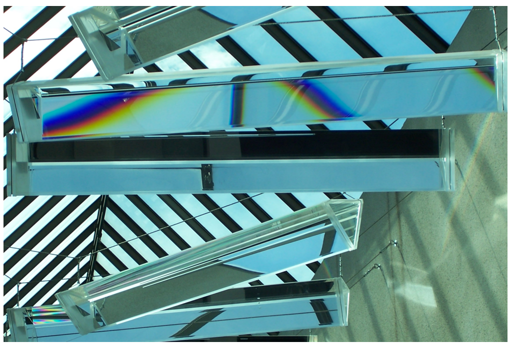
Answer to Essential Question 24.2: We know that 39° exceeds the critical angle for total internal reflection. If the critical angle is 39°, equation 24.4 gives $n_1 = 1.59$. (n_2 in the equation is 1.00, because medium 2 is air.) For the critical angle to be less than 39°, the index of refraction must be larger than 1.59. Thus, we know that the index of refraction of the medium is at least 1.59.

24-3 Dispersion

When a beam of white light shines onto a prism, a rainbow of colors emerges from the prism. Such a situation is shown in Figure 24.11. What does this tell us about white light? What does this tell us about the glass that the prism is made from?



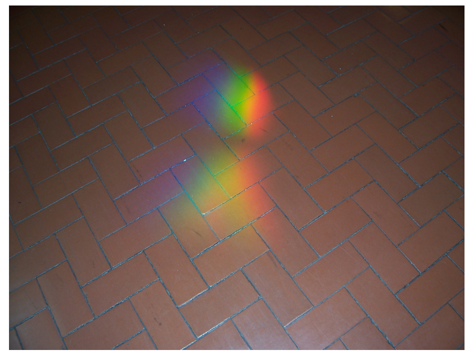


Figure 24.11: The triangular prisms in the picture on the left are suspended beneath the skylights at the Albuquerque Convention Center. Sunlight passing through these prisms produces beautiful rainbows on the floor, as in the photo on the right. Photo credits: A. Duffy.

The fact that a prism splits white light up into various colors of the rainbow tells us that white light consists of all the colors. For the prism to be able to separate out these individual colors, however, the index of refraction of the glass must depend on the wavelength of the light passing through the prism. This phenomenon is known as **dispersion**. Because white light contains all wavelengths of light in the visible spectrum, the different wavelengths (corresponding to different colors) refract at different angles, spreading out the colors.

In general, what we observe for a prism is that violet light, with a wavelength of 400 nm, experiences the largest change in direction, while red light, with a wavelength of 700 nm, experiences the smallest change in direction. As the wavelength increases from 400 to 700 nm, the change in direction decreases, and thus the index of refraction of the glass must also decrease. A graph of the index of refraction as a function of wavelength is shown in Figure 24.12.

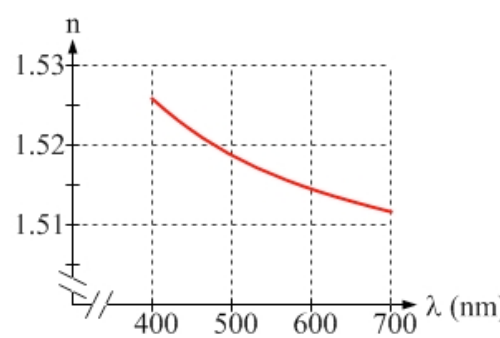


Figure 24.12: A graph of the index of refraction, as a function of wavelength, for a typical sample of glass. The graph is confined to the visible spectrum, from 400 nm (violet) to 700 nm (red).

Refraction, dispersion, and total internal reflection are all important in the formation of a rainbow, such as that in the photograph on the opening page of this chapter. To understand how a rainbow is formed, remember that you can generally only see a rainbow after it has rained, when the Sun is fairly low in the sky, and when you are looking away from the Sun. The rain is important because it produces a lot of water droplets in the sky. Let's begin by looking at how the red light, which is part of the white light coming from the Sun, interacts with a spherical water droplet.

Figure 24.13 shows how red light refracts into a spherical water droplet. Some of the red light reflects from the back of the droplet, and refracts again as it exits the droplet.

Figure 24.13: The path followed by red light inside a water droplet.

Let us now consider the path followed by violet light through the droplet. Water exhibits some dispersion, so when the violet light refracts into the water droplet the angle of refraction for the violet light is a little different from that for red light. Like the red light, some of the violet light reflects from the back of the water droplet, and experiences more refraction as it exits the droplet. As shown in Figure 24.14, the end result is that the beam of violet light coming from that droplet is higher in the sky than the beam of red light from the same droplet. All of the other colors of the visible spectrum lie between those of red and violet, because red and violet are at the two extremes of the visible spectrum.

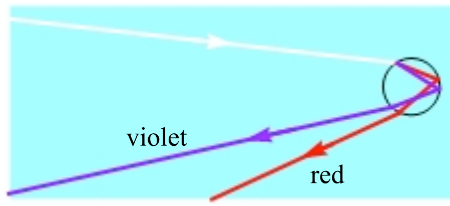
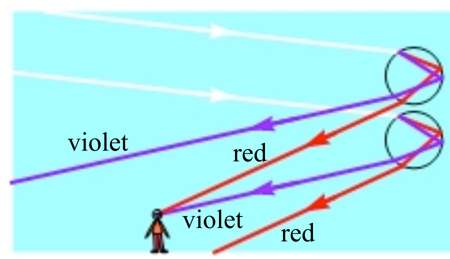


Figure 24.14: The path followed by violet light inside a water droplet, compared to that followed by the red light.

Compare Figure 24.14 to the photograph of the rainbow shown on the first page of this chapter. In Figure 24.14, the beam of violet light that leaves the droplet is higher in the sky than the red light that leaves the droplet. When you look at a rainbow, however, you see the red on the upper arc of the rainbow, and the violet on the lower arc. Is Figure 24.14 at odds with the photo?

Let's try adding the eye of an observer, as well as a second water droplet below the first, to the diagram. These additions are shown in Figure 24.15. When the observer looks at the upper water droplet, what color does it appear to be? It appears to be red, because red light from that droplet enters the observer's eye, while the violet light from that same droplet passes well over the observer's head. The lower droplet appears violet, however, because only violet light from that droplet enters the observer's eye.

Figure 24.15: Adding an observer, and a second water droplet, to the diagram in Figure 24.14 shows why the top arc of the rainbow is red, while the bottom arc is violet. The other colors come from droplets in between these two. The size of the water droplets is exaggerated so that the path taken by the beams is visible.



Other issues related to rainbows

Under the right conditions, you can see a double rainbow (or even a triple rainbow). As can be seen in the chapter-opening photograph, the second rainbow is dimmer than the primary rainbow, higher in the sky, and the order of colors is reversed. The secondary rainbow comes from light that reflects twice inside each water droplet, rather than once for the primary rainbow. Another issue is that rainbows are generally half-circles. Is it possible to see a rainbow that is a complete circle, or at least more than a half circle? Yes, it is. If you view a rainbow from a high vantage point, such as out the window of a plane, you may be able to see the entire circle.

Related End-of-Chapter Exercises: 7, 40.

Essential Question 24.3: After a light rain shower, you look out your window and see a beautiful rainbow in the sky. Your neighbor happens to look out her window at the same time, and also observes a rainbow. Does your neighbor see exactly the same rainbow that you do?