8.8 WAVE FRONTS AND DIFFRACTION

Unlike baseballs, bullets, and other pieces of matter in motion, waves can go around corners. For example, you can hear a voice coming from the other side of a hill, even though there is nothing to reflect the sound to you. You are so used to the fact that sound waves do this that you scarcely notice it. This spreading of the energy of waves into what you might expect to be "shadow" regions is called *diffraction*.

Once again, water waves will illustrate this behavior most clearly. From among all the arrangements that can result in diffraction, we will concentrate on two. The first is shown in the second photograph in Figure 8.22. Straight water waves (coming from the bottom of the second picture) are diffracted as they pass through a narrow slit in a straight barrier. Notice that the slit is less than one wavelength wide. The wave emerges and spreads in all directions. Also notice the *pattern* of the diffracted wave. It is basi-

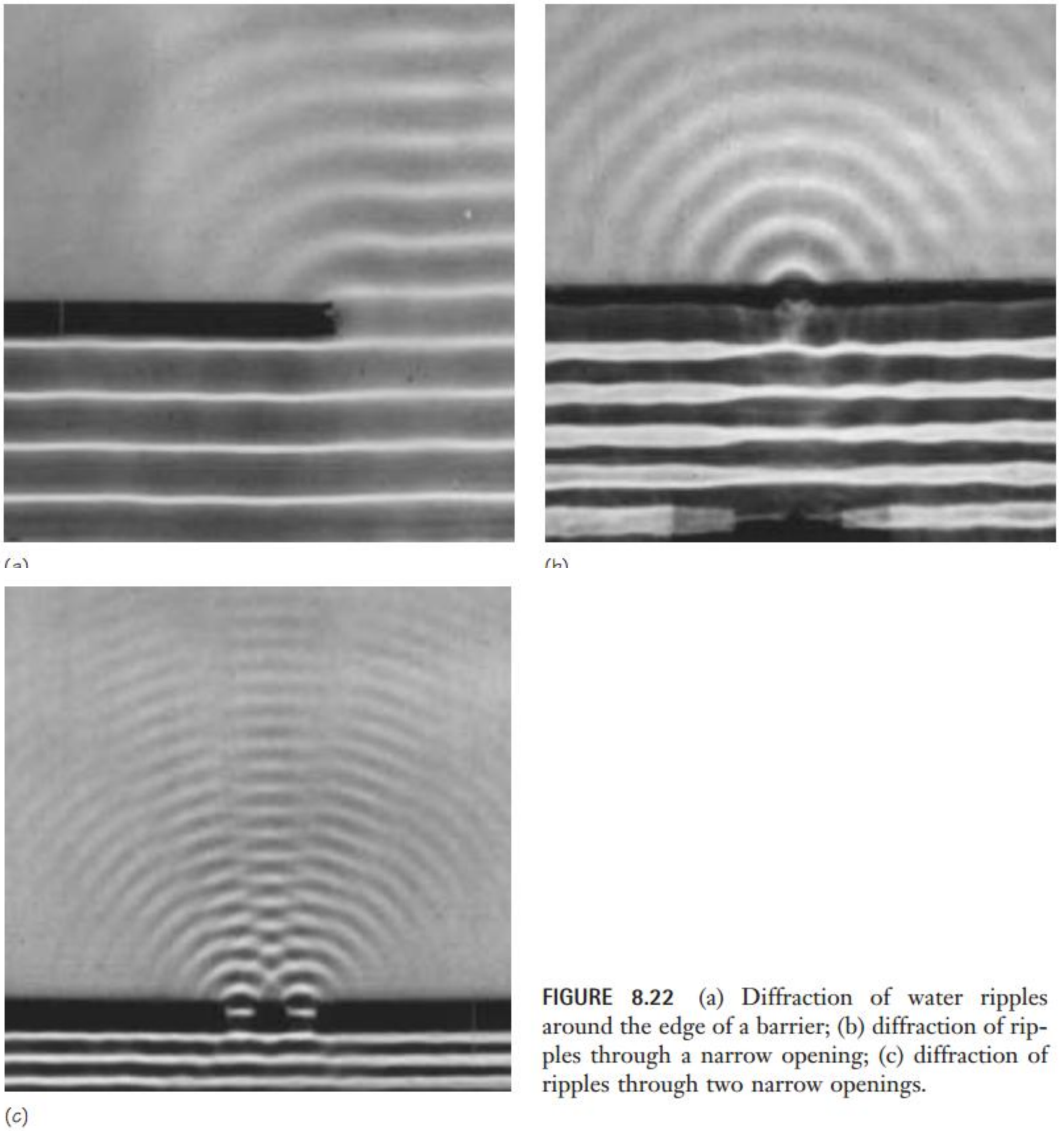

FIGURE 8.22 (a) Diffraction of water ripples around the edge of a barrier; (b) diffraction of ripples through a narrow opening; (c) diffraction of ripples through two narrow openings.

cally the same pattern a vibrating point source would set up if it were placed where the slit is.

The bottom photograph shows a second barrier arrangement. Now there are two narrow slits in the barrier. The pattern resulting from superposition of the diffracted waves from both slits is the same as that produced by two point sources vibrating in phase. The same kind of result is obtained when many narrow slits are put in the barrier; that is, the final pattern just matches that which would appear if a point source were put at the center of each slit, with all sources in phase.

One can describe these and all other effects of diffraction if one understands a basic characteristic of waves. This characteristic was first stated by Christiaan Huygens in 1678 and is now known as *Huygens' principle*. To understand it one first needs the definition of a *wave front*.

For a water wave, a wave front is an imaginary line along the water's surface, with every point along this line in exactly the same stage of vibration; that is, all points on the line are *in phase*. For example, crest lines are wave fronts, since all points on the water's surface along a crest line are in phase. Each has just reached its maximum displacement upward, is momentarily at rest, and will start downward an instant later.

Since a sound wave spreads not over a surface but in three dimensions, its wave fronts form not lines but surfaces. The wave fronts for sound waves from a very small source are very nearly spherical surfaces, just as the wave fronts for ripples, made by a very small source of waves on the surface of water, are circles.

Huygens' principle, as it is generally stated today, is that *every point on a wave front may be considered to behave as a point source for waves generated in the direction of the wave's propagation*. As Huygens said:

> There is the further consideration in the emanation of these waves, that each particle of matter in which a wave spreads, ought not to communicate its motion only to the next particle which is in the straight line drawn from the [source], but that it also imparts some of it necessarily to all others which touch it and which oppose themselves to its movement. So it arises that around each particle there is made a wave of which that particle is the center.

The diffraction patterns seen at slits in a barrier are certainly consistent with Huygens' principle. The wave arriving at the barrier causes the water in the slit to oscillate. The oscillation of the water in the slit acts as a source for waves traveling out from it in all directions. When there are two slits and the wave reaches both slits in phase, the oscillating water in each slit acts like a point source. The resulting interference pattern is similar to the pattern produced by waves from two point sources oscillating in phase.

Consider what happens behind the breakwater wall as in the aerial photograph of the harbor. By Huygens' principle, water oscillation near the end of the breakwater sends circular waves propagating into the "shadow" region.

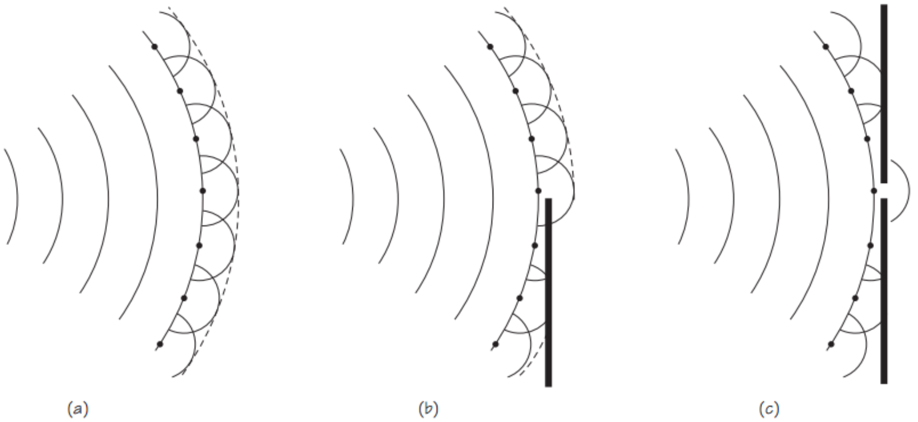

FIGURE 8.23 (a) Each point on a wave front can be thought of as a point source of waves. The waves from all the point sources interfere constructively only along their envelope, which becomes the new wave front. (b) When part of the wave front is blocked, the constructive interference of waves from points on the wave front extends into "shadow" region. (c) When all but a very small portion of a wave front is blocked, the wave propagating away from that small portion is nearly the same as that from a point source.

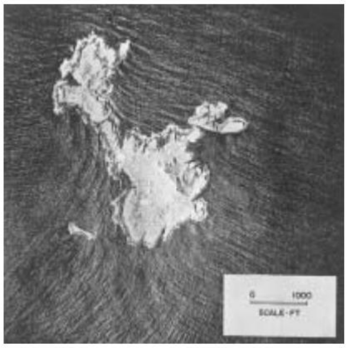

FIGURE 8.24 Reflection, refraction, and diffraction of water waves around an island.

You can understand all diffraction patterns if you keep both Huygens' principle and the superposition principle in mind. For example, consider a slit wider than one wavelength. In this case, the pattern of diffracted waves contains no nodal lines unless the slit width is about λ (see the series of images in Figure 8.25).

Figure 8.26 helps to explain why nodal lines appear. There must be points like P that are just λ farther from side A of the slit than from side B; that is, there must be points P for which distance AP differs from distance BP by exactly λ. For such a point, AP and OP differ by one-half wavelength, $\lambda/2$. By Huygens' principle, you may think of points A and O as in-phase point sources of circular waves. But since AP and OP differ by $\lambda/2$, the two waves will arrive at P completely out of phase. So, according to the superposition principle, the waves from A and O will cancel at point P.

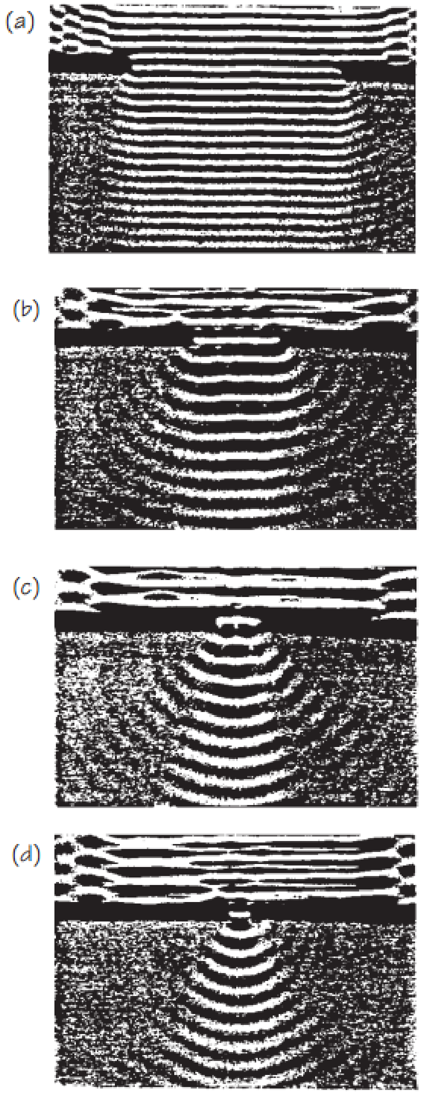

FIGURE 8.25 Single-slit diffraction of water waves with slits of different sizes.

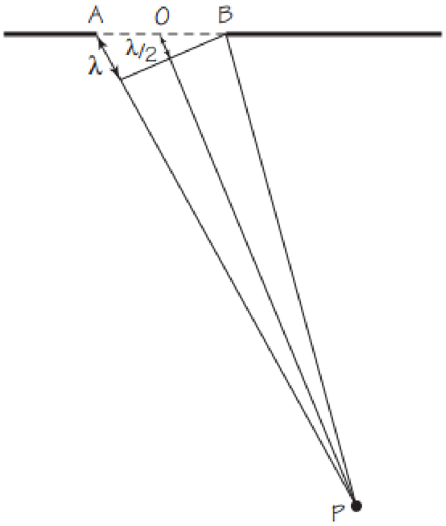

FIGURE 8.26 Diagram of a single slit showing how nodal lines appear (see text).

This argument also holds true for the pair of points consisting of the first point to the right of A and the first to the right of O. In fact, it holds true for *each* such matched pair of points, all the way across the slit. The waves originating at each such pair of points all cancel at point P. Thus, P is a nodal point, located on a nodal line. On the other hand, if the slit width is less than λ, then there can be *no* nodal point. This is obvious, since no point can be a distance λ farther from one side of the slit than from the other. Slits of widths less than λ behave nearly as point sources. The narrower they are, the more nearly their behavior resembles that of point sources.

One can compute the wavelength of a wave from the interference pattern set up where diffracted waves overlap. (See the *Student Guide* for such a calculation.) This is one of the main reasons for interest in the interference of diffracted waves. By locating nodal lines formed beyond a set of slits, you can calculate λ even for waves that you cannot see. Moreover, this

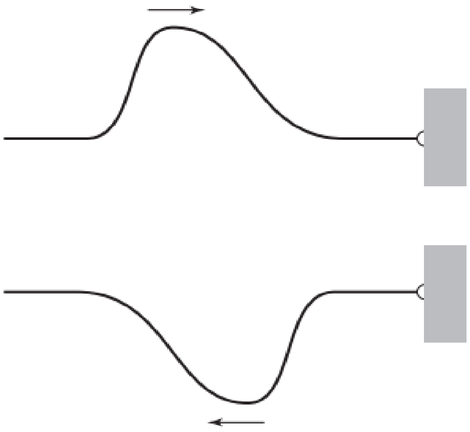

FIGURE 8.27 Wave on rope reflected from a wall to which it is attached.

is one very important way of identifying a series of unknown rays as consisting of either particles or waves.

For two-slit interference, the larger the wavelength compared to the distance between slits, the more the interference pattern spreads out. That is, as λ increases or d decreases, the nodal and antinodal lines make increasingly large angles with the straight-ahead direction. Similarly, for single-slit diffraction, the pattern spreads when the ratio of wavelength to the slit width increases. In general, diffraction of longer wavelengths is more easily detected. Thus, when you hear a band playing around a corner, you hear the bass drums and tubas better than the piccolos and cornets, even if they actually are playing equally loudly.