8.4 Waves in Two Dimensions

Have you ever taken a stroll near a river, either in woodland or perhaps along a city street, and heard the splashing sounds of moving water before you could actually see the river?

Figure 8.21 A river generates sound that often can be heard long before the river is in view. This phenomenon highlights some special properties of sound waves that result from their three-dimensional nature.

So far in this chapter, you have explored the behaviour of waves in linear media such as springs and ropes. However, many wave phenomena that you will be studying, such as sound and light, are not confined to a single dimension. In fact, sound waves can travel around corners, as you can tell whenever you hear a sound before you can see its source. To understand such phenomena, you need to learn about waves in more than one dimension. In this section, you will briefly explore some wave behaviours that emerge when waves travel in two-dimensional media.

Behaviour of Two-Dimensional Waves

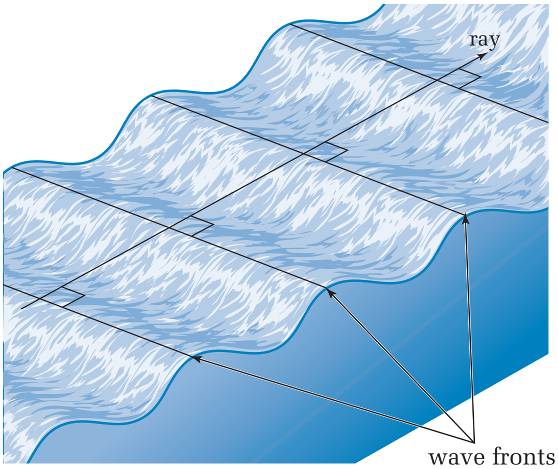
The most visible two-dimensional waves are water waves. Observing and describing water waves will help you tounderstand sound and light waves, as well as many other types of waves. Water waves can take on a variety of shapes. Two examples, straight and circular waves, are shown in Figure 8.22 on the next page. The lines drawn across the crests are called **wavefronts**. Since the distance from one crest to the next is one wavelength, the distance between wavefronts is one wavelength. To indicate the direction of the motion of the wave, lines called **rays** are drawn perpendicular to the wavefronts. Rays are not physically part of the wave, but they do help to model it scientifically.

SECTION OUTCOMES

- Investigate the properties of mechanical waves through experimentation.
- Apply the laws of reflection and the laws of refraction to predict wave behaviour.
- Define and describe the concepts and units related to constructive and destructive interference.
- Draw and interpret interference of waves during transmission through a medium.

KEY TERMS

- wavefront
- ray
- normal line
- angle of incidence
- angle of reflection
- refraction
- diffraction
- nodal line
- antinodal line



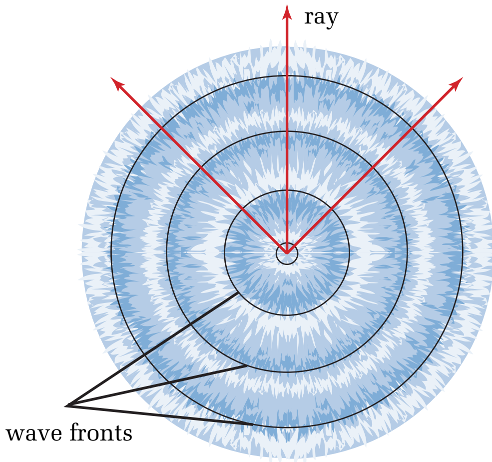


Figure 8.22 **(A)** A straight object rocking back and forth can disturb the water's surface and create waves with straight wavefronts. **(B)** A stone or pebble dropped into water can create circular waves. The crests move out in all directions from a central disturbance to water.

When a water wave encounters a solid barrier, it reflects in a way that is similar to a wave in a rope reflecting from an end that is firmly attached to a wall. However, water waves are not constrained to reflect directly backward. To quantitatively describe the way a two-dimensional wave reflects off a barrier, physicists define specific angles, as shown in Figure 8.23. At the point where a ray strikes the barrier, a line, called a **normal line**, is drawn perpendicular to the barrier surface. The **angle of incidence** is the angle between the normal line and the ray representing the incoming wave. The **angle of reflection** is the angle between the normal line and the ray representing the reflected wave.

PHYSICS FILE

A ripple tank consists of a shallow tank with a glass bottom that allows a light to shine through the water onto a screen as shown in the investigation on the following page. When waves form on the surface of the water, bright and dark regions, corresponding to the crests and troughs of the waves, are produced on the screen.

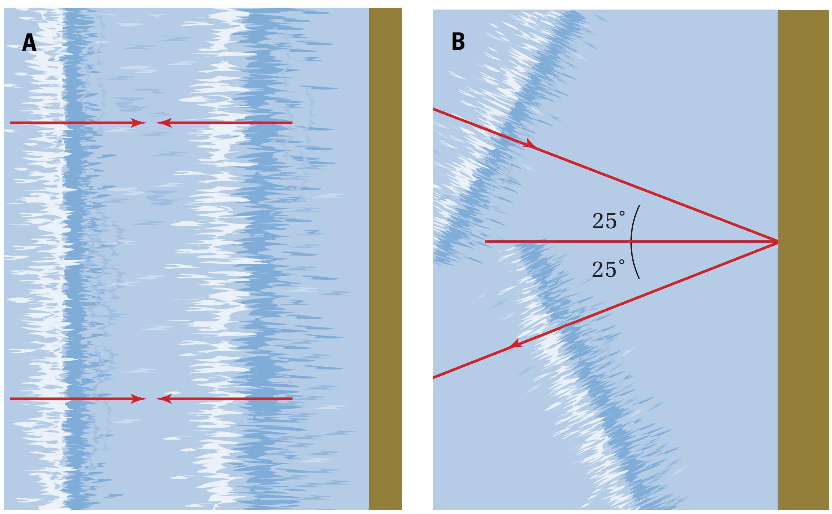


Figure 8.23 **(A)** Waves travelling directly toward a straight barrier reflect straight back. **(B)** Waves arriving at a barrier at an angle reflect off the barrier at an angle.

INVESTIGATION 8-C

Waves on the Surface of Water

TARGET SKILLS
- Identifying variables
- Performing and recording
- Analyzing and interpreting

Patterns occur in a ripple tank because the crests of waves act as lenses that focus the light and produce bright regions on the screen. The troughs act as lenses that spread the light out and produce dark regions.

Problem

How can a ripple tank be used to study waves?

Equipment

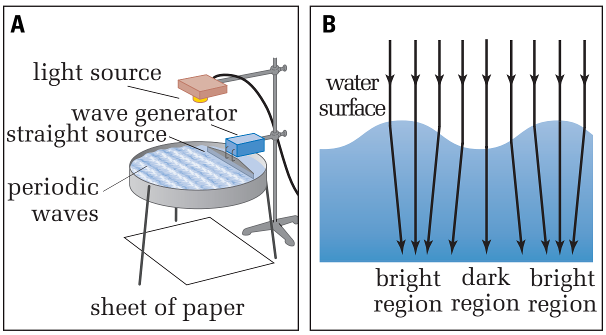
- ripple tank
- wooden dowel
- wave generator
- plastic or paraffin block (about 1 cm thick)

CAUTION

Care must be taken with any electrical equipment near ripple tanks. Firmly attach lights and wave generators to the tank or lab bench, and keep all electrical wiring away from the water.

Procedure

1. Assemble a ripple tank similar to the one shown below. Add water and level the tank so that the depth of the water is approximately 2 cm at all points in the tank.
2. Place a solid barrier in the tank. Use a dowel to generate single wave pulses, one at a time.



(A) You can see the details of water waves by using a ripple tank with a light shining directly onto the surface of the water. **(B)** The curves on the water's surface focus light, creating bright and dark regions.

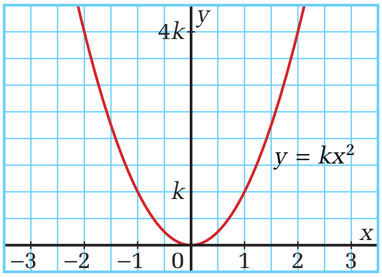
3. First, send a straight wave pulse directly toward the barrier. Then send straight wave pulses toward the barrier at a variety of angles. Draw diagrams of the wavefronts, with rays showing their direction of motion.
4. Next, send straight wave pulses toward a concave barrier roughly the shape of a parabola. Adjust the shape of the barrier until the reflected wave appears to converge toward a point. Keeping the shape of the barrier the same, start a circular wave from the point you just found, using your finger. Observe what happens when these circular waves reflect from the parabolic barrier.
5. To record your observations, draw diagrams of the shape of the wavefronts and include rays to illustrate the path of their motion.
6. Place a block of plastic (or paraffin), approximately 1 cm thick, on the bottom of the tank at one end. With the dowel, make straight wave pulses. First, send the pulses directly toward the edge of the plastic. Then, send straight wave pulses toward the plastic at various angles with the edge of the plastic. Observe any changes in wavelength or direction after the waves pass over the plastic.

Analyze and Conclude

1. Compare the angle of reflection to the angle of incidence when straight waves reflect from a straight barrier. State any general relationship that you observed.
2. How does a straight wave reflect from a parabolic barrier?
3. If a circular wave is started at the point where a parabola focusses a straight wave, what is the shape of the reflected wavefront?
4. How did the wavelength and direction of straight waves change when the waves passed from deeper water into more shallow water?

Math Link

The equation $y = kx^2$ is the equation of a parabola. The vertex of this parabola is located at the origin (0,0) and it opens upward. The rate at which it opens is determined by the value of k. Radar antennas and satellite dishes for television are constructed with parabolic cross sections. They collect waves coming straight in and focus them into a small receiver. Carefully sketch a parabola with equation $y = x^2$, and use ray paths to form a hypothesis about the location of the focus.



Reflection and Refraction of Water Waves

In Investigation 8-C, you probably discovered that, when a straight wave moves directly toward a straight barrier, the wave will be reflected directly backward. If a straight wave meets a barrier at an angle, it will reflect off at an angle. The angle of reflection will equal the angle of incidence.

Barriers with different shapes reflect waves in unique ways. For example, a concave barrier in the shape of a parabola will reflect straight waves so they become curved waves. The waves will converge toward, then pass through, a single point. As they continue through the point, they curve outward, or diverge.

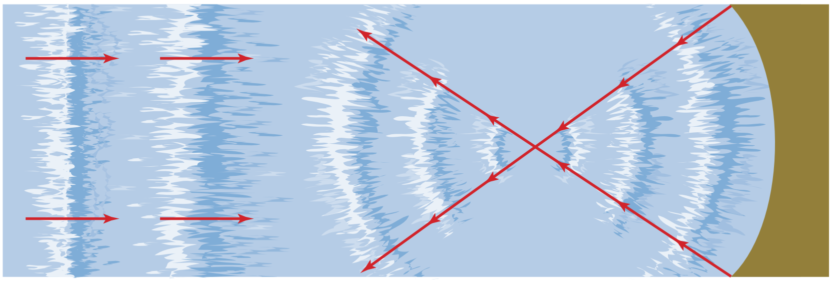


Figure 8.24 A parabolic barrier will reflect straight waves through a single focal point.

QUICK LAB: Diffracting Water Waves

TARGET SKILLS

- Identifying variables
- Analyzing and interpreting

CAUTION Use extreme care when working with electrical equipment near ripple tanks. Ensure that lights and wave generators are firmly attached. Keep all electrical wiring away from the water.

Use a straight wave generator with a ripple tank to generate periodic water waves. Obtain a barrier with an opening that can be varied in size. Place the barrier in the tank, parallel to the straight wave generator. Position the barrier so that you have a good view of the wavefronts after they have passed through the opening. Observe the behaviour of the waves passing through the barrier under the following conditions.

- Vary the size, D, of the opening in the barrier.
- Vary the wavelength, λ, of the waves.

The property of waves that causes them to "bend around corners" is called "diffraction." Choose the size of opening that caused the greatest amount of diffraction and make two openings of that size that are quite close together. Observe the behaviour of straight waves as they reach and pass through the two openings.

Analyze and Conclude

1. Do small or large openings in the barrier cause more diffraction of the water waves?
2. Are small or large wavelengths diffracted more?
3. Describe the pattern you observed that was caused by two openings located close together.

When waves travel from one medium into another, their speed changes. This phenomenon is called **refraction**. As a result of the change in speed, the direction of two-dimensional waves changes. You can demonstrate this effect in water waves without even changing from water to another medium. Refraction occurs in water because the speed of waves in water is influenced by the depth of the water. You probably observed refraction occurring in the ripple tank when you placed the thick sheet of plastic in the tank. Did the waves change direction when they went from the deeper water to the shallower water? You will study refraction of light waves in more depth in Chapter 9.

Bending Around Corners: Diffraction of Waves

Waves and particles behave quite differently when they travel past the edge of a barrier or through one or more small openings in a barrier. Moving particles either reflect off the barrier or pass through the opening and continue in a straight line. What do waves do when they encounter the edge of a barrier or openings in a barrier?

In the previous Quick Lab, you probably discovered that when waves pass through small openings in barriers they do not continue straight through. Instead, they bend around the edges of the barrier. This results in circular waves that radiate outward. This behaviour of waves at barriers is called **diffraction**. The amount of diffraction is greatest when the size of the opening is nearly the same as the size of one wavelength.

Figure 8.25 When straight water waves reach a small opening in a barrier, the tiny part of the wave at the opening acts as a point source, similar to the effect of putting your finger in the water; thus, the waves move out in semicircles. This phenomenon is an example of the diffraction of waves.

Biology Link

Scientists who study bird vocalizations use parabolic reflectors to collect sounds from a distance and focus the sound waves to a point where they have placed a microphone. By aiming the reflector at a distant bird, they can "capture" the sound of that bird and nearly eliminate other sounds. Use print resources and the Internet to find out what researchers have discovered about how songs and calls are learned, and if they have "meaning."

PHYSICS & TECHNOLOGY

Poseidon's Powerhouse: Converting Waves to Watts

According to ancient Greek mythology, Poseidon was the undisputed ruler of the sea, controlling the waves, causing storms, and sinking ships. While we now know that waves are caused by winds created when the sun heats the earth's surface, scientists and engineers around the world continue their Poseidon-like quest to harness the kinetic energy of ocean waves.

Researchers estimate that waves crashing into the world's coastlines produce 2 to 3 million megawatts (MW) of power, which is equivalent to the output of 3000 large power plants. The vertical distance between a wave's crest and valley represents its potential energy. How big a wave is depends on wind speed and "fetch," or the distance the wind has travelled over the ocean's surface. Waves with the highest energy are found off western coastlines facing the open ocean in the 40°–60° latitude range north and south.

Ideas about how to harness the power of waves have existed since 1799, when the first wave power patent was filed. Even with its long history, wave power technology has been slow to develop. It is only within the last thirty years, inspired by growing concern over the effects of greenhouse gases (GHGs) and increasing oil prices, that wave power technology has inched slowly towards being viable for widespread commercial use.

Current wave energy devices fall into two categories: onshore and offshore devices. A common onshore device is the oscillating water column (OWC), which is built along the shoreline and consists of a partially submerged, hollow, vertical steel or concrete column. The OWC is open to the ocean below the water line, and encloses a column of air on top of a column of water. As waves crash into the OWC, the water column rises and falls, compressing and decompressing the air column, which then drives a Wells turbine that is connected to an electric generator. The world's first commercial wave power plant, which opened in 2000 in Scotland, uses OWC technology and generates 500 kW of energy. Unfortunately for onshore devices, by the time a wave washes ashore, it has lost most of its energy to the seabed. Operating in water 40 to 100 metres deep, offshore devices, which consist of heaving buoys or floats anchored to the ocean floor, exploit greater amounts of wave energy to drive hydraulic pumps and pistons which power electrical generators. The energy is transported ashore via underwater power cables.

While the United Kingdom and other countries have been developing and implementing wave energy devices, North America has yet to jump on board. However, on Canada's west coast, BC Hydro plans to add 3 to 4 MW of wave energy to the island's power grid by 2004. On Canada's east coast, Wavemill Energy, a research and development firm in Dartmouth, Nova Scotia, has developed a wave energy device that is a hybrid of the OWC and the heaving buoy. Wavemill, headed up by brothers Alan and Gerry Vowles, is currently working with thirty-five different countries, including Chile, the Philippines, and Nigeria, to implement its technology.

Although it has been slower to catch on than other types of green energy, wave power, which contains one thousand times the kinetic energy of wind, is more promising in the long run. Ocean waves produce a continuous supply of energy, day and night. This could make wave energy literally the "next wave" in green energy development.

Going Further

1. An early wave energy project in the 1970s employed "Salter's Nodding Ducks." If not a rare and endangered species of waterfowl, what are they? Are they now "extinct"?

Interference Patterns in Water Waves

If plane waves pass through two openings in a barrier that are close together, diffraction of the waves creates a unique pattern. A similar pattern is created by two point sources, located close together, generating circular waves that are in phase. As the waves from the two sources meet, interference creates the distinctive pattern seen in Figure 8.26. This pattern results from alternating nodes and antinodes radiating outward from the sources. Although the situation is much like standing waves on a string, the pattern spreads over the two-dimensional water surface.

You can analyze, even predict, the pattern by considering several lines radiating out from the centre and then determining how waves will interfere along these lines. Start with the perpendicular bisector of a line connecting the two sources. Then, pick any point on that line and draw lines from each source to the point, as shown in Figure 8.27 (A). Notice that these lines form congruent triangles because the bases are equal, the angles are equal, and they share a side. Therefore, the lines from the sources are equal in length. Since the two sources are emitting waves in phase, when the two waves pass through each other at point *P*, they will be at exactly the same phase in their cycles. Figure 8.27 (B) shows two crests meeting at point *P*. They will add constructively, making the amplitude at that point double that of each individual wave. A moment later, troughs will meet. This makes a trough that is double the size of each individual trough. This process occurs at every point along this central line. Thus, every point on the surface will be oscillating maximally.

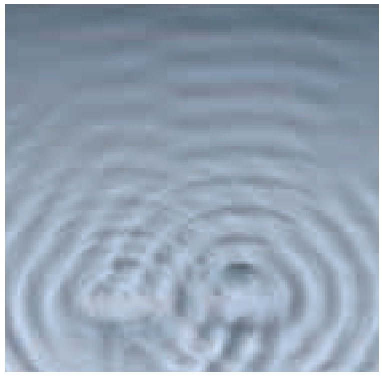


Figure 8.26 A series of antinodes run along the vertical line up the centre. The lines spreading out beside the antinodes are formed by nodes.

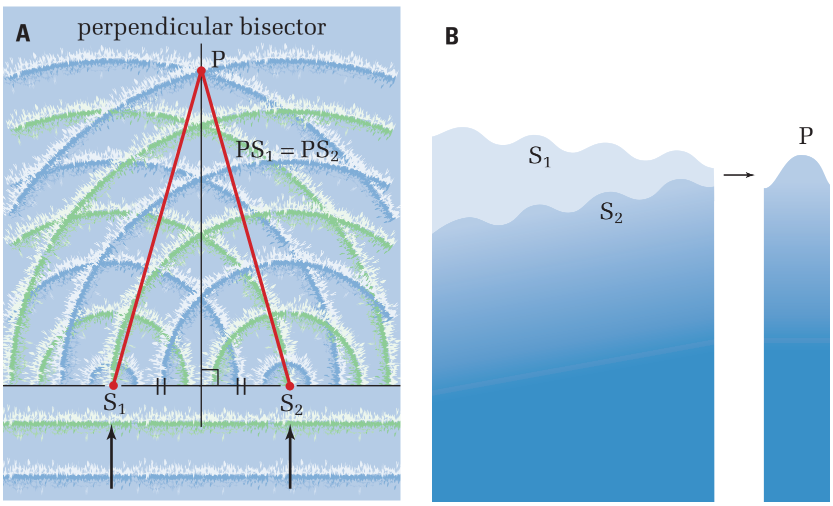
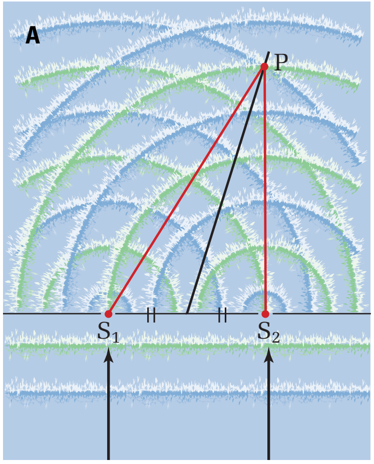


Figure 8.27 **(A)** Constructive interference occurs for a point on the perpendicular bisector because it is an equal distance from both sources. Since the sources are creating waves in phase, they will still be in phase at point *P*. Crests are represented in blue and troughs in green. **(B)** Looking from the side, you can see crests superimposed at point *P*.

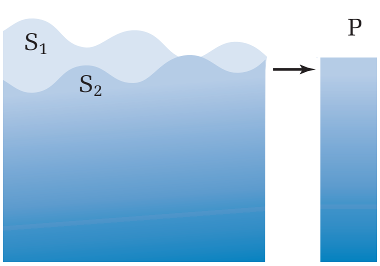
Biology Link

The phenomenon of diffraction provides an important tool in several fields of science. Rosalind Franklin obtained the pattern in the photograph shown here by passing X rays through a crystal of DNA. The pattern produced by the diffraction of X rays is shown on the film. This pattern provided James Watson and Francis Crick with key information that helped them discover the three-dimensional structure of DNA. Find out more about these scientists' amazing discoveries in your biology and chemistry courses, or go to print resources and the Internet for more.

Chemists and biochemists use X-ray diffraction to determine the structure of many crystals and biological molecules.



B



Next, consider a line radiating outward to the right (or left) of the centre line as shown in Figure 8.28 (A). This line is carefully chosen so that the difference in the distances from the sources to any point on this line is exactly one half of a wavelength. Again, Figure 8.28 (B) shows what you would see if you looked, from the side, at waves travelling along these lines. Notice that the waves that pass through each other at point P_1 on this line are exactly out of phase. No matter what stage of the cycle is passing this point, the waves will destructively interfere. The surface of the water along this line will not move. There are nodes all along the line, so it is called a **nodal line**. Although these lines appear straight in Figure 8.26, they are, in reality, slightly curved.

If you were to continue to draw lines radiating outward at greater and greater angles from the perpendicular bisector, you would reach points where the distance from one source would be one full wavelength longer than the other. Again, the waves would constructively interfere as they passed through each other, forming an **antinodal line**. When the distance to points on a line is 1.5 wavelengths, you would find another nodal line.

Figure 8.28 **(A)** Destructive interference occurs at points that are a distance $\frac{1}{2}\lambda$ farther from one source than the other, because the waves will always be half a wavelength out of phase when they reach this line. **(B)** Looking from the side, you can see the result of a crest superimposed on a trough at point *P*.

8.4 Section Review

1. **C** Sketch the wave produced by dipping a finger into water in a ripple tank. Add rays to your diagram to illustrate the directions of wave movement.
2. **I** Two circular waves are sent out from points about 15 cm apart in a ripple tank.
   (a) Sketch their appearance a short period of time after they have met.
   (b) What does this tell you about how the two waves have moved?
3. **I** Sketch the appearance of a straight wave after it has passed through a small opening in a straight barrier. Add rays to your diagram to illustrate the directions of wavefront movement.
4. **C** Sketch a typical interference pattern produced by two point sources vibrating in phase.

UNIT PROJECT PREP

Diffraction is an important concept to consider in a noise policy document.

- Have you ever heard sound waves diffract around barriers?
- What is the relationship between the amount of diffraction and the sound wave frequency?