

constructive
interference
CRESTS

refraction

Surf's Up

From where does the surfer's kinetic energy come? Trace the energy source back as far as you can.

➡ Look at the text on page 329 for the answer.

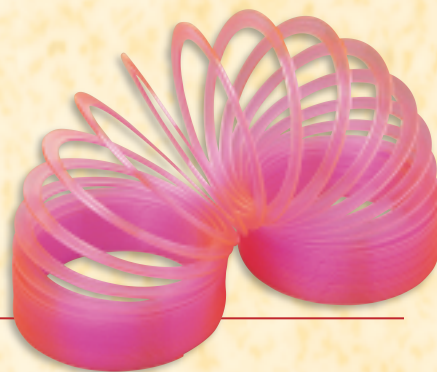
WAVE



frequency

CHAPTER

14 Waves and Energy Transfer



Have you ever been in a wave pool and caught a wave with your body, experiencing a push from the wave? Perhaps you've splashed about in the tub, creating a miniwave and letting the water lift your body upward.

Or maybe you have had the exhilarating experience of riding a surfboard near the ocean shore. As the wave pushes you toward the shore, you gain speed and stay just ahead of the breaking surf. As you surf, you may try to ride almost parallel to the wave at a very high speed, as this surfer does. Surfing, however, can be dangerous. Unless you are skilled, the energy carried by the wave can cause you to wipe out, throwing you into the ocean or up onto the sand.

In each case, your body's kinetic energy increases. The question is, where does this extra energy come from, and how does it get from one place to another?

In the wave pool, you can see the waves move from one end of the pool to the other. Even in the tub, you can see the miniwave move from your head to your toes. At the ocean shore, surfing a wave allows you to come rapidly toward the shore. In each case, you may think the water is moving from one location to another. However, that is not what occurs. In water waves, the wave carries energy from one location to another, while the water itself moves in circles. In the coming chapters, you will study the wave motions of light and sound. You will find out how light waves and sound waves are similar and how they are different.

WHAT YOU'LL LEARN

- You will determine how waves transfer energy.
- You will describe wave reflection and discuss its practical significance.

WHY IT'S IMPORTANT

- Waves enable the sun's energy to reach Earth and make possible all communication through sound.
- Because light waves can be reflected, you are able to see the world around you and even read these very words.
- Knowledge of the behavior of waves is essential to the designing of bridges and many other structures.

PHYSICS
Online



To find out more about waves and energy transfer, visit the Glencoe Science Web site at science.glencoe.com

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CONTENTS



OBJECTIVES

- **Identify** how waves transfer energy without transferring matter.
- **Contrast** transverse and longitudinal waves.
- **Relate** wave speed, wavelength, and frequency.

Both particles and waves carry energy, but there is an important difference in how they do this. Think of a ball as a particle. If you toss the ball to a friend, the ball moves from you to your friend and carries energy. However, if you and your friend hold the ends of a rope and you give your end a quick shake, the rope remains in your hand, and even though no matter is transferred, the rope still carries energy. The waves carry energy through matter.

Mechanical Waves

You have learned how Newton's laws of motion and conservation of energy principles govern the behavior of particles. These laws also govern the motion of waves. There are many kinds of waves. All kinds of waves transmit energy, including the waves you cannot see, such as the sound waves you create when you speak and the light waves that reflect from the leaves on the trees.

Transverse waves A **wave** is a rhythmic disturbance that carries energy through matter or space. Water waves, sound waves, and the waves that travel down a rope or spring are types of mechanical waves. Mechanical waves require a medium. Water, air, ropes, or springs are the materials that carry the energy of mechanical waves. Other kinds of waves, including electromagnetic waves and matter waves, will be described in later chapters. Because many of these waves cannot be directly observed, mechanical waves can serve as models for their study.

The two disturbances that go down the rope shown in **Figure 14–1** are called wave pulses. A **wave pulse** is a single bump or disturbance that travels through a medium. If the person continues to move the rope up and down, a **continuous wave** is generated. Notice that the rope is disturbed in the vertical direction, but the pulse travels horizontally. This wave motion is called a transverse wave. A **transverse wave** is a wave that vibrates perpendicular to the direction of wave motion.

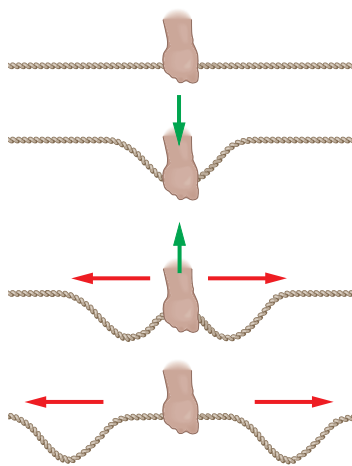


FIGURE 14–1 A quick shake of a rope sends out wave pulses in both directions.

Longitudinal and surface waves In a coiled spring such as a Slinky toy, you can create a wave pulse in a different way. If you squeeze together several turns of the coiled spring and then suddenly release them, pulses of closely spaced turns will move away in both directions, as in **Figure 14–2**. In this case, the disturbance is in the same direction as, or parallel to, the direction of wave motion. Such a wave is called a **longitudinal wave**. Sound waves are longitudinal waves. Fluids such as liquids and gases usually transmit only longitudinal waves.

Although waves deep in a lake or ocean are longitudinal, at the surface of the water, the particles move in a direction that is both parallel

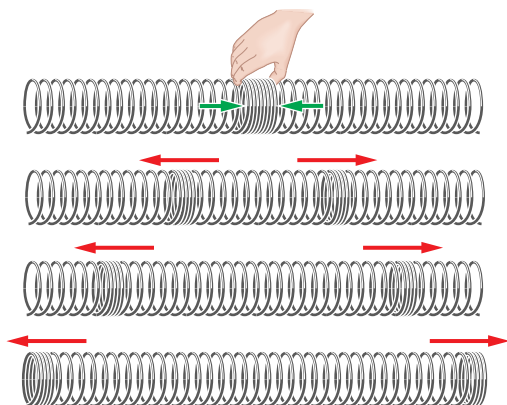


FIGURE 14-2 The squeeze and release of a coiled spring toy sends out wave pulses in both directions.

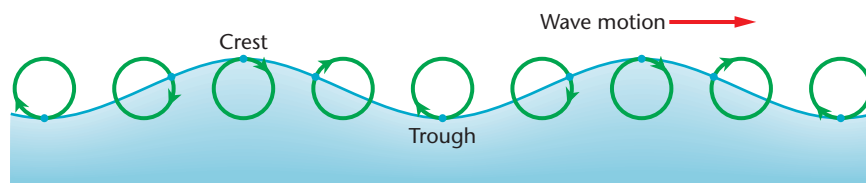
and perpendicular to the direction of wave motion, as shown in **Figure 14-3**. These are **surface waves**, which have characteristics of both transverse and longitudinal waves. The energy of water waves usually comes from storms far away. The energy of the storms initially came from the heating of Earth by solar energy. This energy, in turn, was carried to Earth by transverse electromagnetic waves.

Measuring a Wave

There are many ways to describe or measure a wave. Some methods depend on how the wave is produced, whereas others depend on the medium through which the wave travels.



a



b

Surf's Up

➔ *Answers question from page 326.*



FIGURE 14-3 Surface waves have properties of both longitudinal and transverse waves (**a**). The paths of the particles are circular (**b**).

Waves on a Coiled Spring

Problem

How can you model the properties of transverse waves?

Hypothesis

A coiled spring toy can be used to model transverse waves and to investigate wave properties such as speed, frequency, amplitude, and wavelength.

Possible Materials

a long coiled spring toy
stopwatch
meterstick

Plan the Experiment

1. Work in pairs or groups, and clear a path of about 6 meters for this activity.
2. One member of the team should grip the Slinky firmly with one hand. Another member of the team should stretch the spring to the length suggested by your teacher. Team members should take turns holding the end of the spring. **CAUTION:** *Coiled springs easily get out of control. Do not allow them to get tangled or overstretched.*
3. The second team member should then make a quick sideways snap of the wrist to produce transverse wave pulses. Other team members can assist in measuring, timing, and recording data. It is easier to see the motion from one end of the Slinky, rather than from the side.
4. Design experiments to answer the questions under Analyze and Conclude.
5. **Check the Plan** Make sure your teacher has approved your final plan before you proceed with your experiments.



Analyze and Conclude

1. **Interpreting Data** What happens to the amplitude of the transverse wave as it travels?
2. **Recognizing Cause and Effect** Does the transverse wave's speed depend upon its amplitude?
3. **Observing and Interpreting** If you put two quick transverse wave pulses into the spring and consider the wavelength to be the distance between the pulses, does the wavelength change as the pulses move?
4. **Applying** How can you decrease the wavelength of a transverse wave?
5. **Interpreting** As transverse wave pulses travel back and forth on the spring, do they bounce off each other or pass through each other?

Apply

1. How do the speeds of high frequency (short wavelength) transverse waves compare with the speeds of low frequency (long wavelength) transverse waves?
2. Suppose you designed the experiment using longitudinal waves. How would the procedure for longitudinal waves be different from the procedure for transverse waves?
3. Would you expect the results of an experiment with longitudinal waves to be similar to the results of the transverse wave experiment? Explain why or why not.

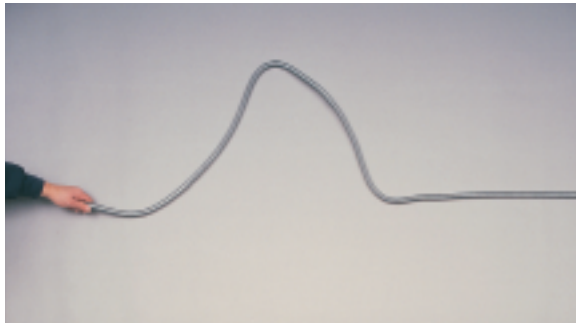


FIGURE 14–4 These two photographs were taken 0.20 s apart. During that time, the crest moved 0.80 m. The velocity of the wave is 4.0 m/s.

Speed and amplitude How fast does a wave move? The speed of the pulse shown in **Figure 14–4** can be found in the same way in which you would determine the speed of a moving car. First, you measure the displacement of the wave peak, Δd ; then you divide this by the time interval, Δt , to find the speed, as shown by $v = \bar{v} = \Delta d / \Delta t$. The speed of a continuous wave, can be found the same way. For most mechanical waves, both transverse and longitudinal, the speed depends only on the medium through which the waves move.

How does the pulse generated by gently shaking a rope differ from the pulse produced by a violent shake? The difference is similar to the difference between a ripple in a pond and a tidal wave. They have different amplitudes. The amplitude of a wave is its maximum displacement from its position of rest, or equilibrium. Two similar waves having different amplitudes are shown in **Figure 14–5**. A wave's amplitude depends on how the wave is generated, but not on its speed. More work has to be done to generate a wave with a larger amplitude. For example, strong winds produce larger water waves than those formed by gentle breezes. Waves with larger amplitudes transfer more energy. Thus, although a small wave might move sand on a beach a few centimeters, a giant wave can uproot and move a tree. For waves that move at the same speed, the rate at which energy is transferred is proportional to the square of the

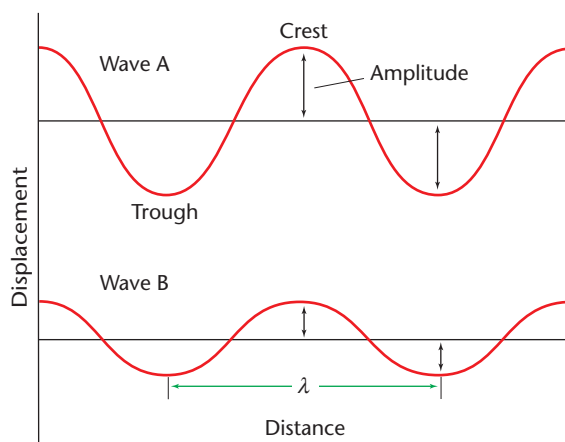
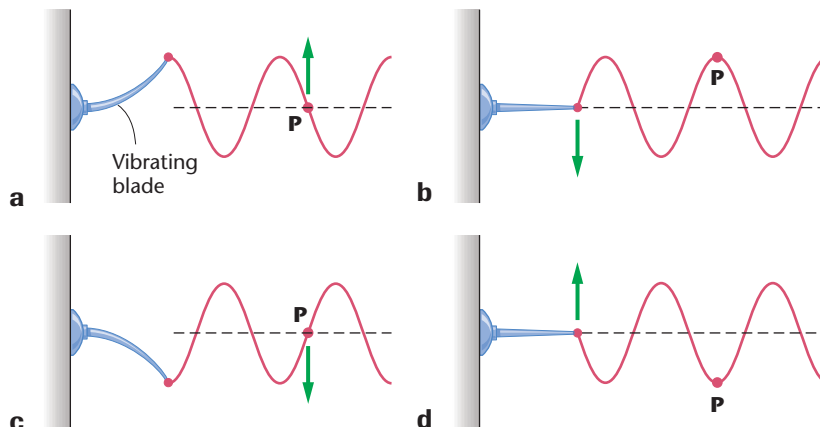


FIGURE 14–5 The amplitude of wave A is larger than that of wave B.

FIGURE 14-6 One end of a string, with a piece of tape at point P, is attached to a vibrating blade. Note the change in position of point P over time.



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amplitude. Thus, doubling the amplitude of a wave increases the amount of energy it transfers each second by a factor of four.

Wavelength Rather than focusing on one point on a wave, imagine taking a snapshot of a wave, so that you can see the whole wave at one instant in time. **Figure 14-5** shows the low points, or **troughs**, and the high points, or **crests**, of a wave. The shortest distance between points where the wave pattern repeats itself is called the **wavelength**. Crests are spaced by one wavelength. Each trough is also one wavelength from the next. The Greek letter lambda, λ , represents wavelength.

Period and frequency Although wave speed and amplitude can describe both pulses and continuous waves, period (T) and frequency (f) apply only to continuous waves. You learned in Chapter 6 that the period of a simple harmonic oscillator, such as a pendulum, is the time it takes for the motion of the oscillator to repeat itself. Such an oscillator is usually the source, or cause, of a continuous wave. The period of a wave is equal to the period of the source. In **Figure 14-6**, the period, T , equals 0.04 s, which is the time it takes the source to return to the same point in its oscillation. The same time is taken by point P, a point on the rope, to return to its initial position.

The **frequency** of a wave, f , is the number of complete oscillations it makes each second. Frequency is measured in hertz. One hertz (Hz) is one oscillation per second. The frequency (f) and period (T) of a wave are related by the following equation.

$$\text{Frequency of a Wave } f = \frac{1}{T}$$

Both the period and the frequency of a wave depend only on its source. They do not depend on the wave's speed or the medium.

Although you can measure a wavelength directly, the wavelength depends on both the frequency of the oscillator and the speed of the

wave. In the time interval of one period, a wave moves one wavelength. Therefore, the speed of a wave is the wavelength divided by the period, $v = \lambda/T$. Because the frequency is more easily found than the period, this equation is more often written as

$$\text{Speed of a Wave } v = \lambda f.$$

F.Y.I.

Because radio waves travel at 3.00×10^8 m/s and sound waves are slower, 3.4×10^2 m/s, a broadcast voice can be heard sooner 10 000 miles away than it can be heard at the back of the room in which it originated.

Example Problem

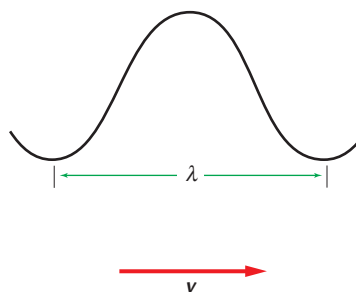
Speed of a Wave

A sound wave has a frequency of 262 Hz and a wavelength measured at 1.29 m.

- What is the speed of the wave?
- How long will it take the wave to travel the length of a football field, 91.4 m?
- What is the period of the wave?

Sketch the Problem

- Draw a model of one wavelength.
- Diagram a velocity vector.



Calculate Your Answer

Known:

$$f = 262 \text{ Hz}$$

$$\lambda = 1.29 \text{ m}$$

$$d = 91.4 \text{ m}$$

Unknown:

$$v = ?$$

$$t = ?$$

$$T = ?$$

Strategy:

- Find the speed of sound from the frequency and wavelength.
- Find the time required from speed and distance.
- Find the period from the frequency.

Calculations:

$$v = \lambda f = (1.29 \text{ m})(262 \text{ Hz}) = 338 \text{ m/s}$$

$$v = \frac{d}{t}, \text{ so } t = \frac{d}{v} = \frac{91.4 \text{ m}}{338 \text{ m/s}} = 0.270 \text{ s}$$

$$T = \frac{1}{f} = \frac{1}{262 \text{ Hz}} = 0.00382 \text{ s}$$

Check Your Answer

- Hz has the units s^{-1} and so $\text{m} \cdot \text{Hz}$ equals m/s , which is correct.
- Are the magnitudes realistic? A typical sound wave travels approximately 343 m/s. You can notice the delay in sound across a football field, so a few tenths of a second is reasonable.

Physics & Society

Predicting Earthquakes

Earthquakes are produced by the sudden motion of rock masses within Earth's crust. Although rocks can bend and twist to some extent, they break if they are exposed to forces that exceed their strength. The friction and crushing motions of breaking rock create seismic waves of energy that radiate outward. These seismic waves cause the shaking and trembling called an earthquake. The breaks in the rock are known as earthquake faults.

The subsurface region where the rock ruptures is called the focus of an earthquake. The point on the surface directly above the focus is known as the epicenter. Several types of seismic waves travel outward from the focus. Waves that travel along the surface are called surface waves. They have characteristics of both transverse and longitudinal waves and cause most major earthquake damage to homes and cities.

How much damage?

Many earthquakes are quite small and are hardly felt. However, catastrophic earthquakes have been recorded in many regions of the world. One example is the deadly earthquake that hit the densely populated region of Izmir, Turkey, in 1999. Eighteen thousand people were killed, and damage estimates reached \$40 billion.

Can earthquakes be predicted?

Most geologists agree that regions along portions of California's famous San Andreas Fault will experience a major earthquake before the middle of the 21st century. The broad time frame of a prediction such as this doesn't enable people to evacuate an area in anticipation of a quake on any particular date.

Efforts are under way to develop more precise earthquake predictions. Scientists

constantly use seismographs to monitor major faults such as the San Andreas Fault for the smallest Earth tremors. A seismograph records the magnitude of seismic waves by suspending a pen on a pendulum over a paper-covered drum. The stronger the motion, the larger the arc of the pen's motion on the drum.

Lasers and creep meters measure differences in land movement on the two sides of a fault. A creep meter consists of wires stretched across a fault, and a laser beam is timed as it returns to its source. Scientists monitor radon and hydrogen concentrations in groundwater to determine how they change prior to an earthquake. Antennae monitor changes in electromagnetic waves coming from deep beneath Earth's surface.

Investigating the Issue

- 1. Acquiring Information** Use your library skills to find out more about the Parkfield experiment near the San Andreas Fault in California. What kinds of instruments are being used by seismologists to monitor the fault? Have any earthquakes predicted for Parkfield actually occurred?
- 2. Debating the Issue** Evaluate the impact of earthquake research on society and the environment. How can studying wave properties and behaviors impact the building industry? What is the responsibility of scientists, government, and citizens with respect to earthquake-resistant structures?

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Practice Problems

1. A sound wave produced by a clock chime is heard 515 m away 1.50 s later.
 - a. What is the speed of sound of the clock's chime in air?
 - b. The sound wave has a frequency of 436 Hz. What is its period?
 - c. What is its wavelength?
2. A hiker shouts toward a vertical cliff 685 m away. The echo is heard 4.00 s later.
 - a. What is the speed of sound of the hiker's voice in air?
 - b. The wavelength of the sound is 0.750 m. What is its frequency?
 - c. What is the period of the wave?
3. If you want to increase the wavelength of waves in a rope, should you shake it at a higher or lower frequency?
4. What is the speed of a periodic wave disturbance that has a frequency of 2.50 Hz and a wavelength of 0.600 m?
5. The speed of a transverse wave in a string is 15.0 m/s. If a source produces a disturbance that has a frequency of 5.00 Hz, what is its wavelength?
6. Five pulses are generated every 0.100 s in a tank of water. What is the speed of propagation of the wave if the wavelength of the surface wave is 1.20 cm?
7. A periodic longitudinal wave that has a frequency of 20.0 Hz travels along a coil spring. If the distance between successive compressions is 0.400 m, what is the speed of the wave?

EARTH SCIENCE CONNECTION

Earth's Core An earthquake produces both transverse and longitudinal waves that travel through Earth. Geologists studying these waves with seismographs found that only the longitudinal waves could pass through Earth's core. Only longitudinal waves can move through a liquid or a gas. From this observation, what can be deduced about the nature of Earth's core?



14.1 Section Review

1. Suppose you and your lab partner are asked to measure the speed of a transverse wave in a giant, coiled spring toy. How could you do it? List the equipment you would need.
2. Describe longitudinal waves. What types of media transmit longitudinal waves?
3. You are creating transverse waves in a rope by shaking your hand from side to side. Without changing the distance your hand moves, you begin to shake it faster and faster. What happens to the amplitude, frequency, period, and velocity of the wave?
4. If you pull on one end of a coiled spring toy, does the pulse reach the other end instantaneously? What if you pull on a rope? What if you hit the end of a metal rod? Compare the responses of these three materials.
5. **Critical Thinking** If a raindrop falls into a pool, small-amplitude waves result. If a swimmer jumps into a pool, a large-amplitude wave is produced. Why doesn't the heavy rain in a thunderstorm produce large waves?



OBJECTIVES

- **Relate** a wave's speed to the medium in which the wave travels.
- **Describe** how waves are reflected and refracted at boundaries between media, and **explain** how waves diffract.
- **Apply** the principle of superposition to the phenomenon of interference.

When a wave encounters the boundary of the medium in which it is traveling, it sometimes reflects back into the medium. In other instances, some or all of the wave passes through the boundary into another medium, often changing direction at the boundary. In addition, many properties of wave behavior result from the fact that two or more waves can exist in the same medium at the same time—quite unlike particles, which consist of matter and take up space.

Waves at Boundaries

Recall that the speed of a mechanical wave depends only on the properties of the medium it passes through, not on the wave's amplitude or frequency. For water waves, the depth of the water affects wave speed. For sound waves in air, the temperature affects wave speed. For waves on a spring, the speed depends upon the spring's rigidity and its mass per unit length.

Examine what happens when a wave moves across a boundary from one medium into another, as in two springs of different thicknesses joined end to end. **Figure 14–7** shows a wave pulse moving from a large spring into a smaller one. The wave that strikes the boundary is called the **incident wave**. One pulse from the larger spring continues in the smaller spring, at the speed of waves on the smaller spring. Note that this transmitted wave pulse remains upward.

Some of the energy of the incident wave's pulse is reflected backward in the larger spring. This returning wave is called the **reflected wave**. Whether or not the reflected wave is upward (erect) or downward (inverted) depends on the comparative thicknesses of the two springs. If waves in the smaller spring have a higher speed because the spring is heavier or stiffer, then the reflected wave will be inverted.

FIGURE 14–7 The junction of the two springs is a boundary between two media. A pulse reaching the boundary **(a)** is partially reflected and partially transmitted **(b)**.



a



b



a



b

What happens if the boundary is a wall rather than another spring? When a wave pulse is sent down a spring connected to a rigid wall, the energy transmitted is reflected back from the wall, as shown in **Figure 14–8**. The wall is the boundary of a new medium through which the wave attempts to pass. The pulse is reflected from the wall with almost exactly the same amplitude as the pulse of the incident wave. Thus, almost all the wave's energy is reflected back. Very little energy is transmitted into the wall. Note also that the pulse is inverted.

FIGURE 14–8 A pulse approaches a rigid wall **(a)** and is reflected back **(b)**. Note that the amplitude of the reflected pulse is nearly equal to the amplitude of the incident pulse, but it is inverted and appears as a downward curve.

Practice Problems

8. A pulse is sent along a spring. The spring is attached to a light-weight thread that is tied to a wall, as shown in **Figure 14–9**.
 - a. What happens when the pulse reaches point A?
 - b. Is the pulse reflected from point A erect or inverted?
 - c. What happens when the transmitted pulse reaches point B?
 - d. Is the pulse reflected from point B erect or inverted?

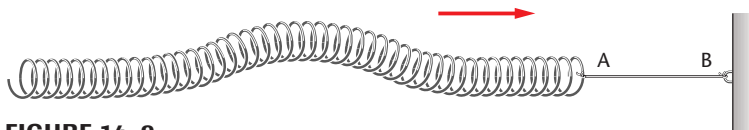


FIGURE 14–9

9. A long spring runs across the floor of a room and out the door. A pulse is sent along the spring. After a few seconds, an inverted pulse returns. Is the spring attached to the wall in the next room or is it lying loose on the floor?
10. A pulse is sent along a thin rope that is attached to a thick rope, which is tied to a wall, as shown in **Figure 14–10**.
 - a. What happens when the pulse reaches point A? Point B?
 - b. Is the pulse reflected from point A displaced in the same direction as the incident pulse, or is it inverted? What about the pulse reflected from point B?

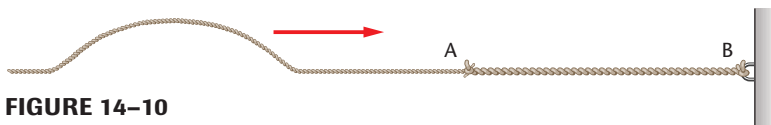


FIGURE 14–10

Pocket Lab

Wave Reflections



Waves lose amplitude and transfer energy when they reflect from a barrier. What happens to the speed of the waves? Use a wave tank with a projection system. Half-fill the tank with water. Dip your finger into the water near one end of the tank and notice how fast the wave that you make moves to the other end.

Analyze Does the wave slow down as it travels? Use a stop-watch to measure the time for a wave to cover two lengths, then four lengths, of the wave tank.

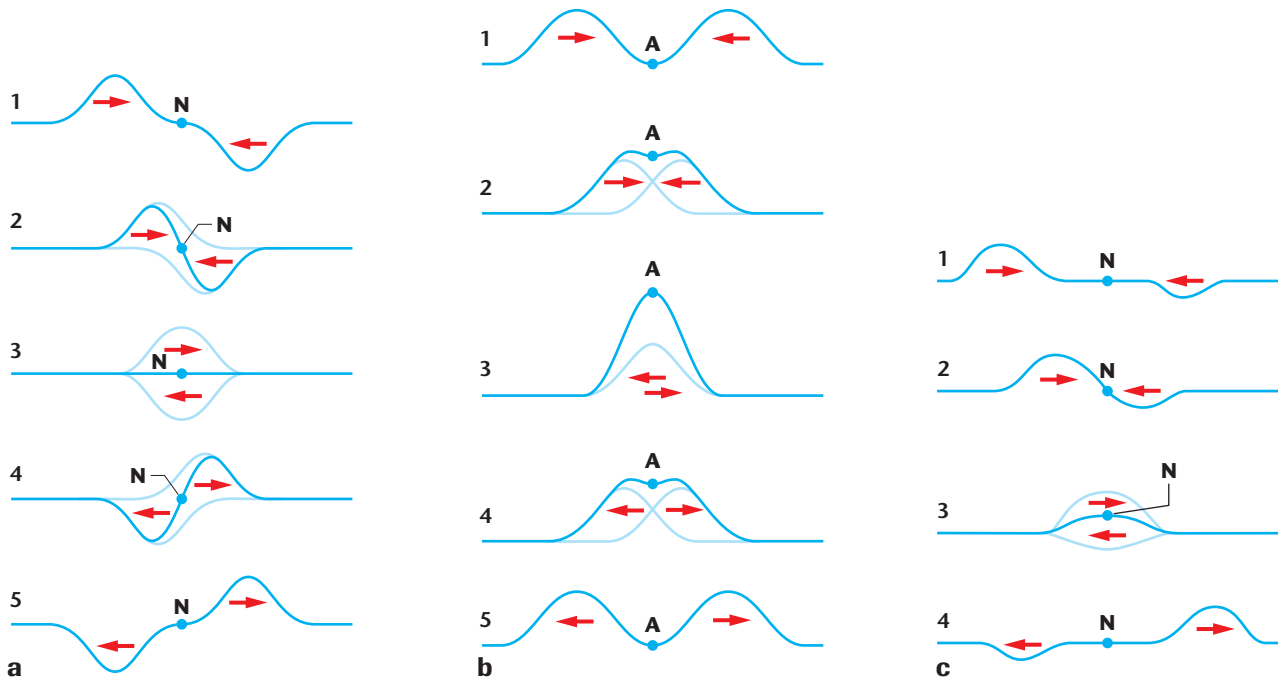
Superposition of Waves

Suppose a pulse traveling down a spring meets a reflected pulse coming back. In this case, two waves exist in the same place in the medium at the same time. Each wave affects the medium independently. The displacement of a medium caused by two or more waves is the algebraic sum of the displacements caused by the individual waves. This is called the **principle of superposition**. In other words, two or more waves can combine to form a new wave. If the waves are in opposite directions, they can cancel or form a new wave of less or greater amplitude. The result of the superposition of two or more waves is called **interference**.

Wave interference Wave interference can be either constructive or destructive. When two pulses with equal but opposite amplitudes meet, the displacement of the medium at each point in the overlap region is reduced. The superposition of waves with equal but opposite amplitudes causes **destructive interference**, as shown in **Figure 14–11a**. When the pulses meet and are in the same location, the displacement is zero. Point N, which doesn't move at all, is called a **node**. The pulses continue to move and eventually resume their original form. As in constructive interference, the waves pass through each other unchanged.

Constructive interference occurs when the wave displacements are in the same direction. The result is a wave that has an amplitude larger than any of the individual waves. **Figure 14–11b** shows the constructive interference of two equal pulses. A larger pulse appears at point A when the two waves meet. Point A has the largest displacement and is called the **antinode**. The two pulses pass through each other without

FIGURE 14–11 When two equal pulses meet there is a point, called the node, (N), where the medium remains undisturbed **(a)**. Constructive interference results in maximum displacement at the antinode, (A), **(b)**. If the opposite pulses have unequal amplitudes, cancellation is incomplete **(c)**.



changing their shapes or sizes. If the pulses have opposite and unequal amplitudes, the resultant pulse at the overlap is the algebraic sum of the two pulses, as shown in **Figure 14–11c**.

Continuous waves You have read how wave pulses move through each other and are reflected from boundaries. What happens when continuous waves meet a boundary? **Figure 14–12a** shows a continuous wave moving from a region with higher speed to a region with lower speed. On the left-hand side of the boundary, the amplitude of the reflected wave has been added to that of the incident wave because some of the wave energy has been reflected.

Recall that velocity of a wave is the product of wavelength and frequency, $v = \lambda f$. Thus, the transmitted wave on the other side of the boundary has a shorter wavelength because of its slower speed. The transmitted wave also has a smaller amplitude because less wave energy is available. Notice in **Figure 14–12b** how the relative amplitudes and wavelengths change when a continuous wave moves from a region with lower speed to one with higher speed.

Standing waves You can use the concept of superimposed waves to control the frequency and formation of waves. If you attach one end of a rope or coiled spring to a fixed point such as a doorknob, and then start to vibrate the other end, the wave leaves your hand, is reflected at the fixed end, is inverted, and returns to your hand. When it reaches your hand, it is inverted and reflected again. Thus, when the wave leaves your hand the second time, its displacement is in the same direction it was when it left your hand the first time.

But what if you want to magnify the amplitude of the wave you create? Suppose you adjust the motion of your hand so that the period of the rope's vibration equals the time needed for the wave to make one round-trip from your hand to the door and back. Then, the displacement

Pocket Lab

Wave Interaction



What happens to the waves coming from different directions when they meet? Do they slow down, bounce off each other, or go through each other?

Design an Experiment

Use a coiled spring toy to test these questions. Record your procedures and observations.

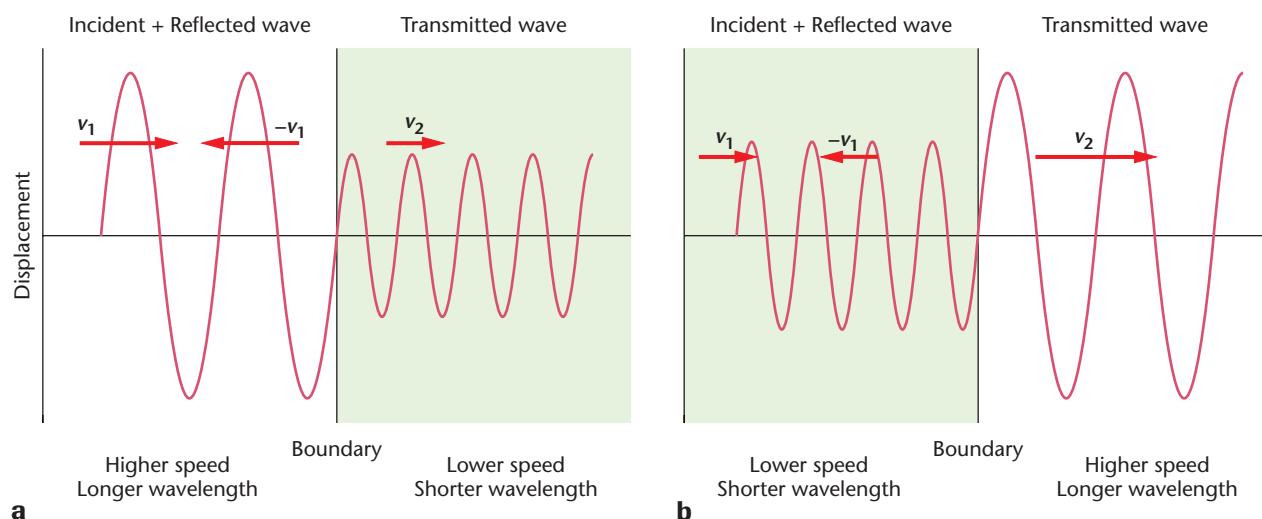
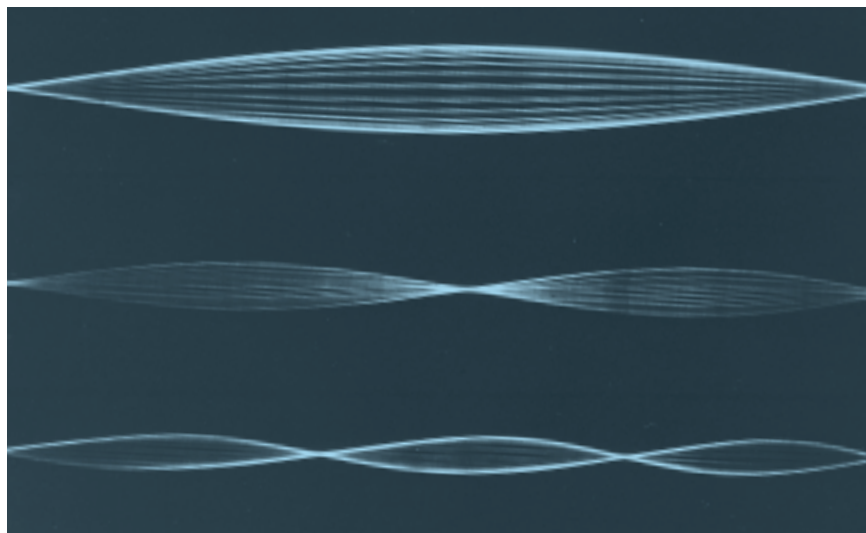


FIGURE 14–12 In each of the two examples below, continuous waves pass from the medium on the left to the medium on the right. Wave speed depends upon the medium. For example, light waves travel faster in air than they do in water.

FIGURE 14–13 Interference produces standing waves in a rope. As the frequency of vibration is increased, as shown from top to bottom, the numbers of nodes and antinodes increase.



Pocket Lab

Bent Out of Shape



What happens to a water wave's speed when the depth of the water changes? How does a change in speed affect the shape of the waves? Try this activity to find out. Use a wave tank with a projection system. Adjust the tank so that the water is shallow on one side and deep on the opposite side. Dip your finger or pencil eraser into the middle of the tank, and gently tap the water to make a circular wave. Watch closely. Do the waves hit the sides of the tank at the same time? What happens to the wavelength in different directions?

Modeling Make a sketch of the shape of the waves. Label the deep and shallow ends on your drawing. Describe the relationship between the depth of the water and the wave's speed (inverse or direct). What did you notice about the wavelength in different directions?

given by your hand to the rope each time will add to the displacement of the reflected wave. As a result, the oscillation of the rope in one segment will be much larger than the motion of your hand, as expected from your knowledge of constructive interference. This large-amplitude oscillation is an example of mechanical resonance. The nodes are at the ends of the rope and an antinode is in the middle, as shown in **Figure 14–13 top**. Thus, the wave appears to be standing still and is called a **standing wave**. If you double the frequency of vibration, you can produce one more node and one more antinode in the rope. Now it appears to vibrate in two segments, as in **Figure 14–13 center**. Further increases in frequency produce even more nodes and antinodes, as shown in **Figure 14–13 bottom**.

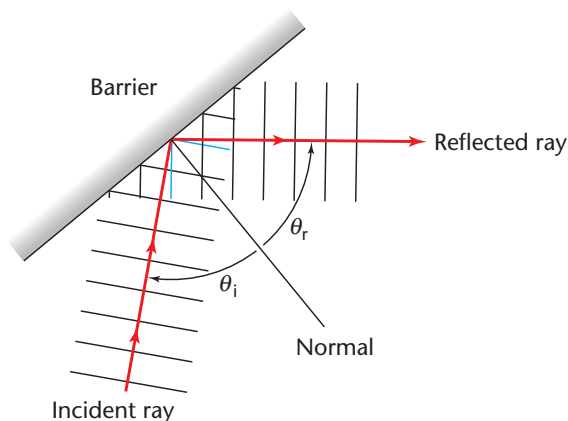
Waves in Two Dimensions

You have studied waves on a rope or spring reflecting from a rigid support, where the amplitude of the wave is forced to be zero by destructive interference. These mechanical waves move in only one dimension. However, waves on the surface of water move in two dimensions, and sound waves and electromagnetic waves will later be shown to move in three dimensions. How can two-dimensional waves be demonstrated?

Reflection of waves in two dimensions A ripple tank can be used to show the properties of two-dimensional waves. A ripple tank contains a thin layer of water. Vibrating boards produce wave pulses or, in this case, traveling waves of water with constant frequency. A lamp above the tank produces shadows below the tank that show the locations of the crests of the waves. **Figure 14–14a** shows a wave pulse traveling toward a rigid barrier that reflects the wave. The incident wave moves upward. The reflected wave moves to the right.



a



b

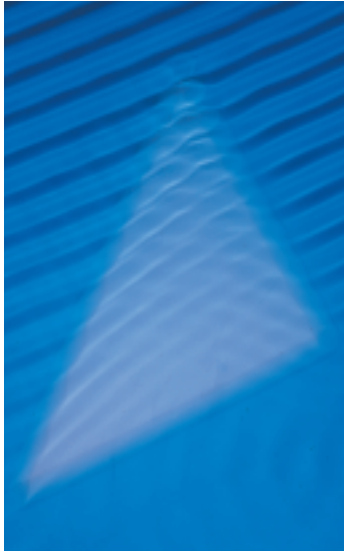
FIGURE 14-14 A wave pulse in a ripple tank is reflected by a barrier **(a)**. The ray diagram models the wave in time sequence as it approaches the barrier and then is reflected to the right **(b)**.

The direction of waves moving in two dimensions can be modeled by ray diagrams. Ray diagrams model the movement of waves. A ray is a line drawn at a right angles to the crests of the waves. **Figure 14-14b** shows the ray diagram for the wave in the ripple tank. The ray representing the incident ray is the arrow pointing upward. The ray representing the reflected ray points to the right.

The direction of the barrier is also shown by a line, which is drawn at a right angle to the barrier. This line is called the normal. The angle between the incident ray and the normal is called the angle of incidence. The angle between the normal and the reflected ray is called the angle of reflection. The **law of reflection** states that the angle of incidence is equal to the angle of reflection.

Refraction of waves in two dimensions A ripple tank also can be used to model the behavior of waves as they move from one medium into another. **Figure 14-15a** shows a glass plate placed in a ripple tank. The water above the plate is shallower than the water in the rest of the tank, and the water there acts like a different medium. As the waves move from deep to shallow water, their wavelength decreases, and the direction of the waves changes. Because the waves in the shallow water are generated by the waves in deep water, their frequency is not changed. Based on the equation $v = \lambda f$, the decrease in the wavelength of the waves means that the velocity is lower in the shallower water. This is similar to what happens to a sound wave in the air that collides with and then travels through another medium such as a wall.

This same phenomenon can be seen at the coast when the land gently slopes down into the sea. In **Figure 14-15b**, the waves approach the shore. The ray direction is not parallel to the normal. Not only does the wavelength decrease over the shallower bottom, but also the direction of the waves changes. The change in the direction of waves at the boundary between two different media is known as **refraction**.



a

FIGURE 14-15 As the water waves move over a shallower region of the ripple tank where a triangular glass plate is placed, they slow down and their wavelength decreases **(a)**. When waves approach the shore, they are refracted by the change in depth of the water **(b)**.



b

Diffraction and Interference of Waves

If particles are thrown at a barrier with holes in it, the particles will either reflect off the barrier or pass straight through the holes. When waves encounter a small hole in a barrier, however, they do not pass straight through. Rather, they bend around the edges of the barrier, forming circular waves that radiate out, as shown in **Figure 14-16**. The spreading of waves around the edge of a barrier, such as a small barrier coral reef, is called **diffraction**. Diffraction also occurs when waves meet a small obstacle. They can bend around the obstacle, producing waves behind it. The smaller the wavelength in comparison to the size of the obstacle, the less the diffraction.

If a barrier has two closely spaced holes, the waves are diffracted by each hole and form circular waves, as shown in **Figure 14-17a**. These two sets of circular waves interfere with each other. There are regions of constructive interference where the resulting waves are large, and bands of destructive interference where the water remains almost undisturbed. Constructive interference occurs where two crests or two troughs of the circular waves meet. The antinodes formed lie on antinodal lines that

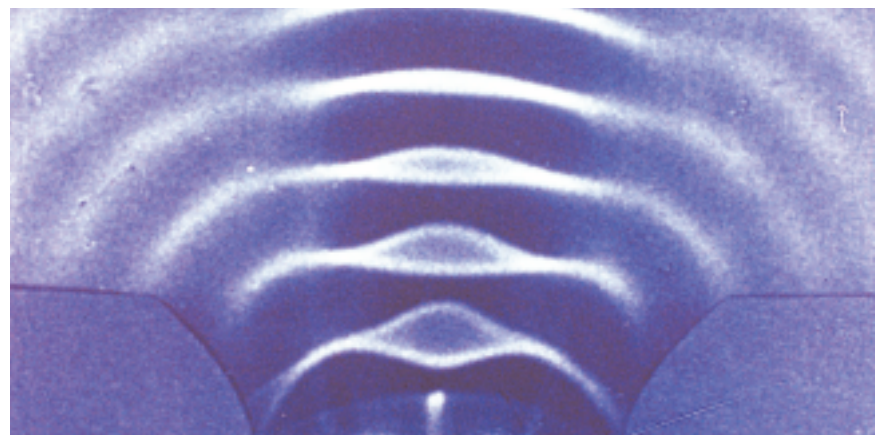
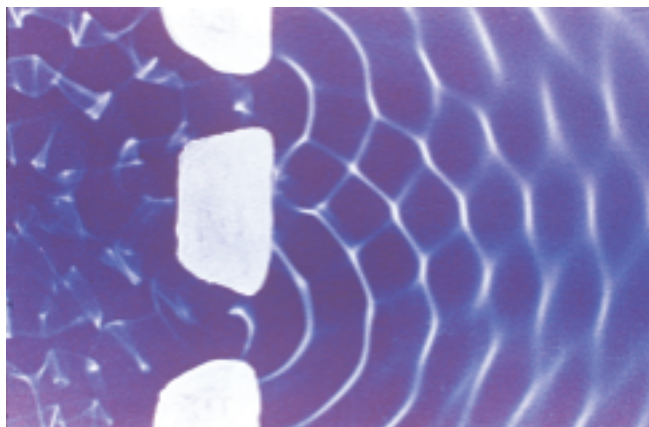
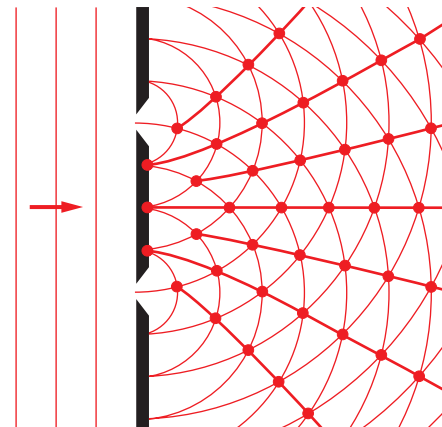


FIGURE 14-16 Waves that bend around the edges of barriers demonstrate diffraction.



a

FIGURE 14-17 Waves are diffracted at two openings in the barrier. At each opening, circular waves are formed that interfere with each other. Points of constructive interference appear as bright spots in the photograph **(a)**. Lines of constructive interference, called antinodal lines, occur where crest meets crest **(b)**.



b

radiate outward from the barrier, **Figure 14-17b**. Between these antinodal lines are areas where a crest of one wave meets a trough from another wave. Destructive interference produces nodes where the water is undisturbed. The lines of nodes, or nodal lines, lie between adjacent antinodal lines. Thus, it is interference of the water waves that produces the series of light and dark lines observed in **Figure 14-17a**.

14.2 Section Review

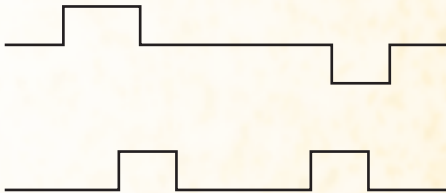
- Which of the following wave characteristics remain unchanged when a wave crosses a boundary into a different medium: frequency, amplitude, wavelength, velocity, or direction?
- A rope vibrates with the two waves shown in **Figure 14-18**. Sketch the resulting wave.

- Describe diffraction. How can diffraction lead to interference?
- Would you expect high-frequency or low-frequency sound waves to be more diffracted when they pass through an open door? Explain.
- Critical Thinking** As another way to understand wave reflection, cover the right-hand side of each drawing in **Figure 14-11a** with a piece of paper. The edge of the paper should be at point N, the node. Now, concentrate on the resultant wave, shown in blue. Note that it acts like a wave reflected from a boundary. Is the boundary a rigid wall or open ended? Repeat this exercise for **Figure 14-11b**.

FIGURE 14-18

CHAPTER 14 REVIEW

Summary



Key Terms

14.1

- wave
- wave pulse
- continuous wave
- transverse wave
- longitudinal wave
- surface wave
- trough
- crest
- wavelength
- frequency

14.2

- incident wave
- reflected wave
- principle of superposition
- interference
- destructive interference
- node
- constructive interference
- antinode
- standing wave
- law of reflection
- refraction
- diffraction

14.1 Wave Properties

- Waves transfer energy without transferring matter.
- Mechanical waves require a medium.
- A continuous wave is a regularly repeating sequence of wave pulses.
- In transverse waves, the displacement of the medium is perpendicular to the direction of wave motion. In longitudinal waves, the displacement is parallel to the wave direction. In surface waves, matter is displaced in both directions.
- The wave source determines the frequency of the wave, f , which is the number of vibrations per second.
- The wavelength of a wave, λ , is the shortest distance between points where the wave pattern repeats itself.
- The medium determines wave speed, which can be calculated for continuous waves using the equation $v = \lambda f$.

14.2 Wave Behavior

- When a wave crosses a boundary between two media, it is partially transmitted and partially reflected, depending on how much the wave velocities in the two media differ.
- When a wave moves to a medium with higher wave speed, the reflected wave is inverted. When moving to a medium with lower wave speed, the displacement of the reflected wave is in the same direction as the incident wave.

- The principle of superposition states that the displacement of a medium resulting from two or more waves is the algebraic sum of the displacements of the individual waves.
- Interference occurs when two or more waves move through a medium at the same time.
- Destructive interference results in decreased wave displacement with its least amplitude at the node.
- Constructive interference results in increased wave displacement with its greatest amplitude at the antinode.
- A standing wave has stationary nodes and antinodes.
- When two-dimensional waves are reflected from boundaries, the angles of incidence and reflection are equal.
- The change in direction of waves at the boundary between two different media is called refraction.
- The spreading of waves around a barrier is called diffraction.

Key Equations

$$14.1 \quad \dots\dots\dots f = \frac{1}{T} \quad v = \lambda f$$

Reviewing Concepts

Section 14.1

1. How many general methods of energy transfer are there? Give two examples of each.
2. What is the primary difference between a mechanical wave and an electromagnetic wave?

3. What are the differences among transverse, longitudinal, and surface waves?
4. Suppose you send a pulse along a rope. How does the position of a point on the rope before the pulse arrives compare to the point's position after the pulse has passed?

5. What is the difference between a wave pulse and a continuous wave?
6. Describe the difference between wave frequency and wave velocity.
7. Suppose you produce a transverse wave by shaking one end of a spring from side to side. How does the frequency of your hand compare with the frequency of the wave?
8. Waves are sent along a spring of fixed length.
 - a. Can the speed of the waves in the spring be changed? Explain.
 - b. Can the frequency of a wave in the spring be changed? Explain.
9. What is the difference between the speed of a transverse wave pulse down a spring and the motion of a point on the spring?
10. Suppose you are lying on a raft in a wave pool. Describe, in terms of the waves you are riding, each of the following: amplitude, period, wavelength, speed, and frequency.
11. What is the amplitude of a wave and what does it represent?
12. Describe the relationship between the amplitude of a wave and the energy it carries.

Section 14.2

13. When a wave reaches the boundary of a new medium, part of the wave is reflected and part is transmitted. What determines the amount of reflection?
14. A pulse reaches the boundary of a medium in which the speed of the pulse becomes higher. Is the reflection of the pulse the same as for the incident pulse or is it inverted?
15. A pulse reaches the boundary of a medium in which the speed is lower than the speed of the medium from which it came. Is the reflected pulse erect or inverted?
16. When a wave crosses a boundary between a thin and a thick rope, its wavelength and speed change, but its frequency does not. Explain why the frequency is constant.
17. When two waves interfere, is there a loss of energy in the system? Explain.
18. What happens to a spring at the nodes of a standing wave?
19. A metal plate is held fixed in the center and sprinkled with sugar. With a violin bow, the plate is stroked along one edge and made to vibrate. The sugar begins to collect in certain areas and move away from others. Describe these regions in terms of standing waves.
20. If a string is vibrating in four parts, there are points where it can be touched without disturbing its motion. Explain. How many of these points exist?
21. How does a spring pulse reflected from a rigid wall differ from the incident pulse?
22. Describe interference. Is interference a property of only some types of waves or all types of waves?

Applying Concepts

23. Suppose you hold a 1-m metal bar in your hand and hit its end with a hammer, first, in a direction parallel to its length, second, in a direction at right angles to its length. Describe the waves you produce in the two cases.
24. Suppose you repeatedly dip your finger into a sink full of water to make circular waves. What happens to the wavelength as you move your finger faster?
25. What happens to the period of a wave as the frequency increases?
26. What happens to the wavelength of a wave as the frequency increases?
27. Suppose you make a single pulse on a stretched spring. How much energy is required to make a pulse with twice the amplitude?
28. Sonar is the detection of sound waves reflected off boundaries in water. A region of warm water in a cold lake can produce a reflection, as can the bottom of the lake. Which would you expect to produce the stronger echo? Explain.
29. You can make water slosh back and forth in a shallow pan only if you shake the pan with the correct frequency. Explain.
30. AM-radio signals have wavelengths between 600 m and 200 m, whereas FM signals have wavelengths of about 3 m, **Figure 14–19**. Explain why AM signals can often be heard behind hills whereas FM signals cannot.



FIGURE 14–19

31. In each of the four waves in **Figure 14–20**, the pulse on the left is the original pulse moving toward the right. The center pulse is a reflected pulse; the pulse on the right is a transmitted pulse. Describe the boundaries at A, B, C, and D.

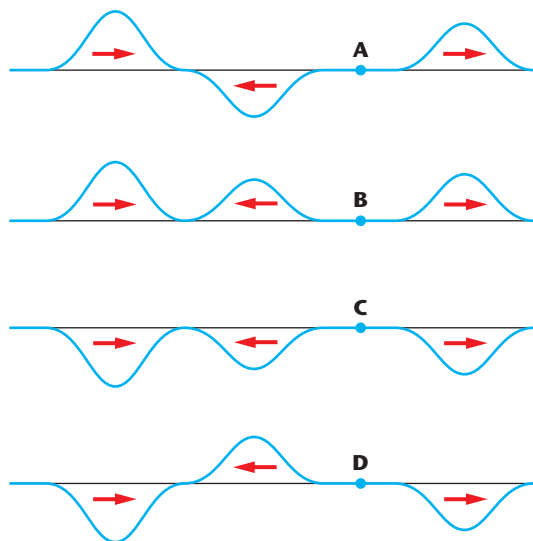


FIGURE 14–20

Problems

Section 14.1

32. The Sears Building in Chicago sways back and forth in the wind with a frequency of about 0.10 Hz. What is its period of vibration?
33. An ocean wave has a length of 10.0 m. A wave passes a fixed location every 2.0 s. What is the speed of the wave?
34. Water waves in a shallow dish are 6.0 cm long. At one point, the water oscillates up and down at a rate of 4.8 oscillations per second.
- What is the speed of the water waves?
 - What is the period of the water waves?
35. Water waves in a lake travel 4.4 m in 1.8 s. The period of oscillation is 1.2 s.
- What is the speed of the water waves?
 - What is their wavelength?
36. The frequency of yellow light is 5.0×10^{14} Hz. Find the wavelength of yellow light. The speed of light is 300 000 km/s.
37. AM-radio signals are broadcast at frequencies between 550 kHz and 1600 kHz (kilohertz) and travel 3.0×10^8 m/s.
- What is the range of wavelengths for these signals?
 - FM frequencies range between 88 MHz and 108 MHz (megahertz) and travel at the same speed. What is the range of FM wavelengths?
38. A sonar signal of frequency 1.00×10^6 Hz has a wavelength of 1.50 mm in water.
- What is the speed of the signal in water?
 - What is its period in water?
 - What is its period in air?
39. A sound wave of wavelength 0.70 m and velocity 330 m/s is produced for 0.50 s.
- What is the frequency of the wave?
 - How many complete waves are emitted in this time interval?
 - After 0.50 s, how far is the front of the wave from the source of the sound?
40. The speed of sound in water is 1498 m/s. A sonar signal is sent straight down from a ship at a point just below the water surface, and 1.80 s later the reflected signal is detected. How deep is the ocean beneath the ship?
41. The time needed for a water wave to change from the equilibrium level to the crest is 0.18 s.
- What fraction of a wavelength is this?
 - What is the period of the wave?
 - What is the frequency of the wave?
42. Pepe and Alfredo are resting on an offshore raft after a swim. They estimate that 3.0 m separates a trough and an adjacent crest of surface waves on the lake. They count 14 crests that pass by the raft in 20.0 s. Calculate how fast the waves are moving.
43. The velocity of the transverse waves produced by an earthquake is 8.9 km/s, and that of the longitudinal waves is 5.1 km/s. A seismograph records the arrival of the transverse waves 73 s before the arrival of the longitudinal waves. How far away was the earthquake?
44. The velocity of a wave on a string depends on how hard the string is stretched, and on the mass per unit length of the string. If F_T is the tension in the string, and μ is the mass/unit length, then the velocity, v , can be determined.

$$v = \sqrt{\frac{F_T}{\mu}}$$

A piece of string 5.30 m long has a mass of 15.0 g. What must the tension in the string be to make the wavelength of a 125-Hz wave 120.0 cm?

Section 14.2

45. Sketch the result for each of the three cases shown in **Figure 14-21**, when centers of the two wave pulses lie on the dashed line so that the pulses exactly overlap.

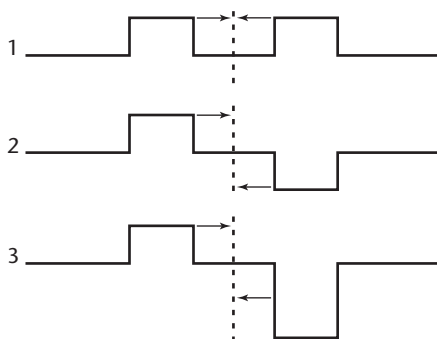


FIGURE 14-21

46. If you slosh the water back and forth in a bathtub at the correct frequency, the water rises first at one end and then at the other. Suppose you can make a standing wave in a 150-cm-long tub with a frequency of 0.30 Hz. What is the velocity of the water wave?
47. The wave speed in a guitar string is 265 m/s. The length of the string is 63 cm. You pluck the center of the string by pulling it up and letting go. Pulses move in both directions and are reflected off the ends of the string.
- How long does it take for the pulse to move to the string end and return to the center?
 - When the pulses return, is the string above or below its resting location?
 - If you plucked the string 15 cm from one end of the string, where would the two pulses meet?

Critical Thinking Problems

48. Gravel roads often develop regularly spaced ridges that are perpendicular to the road. This effect, called washboarding occurs because most cars travel at about the same speed and the springs that connect the wheels to the cars oscillate at about the same frequency. If the ridges are 1.5 m apart and cars travel at about 5 m/s, what is the frequency of the springs' oscillation?

Going Further



Applying Calculators or Computers Use a graphing calculator or computer program to plot the following equation that describes a snapshot of a wave at a fixed time: $y = A \sin (2\pi x/\lambda)$, where y is the displacement, λ the wavelength, x the distance along the wave, and A the amplitude. Evaluate this equation for radians, not degrees. Start with $A = 10$, $\lambda = 6.28$, and let x vary from 0 to 1. Repeat plotting for shorter and longer wavelengths and larger and smaller amplitudes. Display your printed graphs that describe the wave that each set of data represents.

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