Chapter 14 Vibrations and Waves

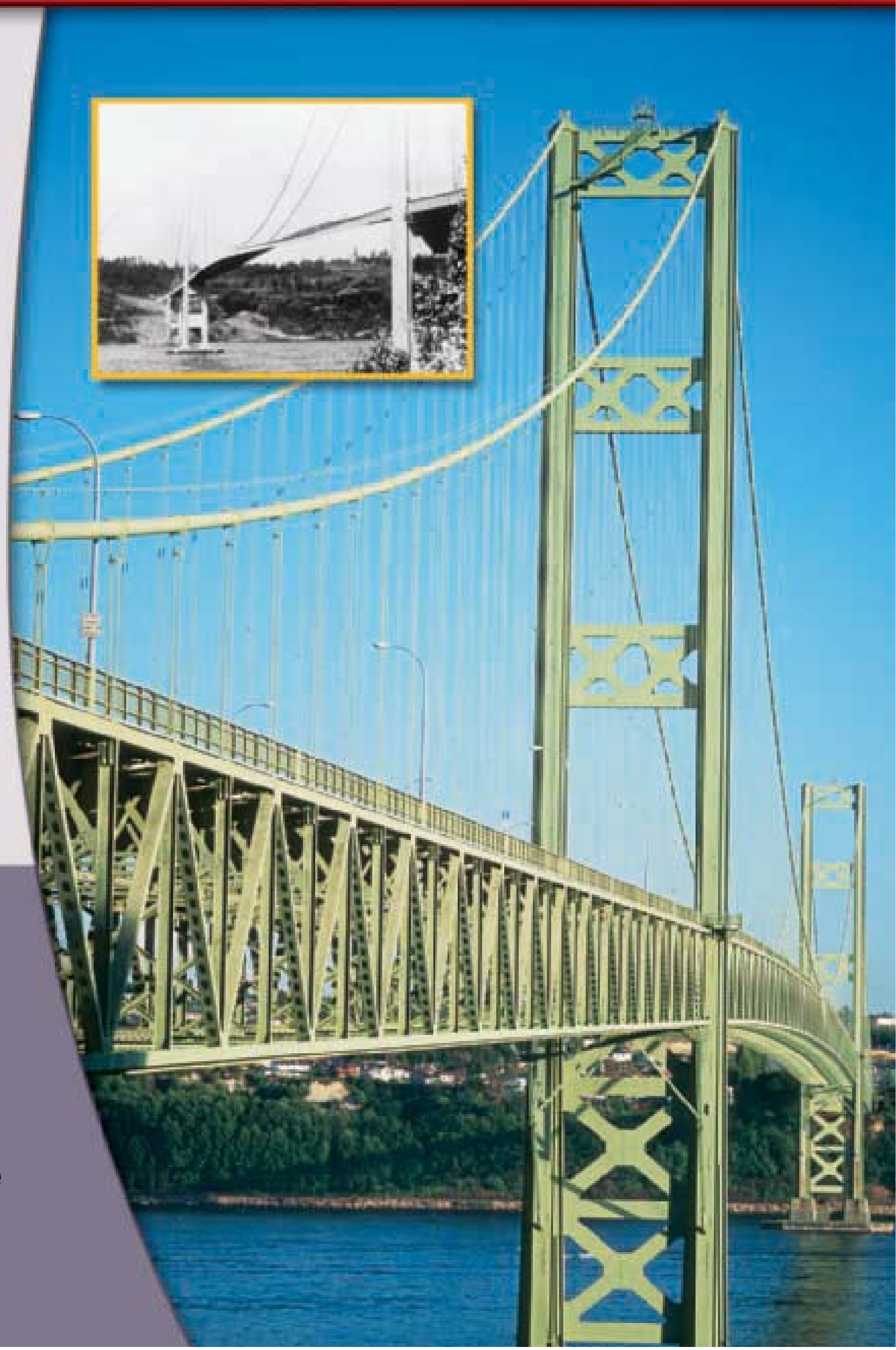
What You'll Learn

- You will examine vibrational motion and learn how it relates to waves.
- You will determine how waves transfer energy.
- You will describe wave behavior and discuss its practical significance.

Why It's Important

Knowledge of the behavior of vibrations and waves is essential to the understanding of resonance and how safe buildings and bridges are built, as well as how communications through radio and television are achieved.

"Galloping Gertie"
Shortly after it was opened to traffic, the Tacoma Narrows Bridge near Tacoma, Washington, began to vibrate whenever the wind blew (see inset). One day, the oscillations became so large that the bridge broke apart and collapsed into the water below.



Think About This ▶

How could a light wind cause the bridge in the inset photo to vibrate with such large waves that it eventually collapsed?

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LAUNCH Lab

How do waves behave in a coiled spring?

Question

How do pulses that are sent down a coiled spring behave when the other end of the spring is stationary?

Procedure

1. Stretch out a coiled spiral spring, but do not overstretch it. One person should hold one end still, while the other person generates a sideways pulse in the spring. Observe the pulse while it travels along the spring and when it hits the held end. Record your observations.
2. Repeat step 1 with a larger pulse. Record your observations.
3. Generate a different pulse by compressing the spring at one end and letting go. Record your observations.
4. Generate a third type of pulse by twisting one end of the spring and then releasing it. Record your observations.

Analysis

What happens to the pulses as they travel through the spring? What happens as they hit the end of the spring? How did the pulse in step 1 compare to that generated in step 2?

Critical Thinking What are some properties that seem to control how a pulse moves through the spring?

14.1 Periodic Motion

You've probably seen a clock pendulum swing back and forth. You would have noticed that every swing followed the same path, and each trip back and forth took the same amount of time. This action is an example of vibrational motion. Other examples include a metal block bobbing up and down on a spring and a vibrating guitar string. These motions, which all repeat in a regular cycle, are examples of **periodic motion.**

In each example, the object has one position at which the net force on it is zero. At that position, the object is in equilibrium. Whenever the object is pulled away from its equilibrium position, the net force on the system becomes nonzero and pulls the object back toward equilibrium. If the force that restores the object to its equilibrium position is directly proportional to the displacement of the object, the motion that results is called **simple harmonic motion.**

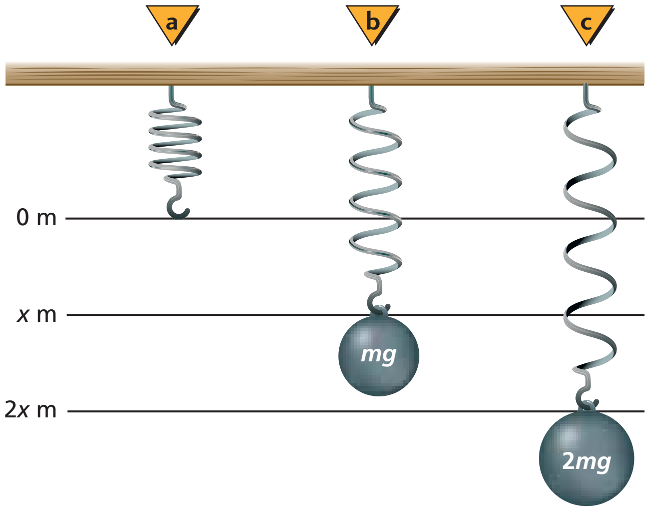
Two quantities describe simple harmonic motion. The **period,** T, is the time needed for an object to repeat one complete cycle of the motion, and the **amplitude** of the motion is the maximum distance that the object moves from equilibrium.

Objectives

- **Describe** the force in an elastic spring.
- **Determine** the energy stored in an elastic spring.
- **Compare** simple harmonic motion and the motion of a pendulum.

Vocabulary

periodic motion
simple harmonic motion
period
amplitude
Hooke's law
pendulum
resonance



■ **Figure 14-1** The force exerted by a spring is directly proportional to the distance the spring is stretched.

The Mass on a Spring

How does a spring react to a force that is applied to it? **Figure 14-1a** shows a spring hanging from a support with nothing attached to it. The spring does not stretch because no external force is exerted on it. **Figure 14-1b** shows the same spring with an object of weight mg hanging from it. The spring has stretched by distance x so that the upward force it exerts balances the downward force of gravity acting on the object. **Figure 14-1c** shows the same spring stretched twice as far, $2x$, to support twice the weight, $2mg$, hanging from it. **Hooke's law** states that the force exerted by a spring is directly proportional to the amount that the spring is stretched. A spring that acts in this way is said to obey Hooke's law, which can be expressed by the following equation.

Hooke's Law $F = -kx$

The force exerted by a spring is equal to the spring constant times the distance the spring is compressed or stretched from its equilibrium position.

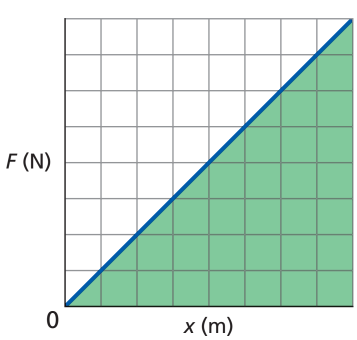
In this equation, k is the spring constant, which depends on the stiffness and other properties of the spring, and x is the distance that the spring is stretched from its equilibrium position. Not all springs obey Hooke's law, but many do. Those that do are called elastic.

Potential energy When a force is applied to stretch a spring, such as by hanging an object on its end, there is a direct linear relationship between the exerted force and the displacement, as shown by the graph in **Figure 14-2.** The slope of the graph is equal to the spring constant, given in units of newtons per meter. The area under the curve represents the work done to stretch the spring, and therefore equals the elastic potential energy that is stored in the spring as a result of that work. The base of the triangle is x, and the height is the force, which, according to the equation for Hooke's law, is equal to kx, so the potential energy in the spring is given by the following equation.

Potential Energy in a Spring $PE_{sp} = \frac{1}{2}kx^2$

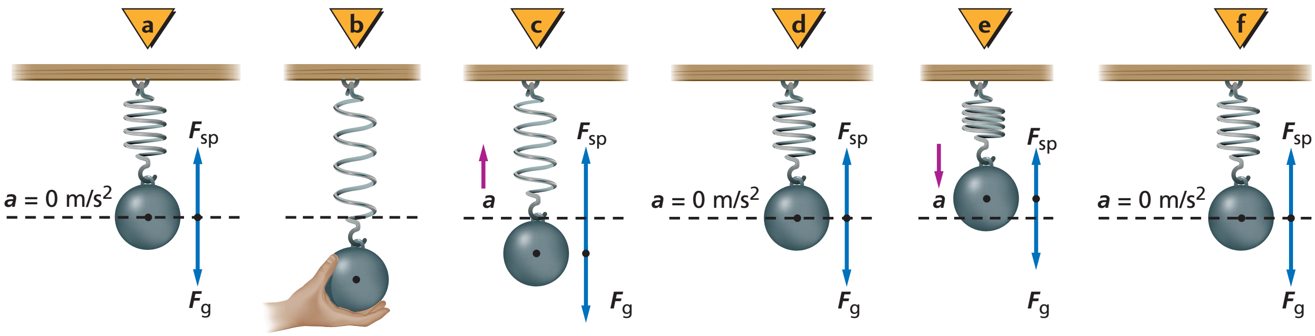
The potential energy in a spring is equal to one-half times the product of the spring constant and the square of the displacement.

■ **Figure 14-2** The spring constant of a spring can be determined from the graph of force versus displacement of the spring.



The units of the area, and thus, of the potential energy, are newton·meters, or joules.

How does the net force depend upon position? When an object hangs on a spring, the spring stretches until its upward force, F_{sp}, balances the object's weight, F_g, as shown in **Figure 14-3a.** The block is then in its equilibrium position. If you pull the object down, as in **Figure 14-3b,** the spring force increases, until it balances the forces exerted by your hand and gravity. When you let go of the object, it accelerates in the upward direction, as in **Figure 14-3c.** However, as the stretch of the spring is reduced, the



■ **Figure 14-3** Simple harmonic motion is demonstrated by the vibrations of an object hanging on a spring.

upward force decreases. In **Figure 14-3d,** the upward force of the spring and the object's weight are equal—there is no acceleration. Because there is no net force, the object continues its upward velocity, moving above the equilibrium position. In **Figure 14-3e,** the net force is in the direction opposite the displacement of the object and is directly proportional to the displacement, so the object moves with a simple harmonic motion. The object returns to the equilibrium position, as in **Figure 14-3f.**

▶ EXAMPLE Problem 1

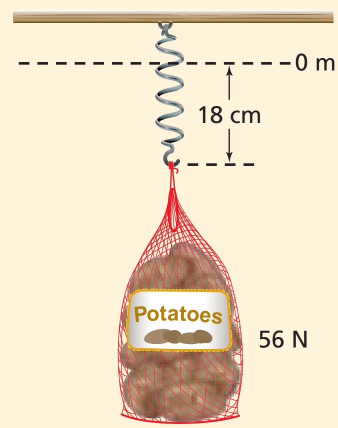
The Spring Constant and the Energy in a Spring A spring stretches by 18 cm when a bag of potatoes weighing 56 N is suspended from its end.

a. Determine the spring constant.

b. How much elastic potential energy is stored in the spring when it is stretched this far?

1 Analyze and Sketch the Problem

- Sketch the situation.
- Show and label the distance that the spring has stretched and its equilibrium position.



Known:	**Unknown:**
$x = 18$ cm	$k = ?$
$F = 56$ N	$PE_{sp} = ?$

2 Solve for the Unknown

a. Use $F = -kx$ and solve for k.

$$k = \frac{F}{x}$$ The minus sign can be dropped because it just means that the force is restoring.

$$= \frac{56\ \text{N}}{0.18\ \text{m}}$$ Substitute $F = 56$ N, $x = 0.18$ m

$$= 310\ \text{N/m}$$

b. $$PE_{sp} = \frac{1}{2}kx^2$$

$$= \frac{1}{2}(310\ \text{N/m})(0.18\ \text{m})^2$$ Substitute $k = 310$ N/m, $x = 0.18$ m

$$= 5.0\ \text{J}$$

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3 Evaluate the Answer

- **Are the units correct?** N/m are the correct units for the spring constant. $(\text{N/m})(\text{m}^2) = \text{N·m} = \text{J}$, which is the correct unit for energy.
- **Is the magnitude realistic?** The spring constant is consistent with a scale used, for example, to weigh groceries. The energy of 5.0 J is equal to the value obtained from $W = Fx = mgh$, when the average force of 28 N is applied.

PRACTICE Problems

- Additional Problems, Appendix B
- Solutions to Selected Problems, Appendix C

1. How much force is necessary to stretch a spring 0.25 m when the spring constant is 95 N/m?
2. A spring has a spring constant of 56 N/m. How far will it stretch when a block weighing 18 N is hung from its end?
3. What is the spring constant of a spring that stretches 12 cm when an object weighing 24 N is hung from it?
4. A spring with a spring constant of 144 N/m is compressed by a distance of 16.5 cm. How much elastic potential energy is stored in the spring?
5. A spring has a spring constant of 256 N/m. How far must it be stretched to give it an elastic potential energy of 48 J?

When the external force holding the object is released, as in Figure 14-3c, the net force and the acceleration are at their maximum, and the velocity is zero. As the object passes through the equilibrium point, Figure 14-3d, the net force is zero, and so is the acceleration. Does the object stop? No, it would take a net downward force to slow the object, and that will not exist until the object rises above the equilibrium position. When the object comes to the highest position in its oscillation, the net force and the acceleration are again at their maximum, and the velocity is zero. The object moves down through the equilibrium position to its starting point and continues to move in this vibratory manner. The period of oscillation, T, depends upon the mass of the object and the strength of the spring.

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Automobiles Elastic potential energy is an important part of the design and building of today's automobiles. Every year, new models of cars are tested to see how well they withstand damage when they crash into barricades at low speeds. A car's ability to retain its integrity depends upon how much of the kinetic energy it had before the crash can be converted into the elastic potential energy of the frame after the crash. Many bumpers are modified springs that store energy as a car hits a barrier in a slow-speed collision. After the car stops and the spring is compressed, the spring returns to its equilibrium position, and the car recoils from the barrier.

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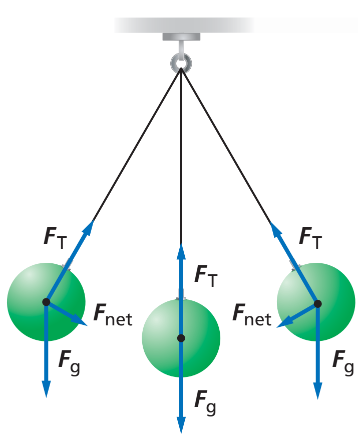
Pendulums

Simple harmonic motion also can be demonstrated by the swing of a pendulum. A simple **pendulum** consists of a massive object, called the bob, suspended by a string or light rod of length l. After the bob is pulled to one side and released, it swings back and forth, as shown in **Figure 14-4.** The string or rod exerts a tension force, $\mathbf{F}_T$, and gravity exerts a force, $\mathbf{F}_g$, on the bob. The vector sum of the two forces produces the net force, shown at three positions in Figure 14-4. At the left and right positions shown in Figure 14-4, the net force and acceleration are maximum, and the velocity is zero. At the middle position in Figure 14-4, the net force and acceleration are zero, and the velocity is maximum. You can see that the net force is a restoring force; that is, it is opposite the direction of the displacement of the bob and is trying to restore the bob to its equilibrium position.

Figure 14-4 $\mathbf{F}_{net}$, the vector sum of $\mathbf{F}_t$ and $\mathbf{F}_g$, is the restoring force for the pendulum.



For small angles (less than about 15°) the restoring force is proportional to the displacement, so the movement is simple harmonic motion. The period of a pendulum is given by the following equation.

Period of a Pendulum $T = 2\pi\sqrt{\frac{l}{g}}$

The period of a pendulum is equal to two pi times the square root of the length of the pendulum divided by the acceleration due to gravity.

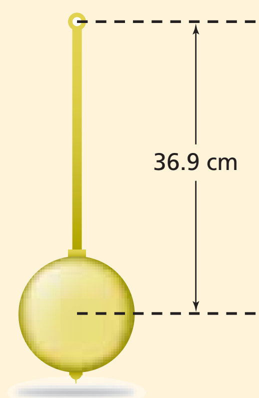
Notice that the period depends only upon the length of the pendulum and the acceleration due to gravity, not on the mass of the bob or the amplitude of oscillation. One application of the pendulum is to measure g, which can vary slightly at different locations on Earth.

EXAMPLE Problem 2

Finding g Using a Pendulum A pendulum with a length of 36.9 cm has a period of 1.22 s. What is the acceleration due to gravity at the pendulum's location?

1 Analyze and Sketch the Problem

- Sketch the situation.
- Label the length of the pendulum.



Known:
$l = 36.9$ cm
$T = 1.22$ s

Unknown:
$g = ?$

2 Solve for the Unknown

$$T = 2\pi\sqrt{\frac{l}{g}}$$

Solve for g.

$$g = \frac{(2\pi)^2 l}{T^2}$$

$$= \frac{4\pi^2(0.369\text{ m})}{(1.22\text{ s})^2} \qquad \text{Substitute } l = 0.369\text{ m}, T = 1.22\text{ s}$$

$$= 9.78\text{ m/s}^2$$

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3 Evaluate the Answer

- **Are the units correct?** m/s^2 are the correct units for acceleration.
- **Is the magnitude realistic?** The calculated value of g is quite close to the standard value of g, 9.80 m/s^2. This pendulum could be at a high elevation above sea level.

PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

6. What is the period on Earth of a pendulum with a length of 1.0 m?
7. How long must a pendulum be on the Moon, where $g = 1.6$ m/s^2, to have a period of 2.0 s?
8. On a planet with an unknown value of g, the period of a 0.75-m-long pendulum is 1.8 s. What is g for this planet?

CHALLENGE PROBLEM

A car of mass m rests at the top of a hill of height h before rolling without friction into a crash barrier located at the bottom of the hill. The crash barrier contains a spring with a spring constant, k, which is designed to bring the car to rest with minimum damage.

1. Determine, in terms of m, h, k, and g, the maximum distance, x, that the spring will be compressed when the car hits it.
2. If the car rolls down a hill that is twice as high, how much farther will the spring be compressed?
3. What will happen after the car has been brought to rest?

APPLYING PHYSICS

▶ **Foucault Pendulum** A Foucault pendulum has a long wire, about 16 m in length, with a heavy weight of about 109 kg attached to one end. According to Newton's first law of motion, a swinging pendulum will keep swinging in the same direction unless it is pushed or pulled in another direction. However, because Earth rotates every 24 h underneath the pendulum, to an observer it would seem as though the pendulum's direction of swing has changed. To demonstrate this, pegs are arranged in a circle on the floor beneath so that the swinging pendulum will knock them down as the floor rotates. At the north pole, this apparent rotation would be 15°/h. ◀

Resonance

To get a playground swing going, you "pump" it by leaning back and pulling the chains at the same point in each swing, or a friend gives you repeated pushes at just the right times. **Resonance** occurs when small forces are applied at regular intervals to a vibrating or oscillating object and the amplitude of the vibration increases. The time interval between applications of the force is equal to the period of oscillation. Other familiar examples of resonance include rocking a car to free it from a snowbank and jumping rhythmically on a trampoline or a diving board. The large-amplitude oscillations caused by resonance can create stresses. Audiences in theater balconies, for example, sometimes damage the structures by jumping up and down with a period equal to the natural oscillation period of the balcony.

Resonance is a special form of simple harmonic motion in which the additions of small amounts of force at specific times in the motion of an object cause a larger and larger displacement. Resonance from wind, combined with the design of the bridge supports, may have caused the original Tacoma Narrows Bridge to collapse.

14.1 Section Review

9. **Hooke's Law** Two springs look alike but have different spring constants. How could you determine which one has the greater spring constant?

10. **Hooke's Law** Objects of various weights are hung from a rubber band that is suspended from a hook. The weights of the objects are plotted on a graph against the stretch of the rubber band. How can you tell from the graph whether or not the rubber band obeys Hooke's law?

11. **Pendulum** How must the length of a pendulum be changed to double its period? How must the length be changed to halve the period?

12. **Energy of a Spring** What is the difference between the energy stored in a spring that is stretched 0.40 m and the energy stored in the same spring when it is stretched 0.20 m?

13. **Resonance** If a car's wheel is out of balance, the car will shake strongly at a specific speed, but not when it is moving faster or slower than that speed. Explain.

14. **Critical Thinking** How is uniform circular motion similar to simple harmonic motion? How are they different?

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14.2 Wave Properties

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. Even though no matter is transferred, the rope still carries energy through the wave that you created. A **wave** is a disturbance that carries energy through matter or space.

You have learned how Newton's laws of motion and principles of conservation of energy govern the behavior of particles. These laws and principles also govern the motion of waves. There are many kinds of waves that transmit energy, including the waves you cannot see.

▶ **Objectives**

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

▶ **Vocabulary**

wave
wave pulse
periodic wave
transverse wave
longitudinal wave
surface wave
trough
crest
wavelength
frequency

Mechanical Waves

Water waves, sound waves, and the waves that travel down a rope or spring are types of mechanical waves. Mechanical waves require a medium, such as water, air, ropes, or a spring. Because many other waves cannot be directly observed, mechanical waves can serve as models.

Transverse waves The two disturbances shown in **Figure 14-5a** are called wave pulses. A **wave pulse** is a single bump or disturbance that travels through a medium. If the wave moves up and down at the same rate, a **periodic wave** is generated. Notice in Figure 14-5a that the rope is disturbed in the vertical direction, but the pulse travels horizontally. A wave with this type of motion is called a transverse wave. A **transverse wave** is one that vibrates perpendicular to the direction of the wave's motion.

Longitudinal waves In a coiled-spring toy, you can create a wave pulse in a different way. If you squeeze together several turns of the coiled-spring toy and then suddenly release them, pulses of closely-spaced turns will move away in both directions, as shown in **Figure 14-5b.** This is called a **longitudinal wave.** The disturbance is in the same direction as, or parallel to, the direction of the wave's motion. Sound waves are longitudinal waves. Fluids usually transmit only longitudinal waves.

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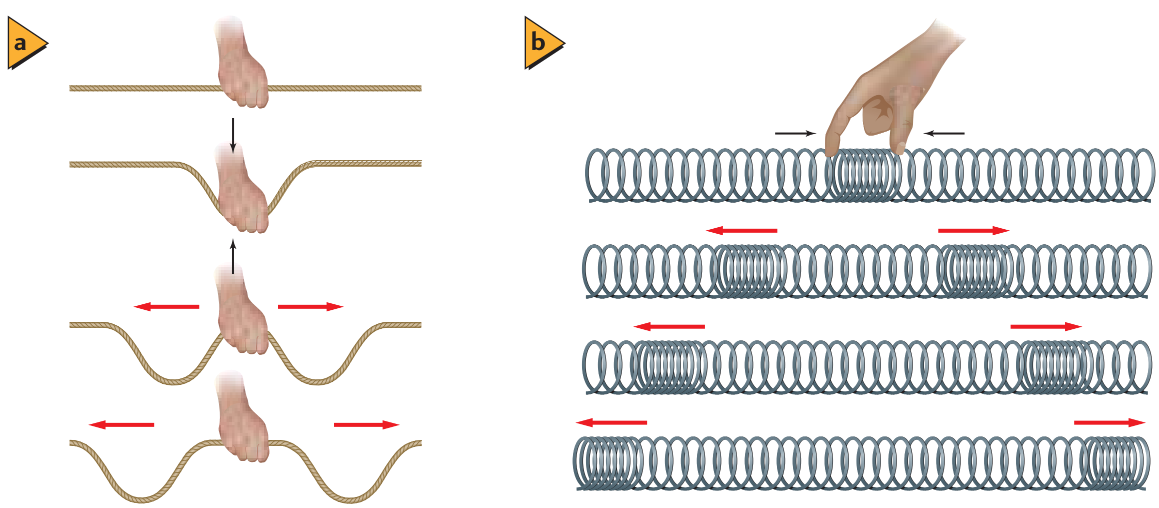
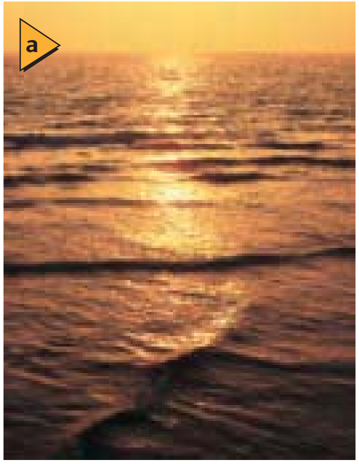
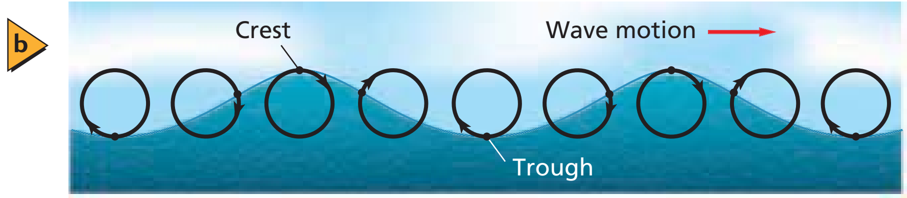


■ **Figure 14-5** A quick shake of a rope sends out transverse wave pulses in both directions **(a).** The squeeze and release of a coiled-spring toy sends out longitudinal wave pulses in both directions **(b).**





■ **Figure 14-6** Surface waves have properties of both transverse and longitudinal waves **(a).** The paths of the individual particles are circular **(b).**

Surface waves Waves that are deep in a lake or ocean are longitudinal; at the surface of the water, however, the particles move in a direction that is both parallel and perpendicular to the direction of wave motion, as shown in **Figure 14-6.** Each of the waves is a **surface wave,** which has characteristics of both transverse and longitudinal waves. The energy of water waves usually comes from distant storms, whose energy initially came from the heating of Earth by solar energy. This energy, in turn, was carried to Earth by transverse electromagnetic waves from the Sun.

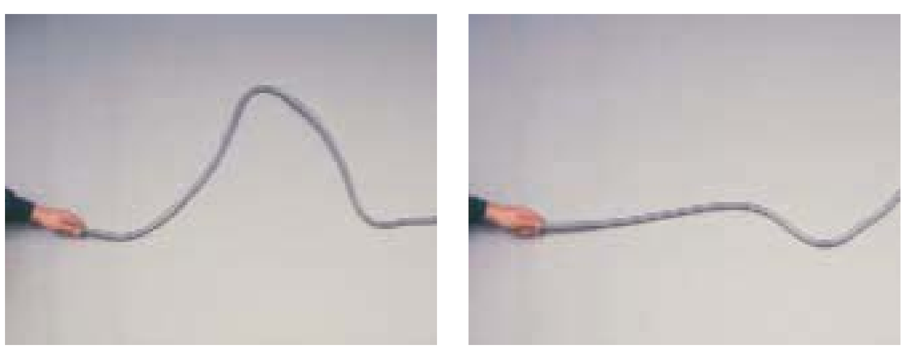
Measuring a Wave

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

Speed How fast does a wave move? The speed of the pulse shown in **Figure 14-7** can be found in the same way as the speed of a moving car is determined. First, measure the displacement of the wave peak, Δd, then divide this by the time interval, Δt, to find the speed, given by $v = \Delta d/\Delta t$. The speed of a periodic wave can be found in the same way. For most mechanical waves, both transverse and longitudinal, the speed depends only on the medium through which the waves move.

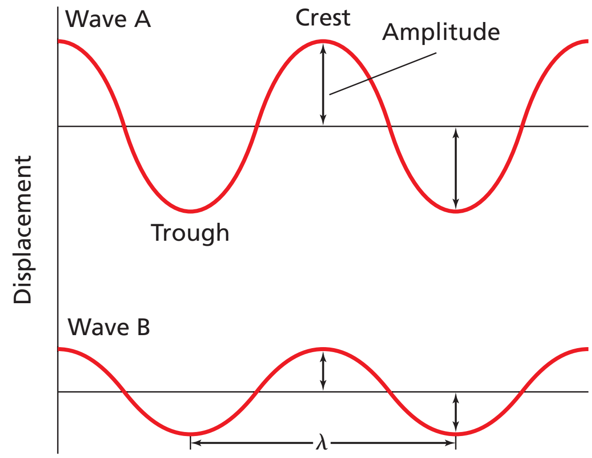
Amplitude How does the pulse generated by gently shaking a rope differ from the pulse produced by a violent shake? The difference is similar to the difference between a ripple in a pond and an ocean breaker: they have different amplitudes. You have learned that the amplitude of a wave is the maximum displacement of the wave from its position of rest, or equilibrium. Two similar waves having different amplitudes are shown in **Figure 14-8.**

A wave's amplitude depends on how it is generated, but not on its speed. More work must be done to generate a wave with a greater amplitude. For example, strong winds produce larger water waves than those formed by gentle breezes. Waves with greater amplitudes transfer more energy.



■ **Figure 14-7** 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.

Whereas 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 amplitude. Thus, doubling the amplitude of a wave increases the amount of energy it transfers each second by a factor of 4.



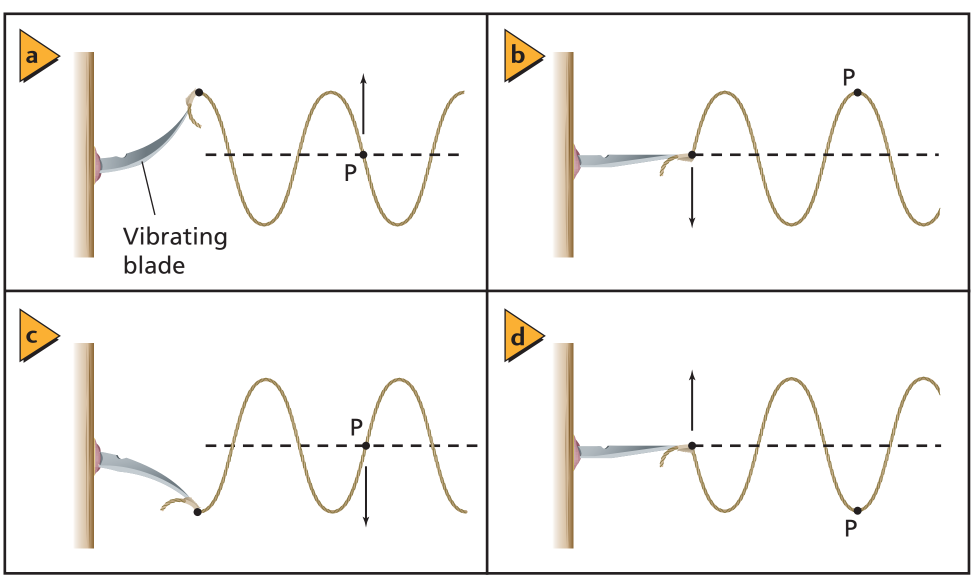
■ **Figure 14-8** The amplitude of wave A is larger than that of wave B.

Wavelength Rather than focusing on one point on a wave, imagine taking a snapshot of the wave so that you can see the whole wave at one instant in time. Figure 14-8 shows each low point, called a **trough,** and each high point, called a **crest,** 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 also is one wavelength from the next. The Greek letter lambda, λ, represents wavelength.

Phase Any two points on a wave that are one or more whole wavelengths apart are in phase. Particles in the medium are said to be in phase with one another when they have the same displacement from equilibrium and the same velocity. Particles in the medium with opposite displacements and velocities are 180° out of phase. A crest and a trough, for example, are 180° out of phase with each other. Two particles in a wave can be anywhere from 0° to 180° out of phase with one another.

Period and frequency Although wave speed and amplitude can describe both pulses and periodic waves, period, T, and frequency, f, apply only to periodic waves. You have learned that the period of a simple harmonic oscillator, such as a pendulum, is the time it takes for the motion of the oscillator to complete one cycle. Such an oscillator is usually the source, or cause, of a periodic wave. The period of a wave is equal to the period of the source. In **Figures 14-9a** through **14-9d,** the period, T, equals 0.04 s, which is the time it takes the source to complete one cycle. The same time is taken by P, a point on the rope, to return to its initial phase.

■ **Figure 14-9** One end of a string, with a piece of tape at point P, is attached to a blade vibrating 25 times per second. Note the change in position of point P over time.



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 and period of a wave are related by the following equation.

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

The frequency of a wave is equal to the reciprocal of the period.

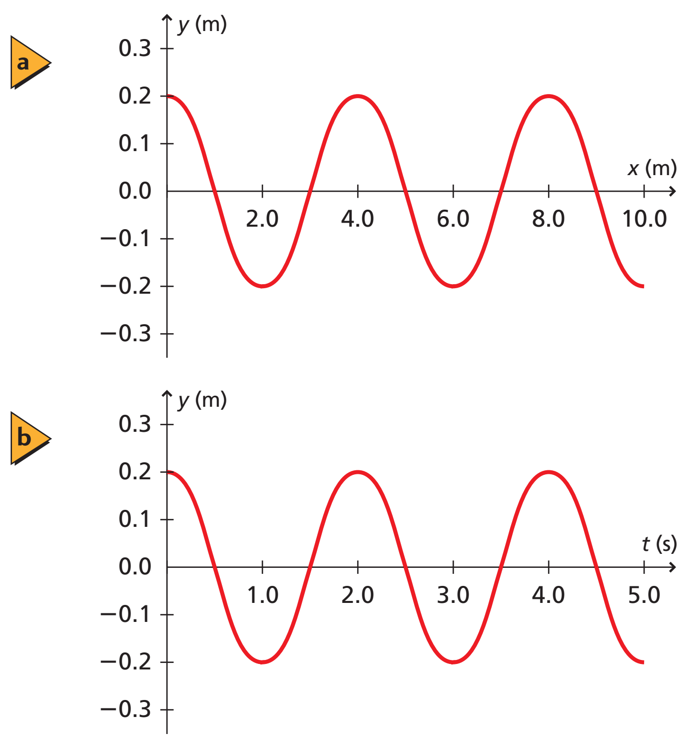
Both the period and the frequency of a wave depend only on its source. They do not depend on the wave's speed or the medium.

Although you can directly measure a wavelength, 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 wavelength of a wave is the speed multiplied by the period, $\lambda = vT$. Because the frequency is usually more easily found than the period, this equation is most often written in the following way.

Wavelength $\lambda = \frac{v}{f}$

The wavelength of a wave is equal to the velocity divided by the frequency.

Picturing waves If you took a snapshot of a transverse wave on a spring, it might look like one of the waves shown in Figure 14-8. This snapshot could be placed on a graph grid to show more information about the wave, as in **Figure 14-10a.** Similarly, if you record the motion of a single particle, such as point P in Figure 14-9, that motion can be plotted on a displacement-versus-time graph, as in **Figure 14-10b.** The period is found using the time axis of the graph. Longitudinal waves can also be depicted by graphs, where the y-axis could represent pressure, for example.



■ **Figure 14-10** Waves can be represented by graphs. The wavelength of this wave is 4.0 m **(a).** The period is 2.0 s **(b).** The amplitude, or displacement, is 0.2 m in both graphs. If these graphs represent the same wave, what is its speed?

▶ EXAMPLE Problem 3

Characteristics of a Wave A sound wave has a frequency of 192 Hz and travels the length of a football field, 91.4 m, in 0.271 s.

a. What is the speed of the wave?

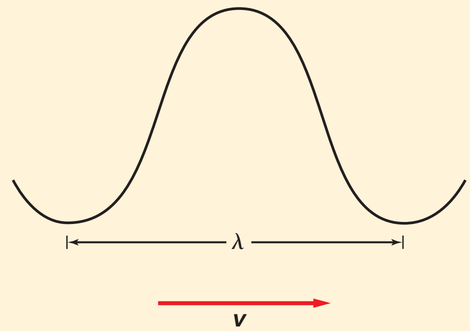
b. What is the wavelength of the wave?

c. What is the period of the wave?

d. If the frequency was changed to 442 Hz, what would be the new wavelength and period?

1 Analyze and Sketch the Problem

- Draw a model of the football field.
- Diagram a velocity vector.



Known:	Unknown:
$f = 192$ Hz	$v = ?$
$d = 91.4$ m	$\lambda = ?$
$t = 0.271$ s	$T = ?$

2 Solve for the Unknown

a. Solve for v.

$$v = \frac{d}{t}$$

$$= \frac{91.4\text{ m}}{0.271\text{ s}}$$ Substitute $d = 91.4$ m, $t = 0.271$ s

$$= 337\text{ m/s}$$

b. Solve for λ.

$$\lambda = \frac{v}{f}$$

$$= \frac{337\text{ m/s}}{192\text{ Hz}}$$ Substitute $v = 337$ m/s, $f = 192$ Hz

$$= 1.76\text{ m}$$

Math Handbook
Operations with Significant Digits
pages 835–836

c. Solve for T.

$$T = \frac{1}{f}$$

$$= \frac{1}{192\text{ Hz}}$$ Substitute $f = 192$ Hz

$$= 0.00521\text{ s}$$

d. $\lambda = \frac{v}{f}$

$$= \frac{337\text{ m/s}}{442\text{ Hz}}$$ Substitute $v = 337$ m/s, $f = 442$ Hz

$$= 0.762\text{ m}$$

$$T = \frac{1}{f}$$

$$= \frac{1}{442\text{ Hz}}$$ Substitute $f = 442$ Hz

$$= 0.00226\text{ s}$$

3 Evaluate the Answer

- **Are the units correct?** Hz has the units s^{-1}, so (m/s)/Hz = (m/s)·s = m, which is correct.
- **Are the magnitudes realistic?** A typical sound wave travels approximately 343 m/s, so 337 m/s is reasonable. The frequencies and periods are reasonable for sound waves. 442 Hz is close to a 440-Hz A above middle-C on a piano.

PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

15. 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 the period of the wave?

c. What is the wave's wavelength?

16. A hiker shouts toward a vertical cliff 465 m away. The echo is heard 2.75 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?

17. If you want to increase the wavelength of waves in a rope, should you shake it at a higher or lower frequency?

18. What is the speed of a periodic wave disturbance that has a frequency of 3.50 Hz and a wavelength of 0.700 m?

19. 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 6.00 Hz, what is its wavelength?

20. 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?

21. A periodic longitudinal wave that has a frequency of 20.0 Hz travels along a coil spring. If the distance between successive compressions is 0.600 m, what is the speed of the wave?

You probably have been intuitively aware that waves carry energy that can do work. You may have seen the massive damage done by the huge storm surge of a hurricane or the slower erosion of cliffs and beaches done by small, everyday waves. It is important to remember that while the amplitude of a mechanical wave determines the amount of energy it carries, only the medium determines the wave's speed.

14.2 Section Review

22. Speed in Different Media If you pull on one end of a coiled-spring toy, does the pulse reach the other end instantaneously? What happens if you pull on a rope? What happens if you hit the end of a metal rod? Compare and contrast the pulses traveling through these three materials.

23. Wave Characteristics You are creating transverse waves in a rope by shaking your hand from side to side. Without changing the distance that your hand moves, you begin to shake it faster and faster. What happens to the amplitude, wavelength, frequency, period, and velocity of the wave?

24. Waves Moving Energy Suppose that you and your lab partner are asked to demonstrate that a transverse wave transports energy without transferring matter. How could you do it?

25. Longitudinal Waves Describe longitudinal waves. What types of media transmit longitudinal waves?

26. Critical Thinking If a raindrop falls into a pool, it creates waves with small amplitudes. If a swimmer jumps into a pool, waves with large amplitudes are produced. Why doesn't the heavy rain in a thunderstorm produce large waves?

Physics Online physicspp.com/self_check_quiz

14.3 Wave Behavior

When a wave encounters the boundary of the medium in which it is traveling, it often 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.

Waves at Boundaries

Recall from Section 14.2 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 tension and 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 14-11** 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, but at the specific speed of waves traveling through the smaller spring. Note that this transmitted wave pulse remains upward.

Some of the energy of the incident wave's pulse is reflected backward into the larger spring. This returning wave is called the **reflected wave.** Whether or not the reflected wave is upright or inverted depends on the characteristics of the two springs. For example, if the waves in the smaller spring have a higher speed because the spring is heavier or stiffer, then the reflected wave will be inverted.

▶ Objectives

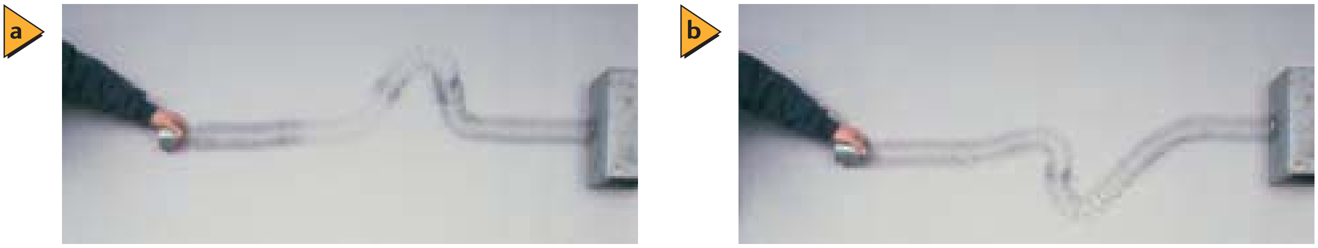
- **Relate** a wave's speed to the medium in which the wave travels.
- **Describe** how waves are reflected and refracted at boundaries between media.
- **Apply** the principle of superposition to the phenomenon of interference.

▶ Vocabulary

incident wave
reflected wave
principle of superposition
interference
node
antinode
standing wave
wave front
ray
normal
law of reflection
refraction

■ **Figure 14-11** 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)**.

Tom Pantages



■ **Figure 14-12** 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.

CLICK HERE

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 14-12.** The wall is the boundary of a new medium through which the wave attempts to pass. Instead of passing through, 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. Also note that the pulse is inverted. If the spring were attached to a loose ring around a pole, a free-moving boundary, the wave would not be inverted.

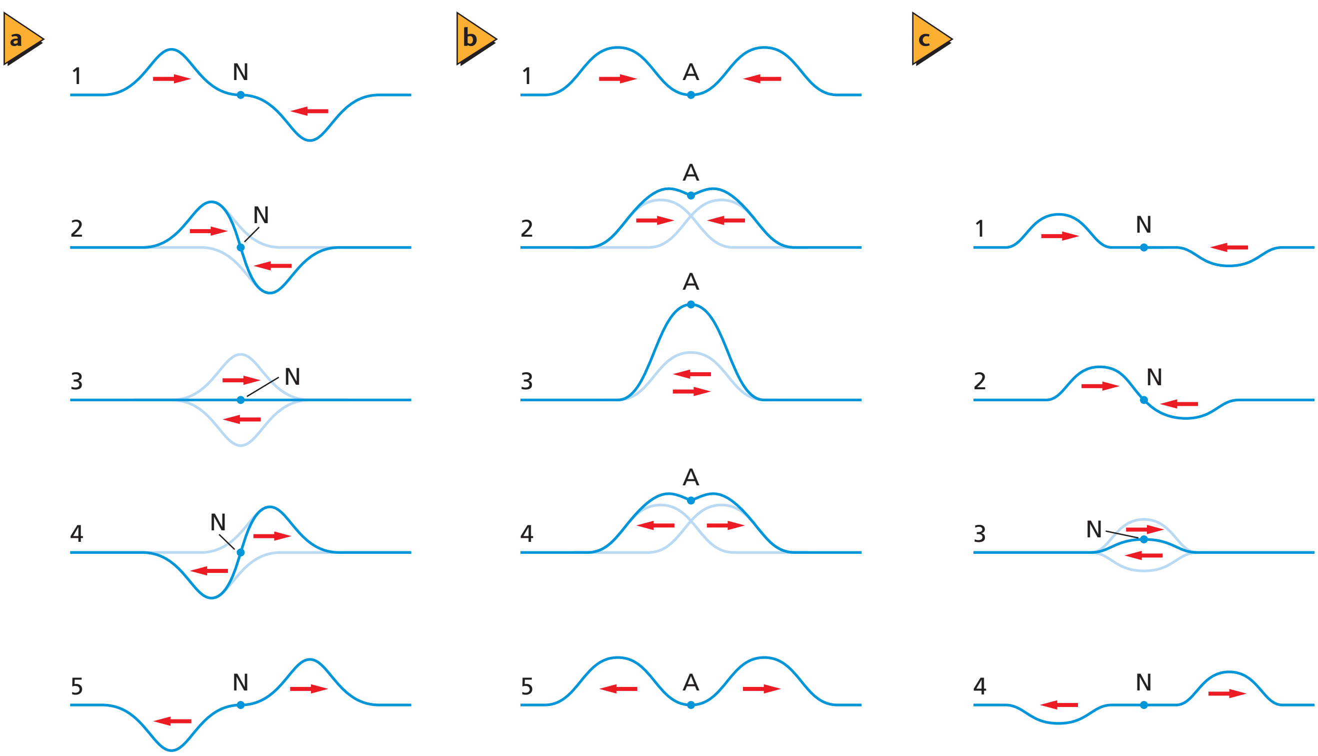
Superposition of Waves

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 **principle of superposition** states that the displacement of a medium caused by two or more waves is the algebraic sum of the displacements caused by the individual waves. In other words, two or more waves can combine to form a new wave. If the waves move in opposite directions, they can cancel or form a new wave of lesser or greater amplitude. The result of the superposition of two or more waves is called **interference.**

■ **Figure 14-13** When two equal pulses meet, there is a point, called the node (N), where the medium remains undisturbed **(a).** Constructive interference results in maximum interference at the antinode (A) **(b).** If the opposite pulses have unequal amplitudes, cancellation is incomplete **(c).**

Concepts In Motion

Interactive Figure To see an animation on wave interference, visit **physicspp.com**.



Tom Pantages

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 14-13a.** When the pulses meet and are in the same location, the displacement is zero. Point N, which does not move at all, is called a **node.** The pulses continue to move and eventually resume their original form.

Constructive interference occurs when wave displacements are in the same direction. The result is a wave that has an amplitude greater than those of any of the individual waves. **Figure 14-13b** 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 changing their shapes or sizes. If the pulses have unequal amplitudes, the resultant pulse at the overlap is the algebraic sum of the two pulses, as shown in **Figure 14-13c.**

Standing waves You can apply the concept of superimposed waves to the control of the formation of large amplitude 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, the reflected wave is inverted and travels back down the rope. Thus, when the wave leaves your hand the second time, its displacement is in the same direction as it was when it left your hand the first time.

What if you want to increase the amplitude of the wave that you create? Suppose you adjust the motion of your hand so that the period of vibration equals the time needed for the wave to make one round-trip from your hand to the door and back. Then, the displacement 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 greater than the motion of your hand. You would expect this based on 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 14-14a.** Thus, the wave appears to be standing still and is called a **standing wave.** You should note, however, that the standing wave is the interference of the two traveling waves moving in opposite directions. If you double the frequency of vibration, you can produce one more node and one more antinode in the rope. Then it appears to vibrate in two segments. Further increases in frequency produce even more nodes and antinodes, as shown in **Figures 14-14b** and **c.**

MINI LAB

Wave Interaction

With a coiled-spring toy, you can create pressure waves, as well as transverse waves of various amplitudes, speeds, and orientations.

1. Design an experiment to test what happens when waves from different directions meet.

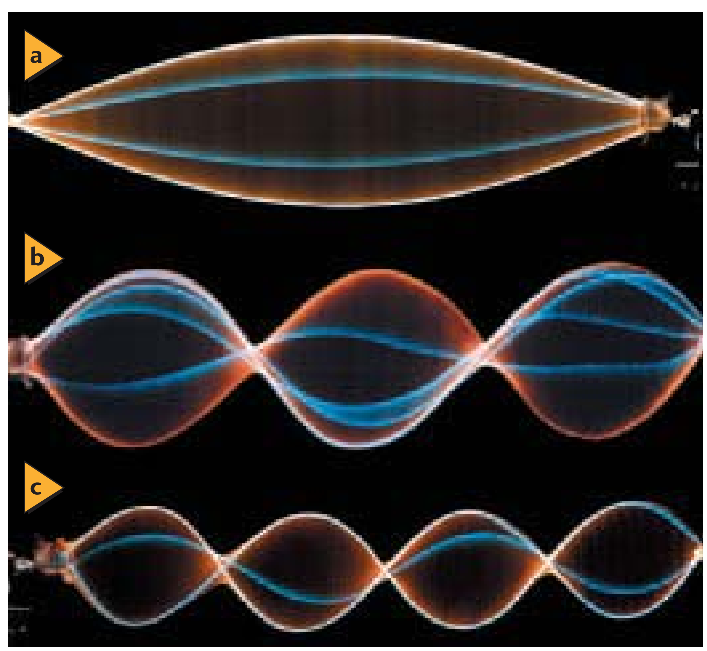
2. Perform your experiment and record your observations.

Analyze and Conclude

3. Does the speed of either wave change?

4. Do the waves bounce off each other, or do they pass through each other?

Figure 14-14 Interference produces standing waves in a rope. As the frequency is increased, as shown from top to bottom, the number of nodes and antinodes increases.



■ **Figure 14-15** Circular waves spread outward from their source **(a).** The wave can be represented by circles drawn at their crests **(b).** Notice that the rays are perpendicular to the wave fronts.

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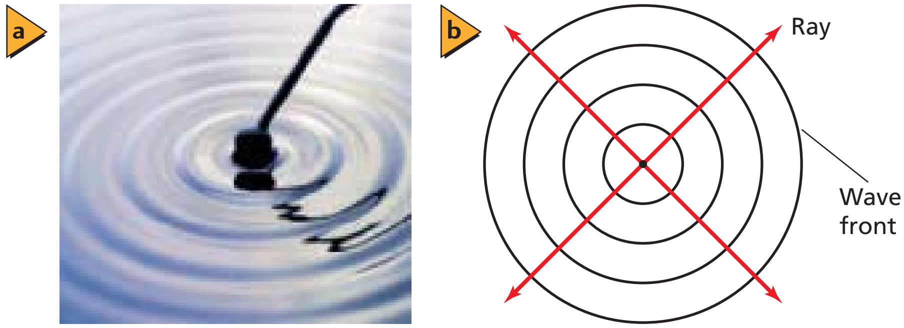


Waves in Two Dimensions

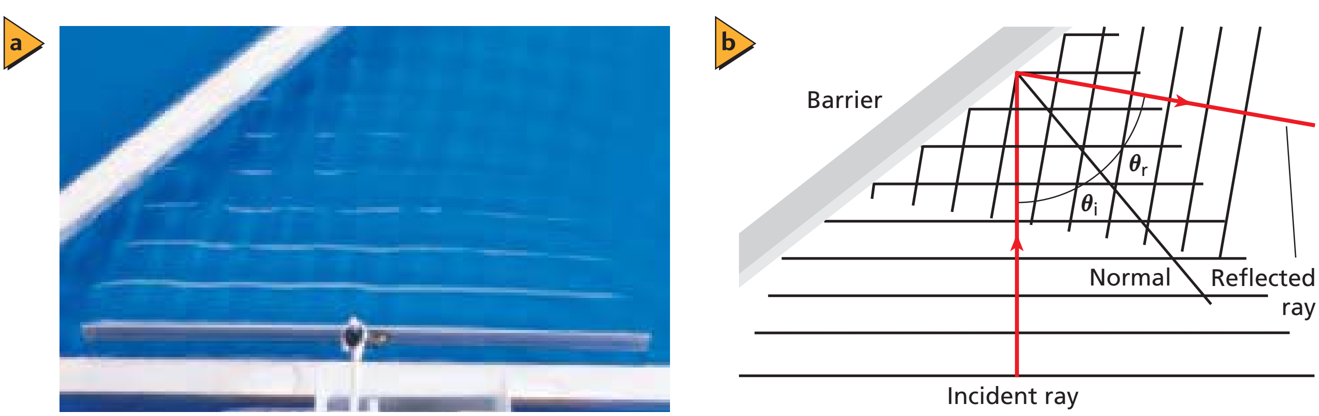
You have studied waves on a rope and on a spring reflecting from rigid supports, where the amplitude of the waves is forced to be zero by destructive interference. These mechanical waves move in only one dimension. However, waves on the surface of water move in two dimensions, and sound waves and electromagnetic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

Picturing waves in two dimensions When you throw a small stone into a calm pool of water, you see the circular crests and troughs of the resulting waves spreading out in all directions. You can sketch those waves by drawing circles to represent the wave crests. If you dip your finger into water with a constant frequency, the resulting sketch would be a series of concentric circles, called wave fronts, centered on your finger. A **wave front** is a line that represents the crest of a wave in two dimensions, and it can be used to show waves of any shape, including circular waves and straight waves. **Figure 14-15a** shows circular waves in water, and **Figure 14-15b** shows the wave fronts that represent those water waves. Wave fronts drawn to scale show the wavelengths of the waves, but not their amplitudes.

Whatever their shape, two-dimensional waves always travel in a direction that is perpendicular to their wave fronts. That direction can be represented by a **ray,** which is a line drawn at a right angle to the crest of the wave. When all you want to show is the direction in which a wave is traveling, it is convenient to draw rays instead of wave fronts.

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 the case of

■ **Figure 14-16** 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 is then reflected to the right **(b).**

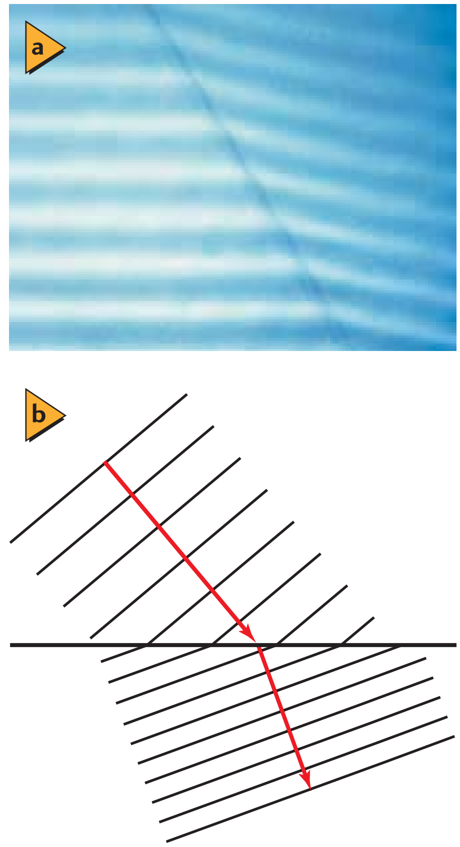


(t)Fundamental Photographs, (b)Runk/Shoenberger from Grant Heilman

Figure 14-16a, 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. The wave pulse travels toward a rigid barrier that reflects the wave: the incident wave moves upward, and the reflected wave moves to the right.

The direction of wave motion can be modeled by a ray diagram. **Figure 14-16b** shows the ray diagram for the waves in the ripple tank. The ray representing the incident wave is the arrow pointing upward. The ray representing the reflected wave points to the right.

The direction of the barrier also is shown by a line, which is drawn at a right angle, or perpendicular, to the barrier, 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 14-17a** 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 acts like a different medium. As the waves move from deep to shallow water, their speed decreases, and the direction of the waves changes. Because the waves in the shallow water are generated by the waves in the deep water, their frequency is not changed. Based on the equation $\lambda = v/f$, the decrease in the speed of the waves means that the wavelength is shorter in the shallower water. The change in the direction of waves at the boundary between two different media is known as **refraction. Figure 14-17b** shows a wave front and ray model of refraction. When you study the reflection and refraction of light in Chapter 17, you will learn the law of refraction, called Snell's law.

You may not be aware that echoes are caused by the reflection of sound off hard surfaces, such as the walls of a large warehouse or a distant cliff face. Refraction is partly responsible for rainbows. When white light passes through a raindrop, refraction separates the light into its individual colors.

Figure 14-17 As the water waves move over a shallower region of the ripple tank where a glass plate is placed, they slow down and their wavelength decreases **(a).** Refraction can be represented by a diagram of wave fronts and rays **(b).**

14.3 Section Review

27. Waves at Boundaries Which of the following wave characteristics remain unchanged when a wave crosses a boundary into a different medium: frequency, amplitude, wavelength, velocity, and/or direction?

28. Refraction of Waves Notice in Figure 14-17a how the wave changes direction as it passes from one medium to another. Can two-dimensional waves cross a boundary between two media without changing direction? Explain.

29. Standing Waves In a standing wave on a string fixed at both ends, how is the number of nodes related to the number of antinodes?

30. Critical Thinking As another way to understand wave reflection, cover the right-hand side of each drawing in Figure 14-13a 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 darker blue. Note that it acts like a wave reflected from a boundary. Is the boundary a rigid wall, or is it open-ended? Repeat this exercise for Figure 14-13b.

Physics Online physicspp.com/self_check_quiz

PHYSICS LAB • Design Your Own

Pendulum Vibrations

A pendulum can provide a simple model for the investigation of wave properties. In this experiment, you will design a procedure to use the pendulum to examine amplitude, period, and frequency of a wave. You also will determine the acceleration due to gravity from the period and length of the pendulum.

QUESTION

How can a pendulum demonstrate the properties of waves?

Objectives

- **Determine** what variables affect a pendulum's period.
- **Investigate** the frequency and period amplitude of a pendulum.
- **Measure** *g*, the acceleration due to gravity, using the period and length of a pendulum.

Safety Precautions

Possible Materials

string (1.5 m)
three sinkers
paper clip
ring stand with ring
stopwatch

Procedure

1. Design a pendulum using a ring stand, a string with a paper clip, and a sinker attached to the paper clip. Be sure to check with your teacher and have your design approved before you proceed with the lab.
2. For this investigation, the length of the pendulum is the length of the string plus half the length of the bob. The amplitude is how far the bob is pulled from its equilibrium point. The frequency is the cycles/s of the bob. The period is the time for the bob to travel back and forth (one cycle). When collecting data for the period, find the time it takes to make ten cycles, and then calculate the period in s/cycles. When finding frequency, count how many cycles occur in 10 s, and then convert your value to cycles/s.
3. Design a procedure that keeps the mass of the bob and the amplitude constant, but varies the length. Determine the frequency and period of the pendulum. Record your results in the data table. Use several trials at several lengths to collect your data.
4. Design a procedure that keeps length and amplitude constant, but varies the mass of the bob. Determine the frequency and period of the pendulum. Record your results in the data table. Use several trials to collect your data.
5. Design a procedure that keeps length and mass of the bob constant, but varies the amplitude of the pendulum. Determine the frequency and period of the pendulum. Record your results in the data table. Use several trials to collect your data.
6. Design a procedure using the pendulum to calculate *g*, the acceleration due to gravity, using the equation $T = 2\pi\sqrt{\ell/g}$. T is the period, and ℓ is the length of the pendulum string. Remember to use several trials to collect your data.

Horizons Companies

Data Table 1

This data table format can be used for steps 2–5.

	Trial 1	Trial 2	Trial 3	Average	Period (s/cycle)	Frequency (cycles/s)
Length 1					———	
Length 2						———
Length 3						
Mass 1					———	
Mass 2						———
Mass 3						
Amplitude 1					———	
Amplitude 2						———
Amplitude 3						

Data Table 2

This data table format can be used for step 6, finding *g*.

	Trial 1	Trial 2	Trial 3	Average	Period (s/cycle)	Length of String (m)
Length 1						
Length 2						
Length 3						

Analyze

1. **Summarize** What is the relationship between the pendulum's amplitude and its period?
2. **Summarize** What is the relationship between the pendulum's bob mass and its period?
3. **Compare and Contrast** How are the period and length of a pendulum related?
4. **Analyze** Calculate g from your data in step 6.
5. **Error Analysis** What is the percent error of your experimental g value? What are some possible reasons for the difference between your experimental value of g and the accepted value of g?

Conclude and Apply

1. **Infer** What variable(s) affects a pendulum's period?
2. **Analyze** Why is it better to run three or more trials to obtain the frequency and period of each pendulum?
3. **Compare** How is the motion of a pendulum like that of a wave?
4. **Analyze and Conclude** When does the pendulum bob have the greatest kinetic energy?
5. **Analyze and Conclude** When does the pendulum bob have the greatest potential energy?

Going Further

Suppose you had a very long pendulum. What other observations could be made, over the period of a day, of this pendulum's motion?

Real-World Physics

Pendulums are used to drive some types of clocks. Using the observations from your experiments, what design problems are there in using your pendulum as a time-keeping instrument?

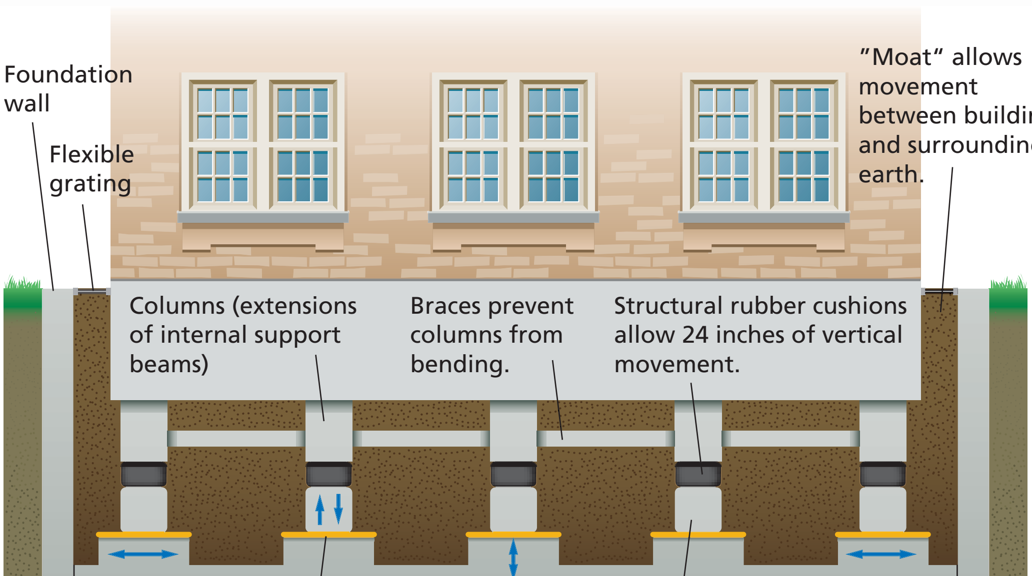
Physics Online

To find out more about the behavior of waves, visit the Web site: **physicspp.com**

Technology and Society

Earthquake Protection

An earthquake is the equivalent of a violent explosion somewhere beneath the surface of Earth. The mechanical waves that radiate from an earthquake are both transverse and longitudinal. Transverse waves shake a structure horizontally, while longitudinal waves cause vertical shaking. Earthquakes cannot be predicted or prevented, so we must construct our buildings to withstand them.



New building designs reduce damage by earthquakes.

As our knowledge of earthquakes increases, existing buildings must be retrofitted to withstand newly discovered types of earthquake-related failures.

Reducing Damage Most bridges and parking ramps were built by stacking steel-reinforced concrete sections atop one another. Gravity keeps them in place. These structures are immensely strong under normal conditions, but they can be shaken apart by a strong earthquake. New construction codes dictate that their parts must be bonded together by heavy steel straps.

Earthquake damage to buildings also can be reduced by allowing a small amount of controlled movement between the building frame and its foundation. To minimize vertical shaking of a building, springs are inserted into the vertical members of the framework. These springs are made of a strong rubber compound compressed within heavy structural steel cylinders. Sideways shaking is diminished by placing sliding supports beneath the building columns. These allow the structure to remain stationary if the ground beneath it moves sideways.

Long structures, like tunnels and bridges, must be constructed to survive vertical or horizontal shearing fractures of the earth beneath. The Bay Area Rapid Transit tunnel that runs beneath San Francisco Bay has flexible couplings for stability should the bay floor buckle.

Going Further

1. **Research** What is the framework of your school made of and how were the foundations built?
2. **Observe** Find a brick building that has a crack in one of its walls. See if you can tell why the crack formed and why it took the path that it did. What might this have to do with earthquakes?

Chapter 14

Study Guide

14.1 Periodic Motion

Vocabulary

- periodic motion (p. 375)
- simple harmonic motion (p. 375)
- period (p. 375)
- amplitude (p. 375)
- Hooke's law (p. 376)
- pendulum (p. 378)
- resonance (p. 380)

Key Concepts

- Periodic motion is any motion that repeats in a regular cycle.
- Simple harmonic motion results when the restoring force on an object is directly proportional to the object's displacement from equilibrium. Such a force obeys Hooke's law.

$$F = -kx$$

- The elastic potential energy stored in a spring that obeys Hooke's law is expressed by the following equation.

$$PE_{sp} = \frac{1}{2}kx^2$$

- The period of a pendulum can be found with the following equation.

$$T = 2\pi\sqrt{\frac{l}{g}}$$

14.2 Wave Properties

Vocabulary

- wave (p. 381)
- wave pulse (p. 381)
- periodic wave (p. 381)
- transverse wave (p. 381)
- longitudinal wave (p. 381)
- surface wave (p. 382)
- trough (p. 383)
- crest (p. 383)
- wavelength (p. 383)
- frequency (p. 384)

Key Concepts

- Waves transfer energy without transferring matter.
- 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 direction of wave motion.
- Frequency is the number of cycles per second and is related to period by:

$$f = \frac{1}{T}$$

- The wavelength of a continuous wave can be found by using the following equation.

$$\lambda = \frac{v}{f}$$

14.3 Wave Behavior

Vocabulary

- incident wave (p. 387)
- reflected wave (p. 387)
- principle of superposition (p. 388)
- interference (p. 388)
- node (p. 389)
- antinode (p. 389)
- standing wave (p. 389)
- wave front (p. 390)
- ray (p. 390)
- normal (p. 391)
- law of reflection (p. 391)
- refraction (p. 391)

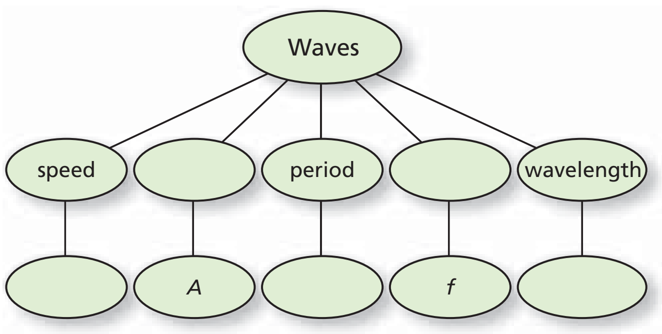
Key Concepts

- When a wave crosses a boundary between two media, it is partially transmitted and partially reflected.
- 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.
- 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.

Chapter 14 Assessment

Concept Mapping

31. Complete the concept map using the following terms and symbols: *amplitude, frequency, v, λ, T.*



Mastering Concepts

32. What is periodic motion? Give three examples of periodic motion. (14.1)

33. What is the difference between frequency and period? How are they related? (14.1)

34. What is simple harmonic motion? Give an example of simple harmonic motion. (14.1)

35. If a spring obeys Hooke's law, how does it behave? (14.1)

36. How can the spring constant of a spring be determined from a graph of force versus displacement? (14.1)

37. How can the potential energy in a spring be determined from the graph of force versus displacement? (14.1)

38. Does the period of a pendulum depend on the mass of the bob? The length of the string? Upon what else does the period depend? (14.1)

39. What conditions are necessary for resonance to occur? (14.1)

40. How many general methods of energy transfer are there? Give two examples of each. (14.2)

41. What is the primary difference between a mechanical wave and an electromagnetic wave? (14.2)

42. What are the differences among transverse, longitudinal, and surface waves? (14.2)

43. Waves are sent along a spring of fixed length. (14.2)

- **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.

44. What is the wavelength of a wave? (14.2)

45. 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? (14.2)

46. What is the difference between a wave pulse and a periodic wave? (14.2)

47. Describe the difference between wave frequency and wave velocity. (14.2)

48. 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? (14.2)

49. When are points on a wave in phase with each other? When are they out of phase? Give an example of each. (14.2)

50. What is the amplitude of a wave and what does it represent? (14.2)

51. Describe the relationship between the amplitude of a wave and the energy it carries. (14.2)

52. When a wave reaches the boundary of a new medium, what happens to it? (14.3)

53. When a wave crosses a boundary between a thin and a thick rope, as shown in **Figure 14-18,** its wavelength and speed change, but its frequency does not. Explain why the frequency is constant. (14.3)

Figure 14-18

54. How does a spring pulse reflected from a rigid wall differ from the incident pulse? (14.3)

55. Describe interference. Is interference a property of only some types of waves or all types of waves? (14.3)

56. What happens to a spring at the nodes of a standing wave? (14.3)

57. **Violins** 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. (14.3)

58. 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? (14.3)

59. Wave fronts pass at an angle from one medium into a second medium, where they travel with a different speed. Describe two changes in the wave fronts. What does not change? (14.3)

Applying Concepts

60. A ball bounces up and down on the end of a spring. Describe the energy changes that take place during one complete cycle. Does the total mechanical energy change?

61. Can a pendulum clock be used in the orbiting *International Space Station?* Explain.

62. 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, and second, in a direction at right angles to its length. Describe the waves produced in the two cases.

63. 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?

64. What happens to the period of a wave as the frequency increases?

65. What happens to the wavelength of a wave as the frequency increases?

66. Suppose you make a single pulse on a stretched spring. How much energy is required to make a pulse with twice the amplitude?

67. You can make water slosh back and forth in a shallow pan only if you shake the pan with the correct frequency. Explain.

68. In each of the four waves in **Figure 14-19,** 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 rigidity of the boundaries at A, B, C, and D.

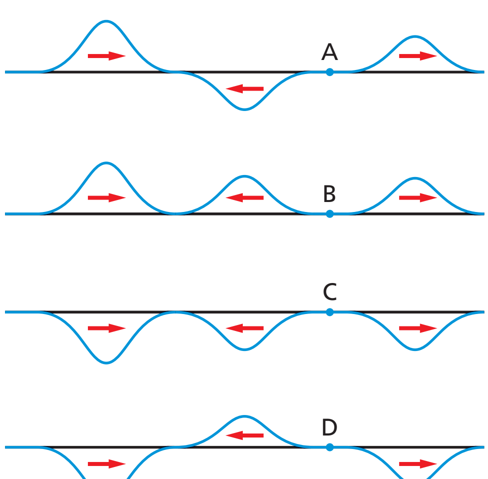


Figure 14-19

Mastering Problems

14.1 Periodic Motion

69. A spring stretches by 0.12 m when some apples weighing 3.2 N are suspended from it, as shown in **Figure 14-20.** What is the spring constant of the spring?

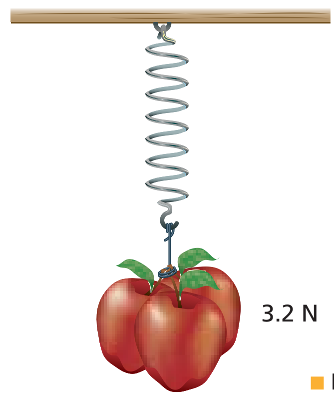


Figure 14-20

70. Car Shocks Each of the coil springs of a car has a spring constant of 25,000 N/m. How much is each spring compressed if it supports one-fourth of the car's 12,000-N weight?

71. How much potential energy is stored in a spring with a spring constant of 27 N/m if it is stretched by 16 cm?

72. Rocket Launcher A toy rocket-launcher contains a spring with a spring constant of 35 N/m. How far must the spring be compressed to store 1.5 J of energy?

73. Force-versus-length data for a spring are plotted on the graph in **Figure 14-21.**
   a. What is the spring constant of the spring?
   b. What is the energy stored in the spring when it is stretched to a length of 0.50 m?

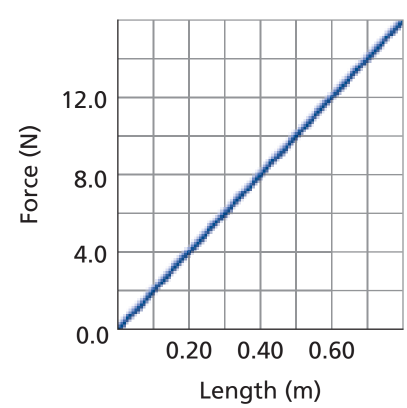


Figure 14-21

74. How long must a pendulum be to have a period of 2.3 s on the Moon, where $g = 1.6\ m/s^2$?

14.2 Wave Properties

75. Building Motion The Sears Tower in Chicago, shown in **Figure 14-22,** sways back and forth in the wind with a frequency of about 0.12 Hz. What is its period of vibration?

■ Figure 14-22

76. Ocean Waves An ocean wave has a length of 12.0 m. A wave passes a fixed location every 3.0 s. What is the speed of the wave?

77. Water waves in a shallow dish are 6.0-cm long. At one point, the water moves up and down at a rate of 4.8 oscillations/s.
a. What is the speed of the water waves?
b. What is the period of the water waves?

78. Water waves in a lake travel 3.4 m in 1.8 s. The period of oscillation is 1.1 s.
a. What is the speed of the water waves?
b. What is their wavelength?

79. Sonar A sonar signal of frequency 1.00×10^6 Hz has a wavelength of 1.50 mm in water.
a. What is the speed of the signal in water?
b. What is its period in water?
c. What is its period in air?

80. A sound wave of wavelength 0.60 m and a velocity of 330 m/s is produced for 0.50 s.
a. What is the frequency of the wave?
b. How many complete waves are emitted in this time interval?
c. After 0.50 s, how far is the front of the wave from the source of the sound?

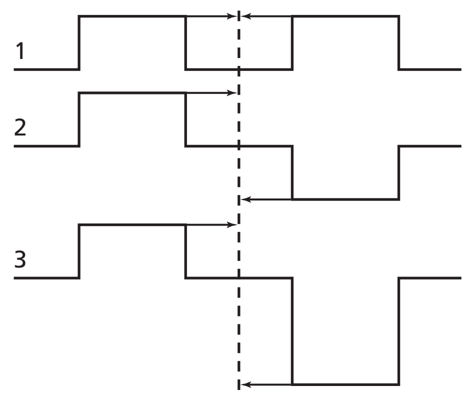
81. The speed of sound in water is 1498 m/s. A sonar signal is sent straight down from a ship at a point just below the water surface, and 1.80 s later, the reflected signal is detected. How deep is the water?

82. 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 each surface wave on the lake. They count 12 crests that pass by the raft in 20.0 s. Calculate how fast the waves are moving.

83. Earthquakes 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 68 s before the arrival of the longitudinal waves. How far away is the earthquake?

14.3 Wave Behavior

84. Sketch the result for each of the three cases shown in **Figure 14-23,** when the centers of the two approaching wave pulses lie on the dashed line so that the pulses exactly overlap.



■ Figure 14-23

85. If you slosh the water 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?

86. Guitars 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.
a. How long does it take for the pulse to move to the string end and return to the center?
b. When the pulses return, is the string above or below its resting location?
c. If you plucked the string 15 cm from one end of the string, where would the two pulses meet?

 For more problems, go to Additional Problems, Appendix B.

87. Sketch the result for each of the four cases shown in **Figure 14-24,** when the centers of each of the two wave pulses lie on the dashed line so that the pulses exactly overlap.

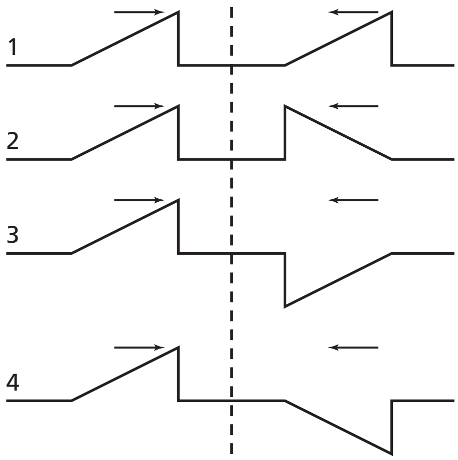


Figure 14-24

Mixed Review

88. What is the period of a pendulum with a length of 1.4 m?

89. The frequency of yellow light is 5.1×10^{14} Hz. Find the wavelength of yellow light. The speed of light is 3.00×10^{8} m/s.

90. Radio Wave AM-radio signals are broadcast at frequencies between 550 kHz (kilohertz) and 1600 kHz and travel 3.0×10^{8} m/s.

a. What is the range of wavelengths for these signals?

b. FM frequencies range between 88 MHz (megahertz) and 108 MHz and travel at the same speed. What is the range of FM wavelengths?

91. You are floating just offshore at the beach. Even though the waves are steadily moving in toward the beach, you don't move any closer to the beach.

a. What type of wave are you experiencing as you float in the water?

b. Explain why the energy in the wave does not move you closer to shore.

c. In the course of 15 s you count ten waves that pass you. What is the period of the waves?

d. What is the frequency of the waves?

e. You estimate that the wave crests are 3 m apart. What is the velocity of the waves?

f. After returning to the beach, you learn that the waves are moving at 1.8 m/s. What is the actual wavelength of the waves?

92. Bungee Jumper A high-altitude bungee jumper jumps from a hot-air balloon using a 540-m-bungee cord. When the jump is complete and the jumper is just suspended from the cord, it is stretched 1710 m. What is the spring constant of the bungee cord if the jumper has a mass of 68 kg?

93. The time needed for a water wave to change from the equilibrium level to the crest is 0.18 s.

a. What fraction of a wavelength is this?

b. What is the period of the wave?

c. What is the frequency of the wave?

94. When a 225-g mass is hung from a spring, the spring stretches 9.4 cm. The spring and mass then are pulled 8.0 cm from this new equilibrium position and released. Find the spring constant of the spring and the maximum speed of the mass.

95. Amusement Ride You notice that your favorite amusement-park ride seems bigger. The ride consists of a carriage that is attached to a structure so it swings like a pendulum. You remember that the carriage used to swing from one position to another and back again eight times in exactly 1 min. Now it only swings six times in 1 min. Give your answers to the following questions to two significant digits.

a. What was the original period of the ride?

b. What is the new period of the ride?

c. What is the new frequency?

d. How much longer is the arm supporting the carriage on the larger ride?

e. If the park owners wanted to double the period of the ride, what percentage increase would need to be made to the length of the pendulum?

96. Clocks The speed at which a grandfather clock runs is controlled by a swinging pendulum.

a. If you find that the clock loses time each day, what adjustment would you need to make to the pendulum so it will keep better time?

b. If the pendulum currently is 15.0 cm, by how much would you need to change the length to make the period lessen by 0.0400 s?

97. Bridge Swinging In the summer over the New River in West Virginia, several teens swing from bridges with ropes, then drop into the river after a few swings back and forth.

a. If Pam is using a 10.0-m length of rope, how long will it take her to reach the peak of her swing at the other end of the bridge?

b. If Mike has a mass that is 20 kg more than Pam, how would you expect the period of his swing to differ from Pam's?

c. At what point in the swing is *KE* at a maximum?

d. At what point in the swing is *PE* at a maximum?

e. At what point in the swing is *KE* at a minimum?

f. At what point in the swing is *PE* at a minimum?

98. You have a mechanical fish scale that is made with a spring that compresses when weight is added to a hook attached below the scale. Unfortunately, the calibrations have completely worn off of the scale. However, you have one known mass of 500.0 g that displaces the spring 2.0 cm.
a. What is the spring constant for the spring?
b. If a fish displaces the spring 4.5 cm, what is the mass of the fish?

99. Car Springs When you add a 45-kg load to the trunk of a new small car, the two rear springs compress an additional 1.0 cm.
a. What is the spring constant for each of the springs?
b. How much additional potential energy is stored in each of the car springs after loading the trunk?

100. The velocity of a wave on a string depends on how tightly 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 by the following equation.

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

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?

Thinking Critically

101. Analyze and Conclude A 20-N force is required to stretch a spring by 0.5 m.
a. What is the spring constant?
b. How much energy is stored in the spring?
c. Why isn't the work done to stretch the spring equal to the force times the distance, or 10 J?

102. Make and Use Graphs Several weights were suspended from a spring, and the resulting extensions of the spring were measured. **Table 14-1** shows the collected data.

Table 14-1
Weights on a Spring

Force, F (N)	Extension, x (m)
2.5	0.12
5.0	0.26
7.5	0.35
10.0	0.50
12.5	0.60
15.0	0.71

a. Make a graph of the force applied to the spring versus the spring length. Plot the force on the y-axis.
b. Determine the spring constant from the graph.
c. Using the graph, find the elastic potential energy stored in the spring when it is stretched to 0.50 m.

103. Apply Concepts Gravel roads often develop regularly spaced ridges that are perpendicular to the road, as shown in **Figure 14-25.** 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 on a road are 1.5 m apart and cars travel on it at about 5 m/s, what is the frequency of the springs' oscillation?

Figure 14-25

Writing in Physics

104. Research Christiaan Huygens' work on waves and the controversy between him and Newton over the nature of light. Compare and contrast their explanations of such phenomena as reflection and refraction. Whose model would you choose as the best explanation? Explain why.

Cumulative Review

105. A 1400-kg drag racer automobile can complete a one-quarter mile (402 m) course in 9.8 s. The final speed of the automobile is 250 mi/h (112 m/s). (Chapter 11)
a. What is the kinetic energy of the automobile?
b. What is the minimum amount of work that was done by its engine? Why can't you calculate the total amount of work done?
c. What was the average acceleration of the automobile?

106. How much water would a steam engine have to evaporate in 1 s to produce 1 kW of power? Assume that the engine is 20 percent efficient. (Chapter 12)

Standardized Test Practice

Multiple Choice

1. What is the value of the spring constant of a spring with a potential energy of 8.67 J when it's stretched 247 mm?

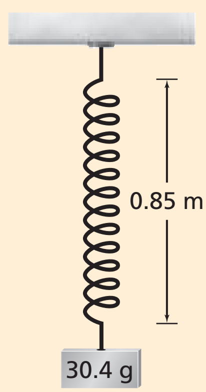
(A) 70.2 N/m (C) 142 N/m
(B) 71.1 N/m (D) 284 N/m

2. What is the force acting on a spring with a spring constant of 275 N/m that is stretched 14.3 cm?

(A) 2.81 N (C) 39.3 N
(B) 19.2 N (D) 3.93×10^{30} N

3. A mass stretches a spring as it hangs from the spring. What is the spring constant?

(A) 0.25 N/m (C) 26 N/m
(B) 0.35 N/m (D) 3.5×10^{2} N/m



4. A spring with a spring constant of 350 N/m pulls a door closed. How much work is done as the spring pulls the door at a constant velocity from an 85.0-cm stretch to a 5.0-cm stretch?

(A) 112 N·m (C) 224 N·m
(B) 130 J (D) 1.12×10^{3} J

5. What is the correct rearrangement of the formula for the period of a pendulum to find the length of the pendulum?

(A) $l = \frac{4\pi^2 g}{T^2}$ (C) $l = \frac{T^2 g}{(2\pi)^2}$
(B) $l = \frac{gT}{4\pi^2}$ (D) $l = \frac{Tg}{2\pi}$

6. What is the frequency of a wave with a period of 3 s?

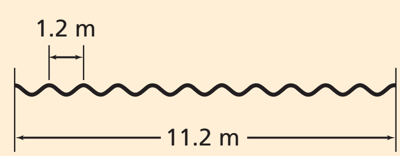
(A) 0.3 Hz (C) $\frac{\pi}{3}$ Hz
(B) $\frac{3}{c}$ Hz (D) 3 Hz

7. Which option describes a standing wave?

	Waves	Direction	Medium
(A)	Identical	Same	Same
(B)	Nonidentical	Opposite	Different
(C)	Identical	Opposite	Same
(D)	Nonidentical	Same	Different

8. A 1.2-m wave travels 11.2 m to a wall and back again in 4 s. What is the frequency of the wave?

(A) 0.2 Hz (C) 5 Hz
(B) 2 Hz (D) 9 Hz



9. What is the length of a pendulum that has a period of 4.89 s?

(A) 5.94 m (C) 24.0 m
(B) 11.9 m (D) 37.3 m

Extended Answer

10. Use dimensional analysis of the equation $kx = mg$ to derive the units of k.

✓ Test-Taking TIP

Practice, Practice, Practice

Practice to improve your performance on standardized tests. Don't compare yourself to anyone else.