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.

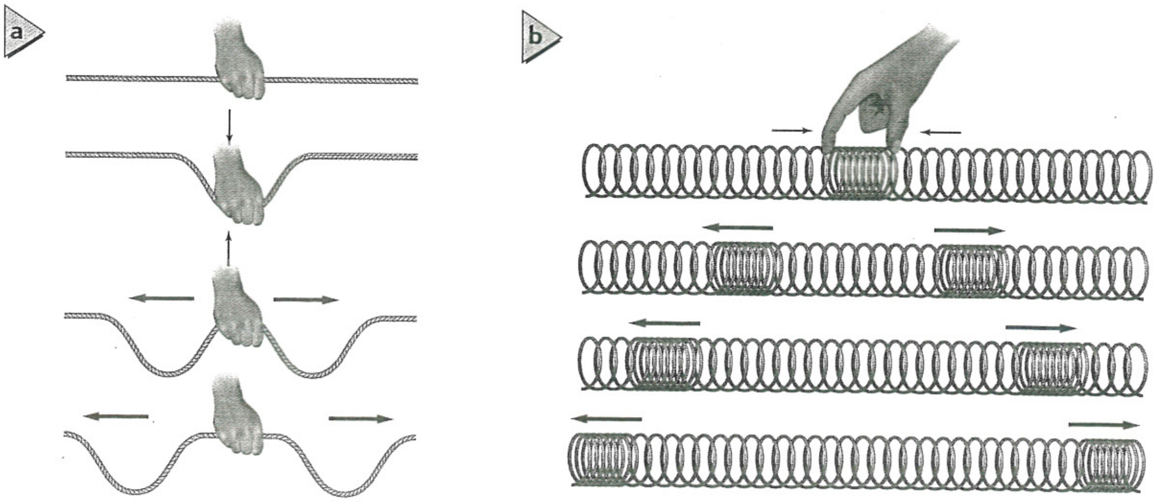
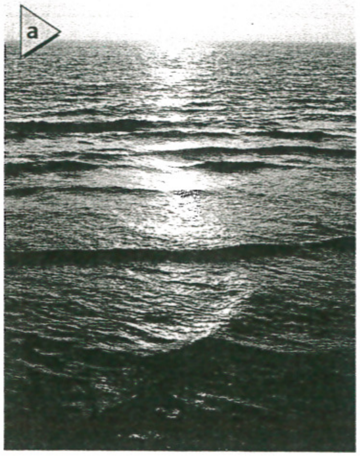


Figure 14-5 A quick shake of a rope sends out transverse wave pulses in both directions **(a).** The squeeze and release of a coiled-spring toy sends out longitudinal wave pulses in both directions **(b).**



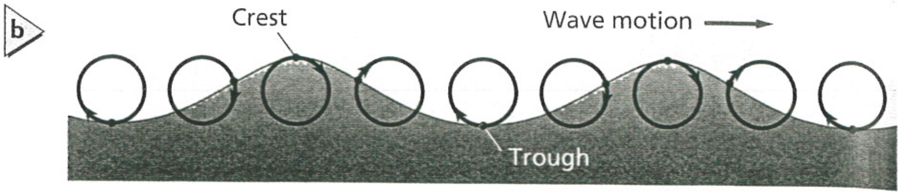


Figure 14-6 Surface waves have properties of both transverse and longitudinal waves **(a).** The paths of the individual particles are circular **(b).**

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.

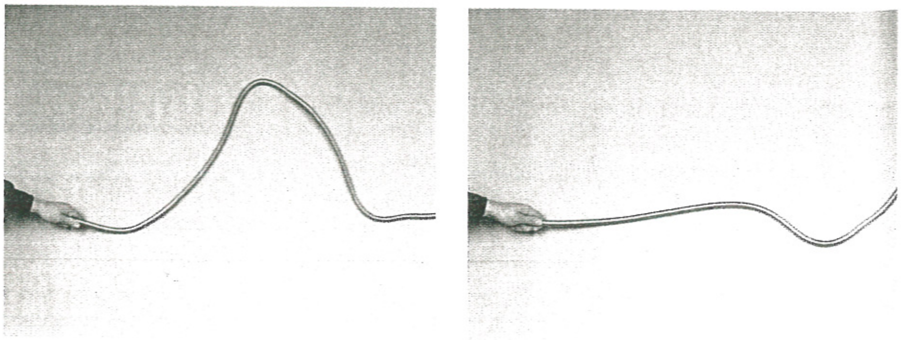


Figure 14-7 These two photographs were taken 0.20 s apart. During that time, the crest moved 0.80 m. The velocity of the wave is 4.0 m/s.

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.

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.

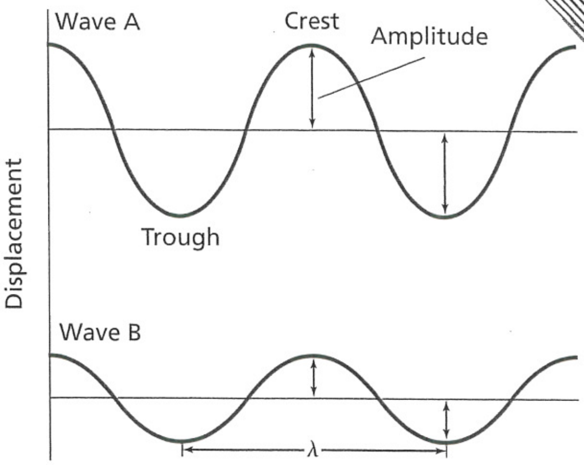


Figure 14-8 The amplitude of wave A is larger than that of wave B.

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.

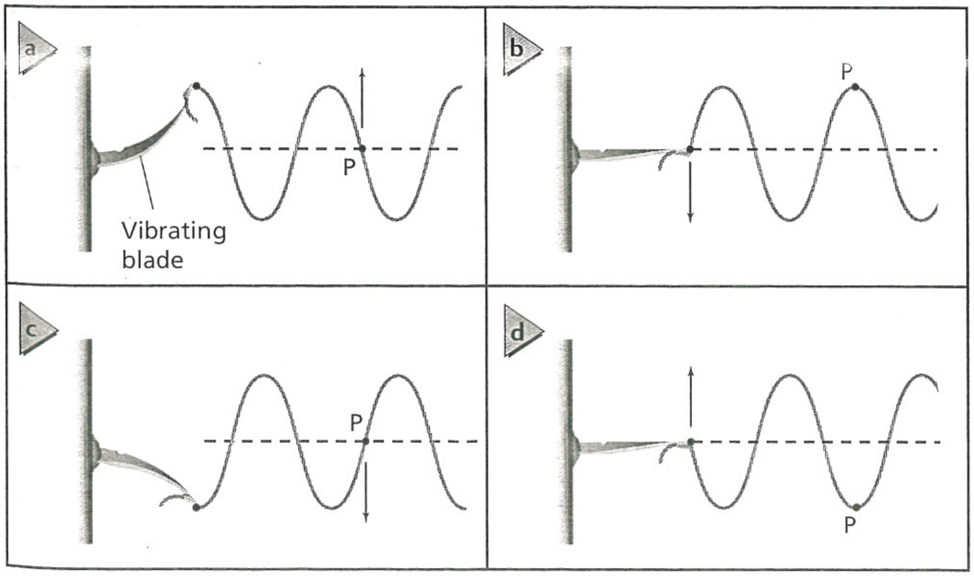


Figure 14-9 One end of a string, with a piece of tape at point P, is attached to a blade vibrating 25 times per second. Note the change in position of point P over time.

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.

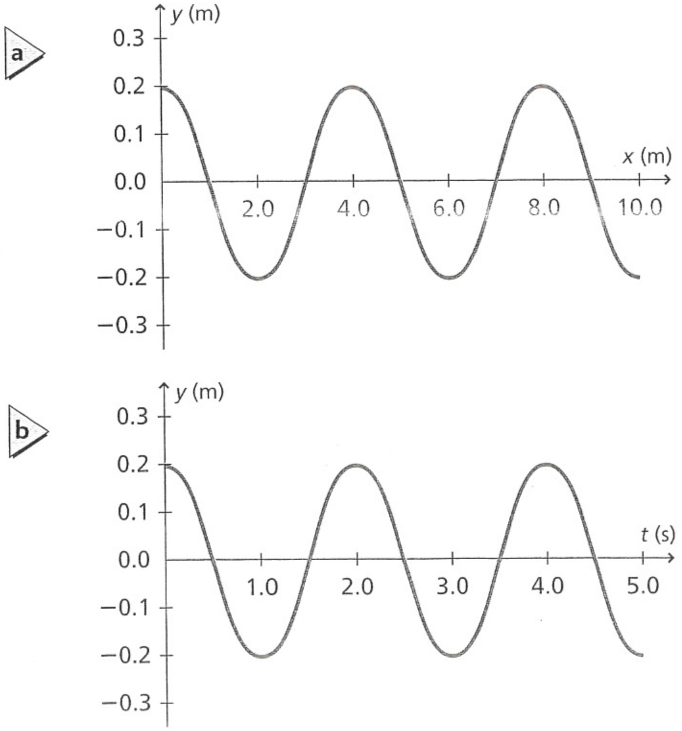


Figure 14-10 Waves can be represented by graphs. The wavelength of this wave is 4.0 m **(a).** The period is 2.0 s **(b).** The amplitude, or displacement, is 0.2 m in both graphs. If these graphs represent the same wave, what is its speed?

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▶ 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?

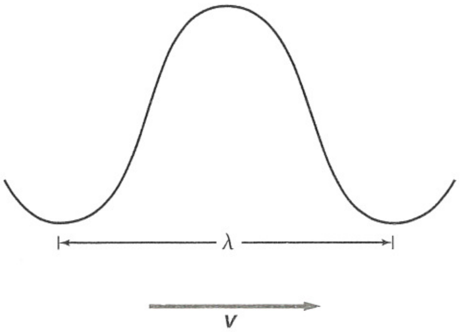
c. What is the period of the wave?

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

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

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b. Solve for λ.

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

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

$$= 1.76\text{ m}$$

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?

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