SECTION 3

Properties of Waves

SECTION OBJECTIVES

- Distinguish local particle vibrations from overall wave motion.
- Differentiate between pulse waves and periodic waves.
- Interpret waveforms of transverse and longitudinal waves.
- Apply the relationship among wave speed, frequency, and wavelength to solve problems.
- Relate energy and amplitude.

WAVE MOTION

Consider what happens to the surface of a pond when you drop a pebble into the water. The disturbance created by the pebble generates water waves that travel away from the disturbance, as seen in **Figure 8.** If you examined the motion of a leaf floating near the disturbance, you would see that the leaf moves up and down and back and forth about its original position. However, the leaf does not undergo any net displacement from the motion of the waves.

The leaf's motion indicates the motion of the particles in the water. The water molecules move locally, like the leaf does, but they do not travel across the pond. That is, the water wave moves from one place to another, but the water itself is not carried with it.

Figure 8
A pebble dropped into a pond creates ripple waves similar to those shown here.

A wave is the motion of a disturbance

Ripple waves in a pond start with a disturbance at some point in the water. This disturbance causes water on the surface near that point to move, which in turn causes points farther away to move. In this way, the waves travel outward in a circular pattern away from the original disturbance.

In this example, the water in the pond is the **medium** through which the disturbance travels. Particles in the medium—in this case, water molecules—move in vertical circles as waves pass. Note that the medium does not actually travel with the waves. After the waves have passed, the water returns to its original position.

medium
a physical environment through which a disturbance can travel

Waves of almost every kind require a material medium in which to travel. Sound waves, for example, cannot travel through outer space, because space is very nearly a vacuum. In order for sound waves to travel, they must have a medium such as air or water. Waves that require a material medium are called **mechanical waves.**

mechanical wave
a wave that requires a medium through which to travel

Not all wave propagation requires a medium. Electromagnetic waves, such as visible light, radio waves, microwaves, and X rays, can travel through a vacuum. You will study electromagnetic waves in later chapters.

WAVE TYPES

One of the simplest ways to demonstrate wave motion is to flip one end of a taut rope whose opposite end is fixed, as shown in **Figure 9.** The flip of your wrist creates a pulse that travels to the fixed end with a definite speed. A wave that consists of a single traveling pulse is called a *pulse wave.*

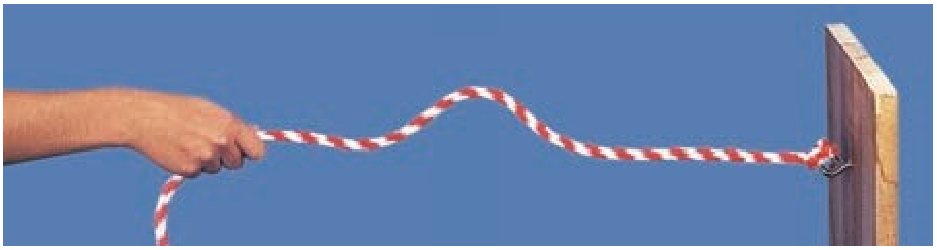

Figure 9
A single flip of the wrist creates a pulse wave on a taut rope.

Now imagine that you continue to generate pulses at one end of the rope. Together, these pulses form what is called a *periodic wave.* Whenever the source of a wave's motion is a periodic motion, such as the motion of your hand moving up and down repeatedly, a periodic wave is produced.

Sine waves describe particles vibrating with simple harmonic motion

Figure 10 depicts a blade that vibrates with simple harmonic motion and thus makes a periodic wave on a string. As the wave travels to the right, any single point on the string vibrates up and down. Because the blade is vibrating with simple harmonic motion, the vibration of each point of the string is also simple harmonic. A wave whose source vibrates with simple harmonic motion is called a *sine wave.* Thus, a sine wave is a special case of a periodic wave in which the periodic motion is simple harmonic. The wave in **Figure 10** is called a sine wave because a graph of the trigonometric function $y = \sin x$ produces this curve when plotted.

A close look at a single point on the string illustrated in **Figure 10** shows that its motion resembles the motion of a mass hanging from a vibrating spring. As the wave travels to the right, the point vibrates around its equilibrium position with simple harmonic motion. This relationship between simple harmonic motion and wave motion enables us to use some of the terms and concepts from simple harmonic motion in our study of wave motion.

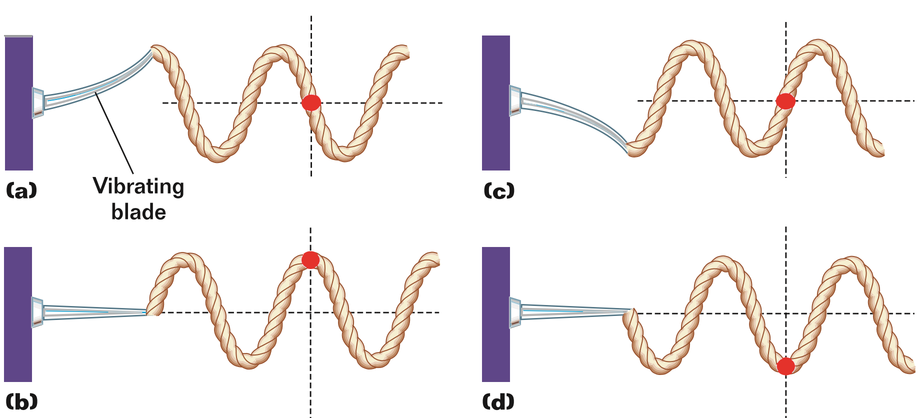

Figure 10
As the sine wave created by this vibrating blade travels to the right, a single point on the string vibrates up and down with simple harmonic motion.

Vibrations of a transverse wave are perpendicular to the wave motion

Figure 11(a) is a representation of the wave shown in **Figure 10** (on the previous page) at a specific instant of time, *t*. This wave travels to the right as the particles of the rope vibrate up and down. Thus, the vibrations are perpendicular to the direction of the wave's motion. A wave such as this, in which the particles of the disturbed medium move perpendicularly to the wave motion, is called a **transverse wave.**

transverse wave

a wave whose particles vibrate perpendicularly to the direction the wave is traveling

The wave shown in **Figure 11(a)** can be represented on a coordinate system, as shown in **Figure 11(b).** A picture of a wave like the one in **Figure 11(b)** is sometimes called a *waveform.* A waveform can represent either the displacements of each point of the wave at a single moment in time or the displacements of a single particle as time passes.

In this case, the waveform depicts the displacements at a single instant. The x-axis represents the equilibrium position of the string, and the y coordinates of the curve represent the displacement of each point of the string at time t. For example, points where the curve crosses the x-axis (where $y = 0$) have zero displacement. Conversely, at the highest and lowest points of the curve, where displacement is greatest, the absolute values of y are greatest.

Wave measures include crest, trough, amplitude, and wavelength

A wave can be measured in terms of its displacement from equilibrium. The highest point above the equilibrium position is called the wave **crest.** The lowest point below the equilibrium position is the **trough** of the wave. As in simple harmonic motion, amplitude is a measure of maximum displacement from equilibrium. The amplitude of a wave is the distance from the equilibrium position to a crest or to a trough, as shown in **Figure 11(b).**

crest

the highest point above the equilibrium position

trough

the lowest point below the equilibrium position

As a wave passes a given point along its path, that point undergoes cyclical motion. The point is displaced first in one direction and then in the other direction. Finally, the point returns to its original equilibrium position, thereby completing one cycle. The distance the wave travels along its path during one cycle is called the **wavelength,** λ (the Greek letter *lambda*). A simple way to find the wavelength is to measure the distance between two adjacent similar points of the wave, such as from crest to crest or from trough to trough. Notice in **Figure 11(b)** that the distances between adjacent crests or troughs in the waveform are equal.

wavelength

the distance between two adjacent similar points of a wave, such as from crest to crest or from trough to trough

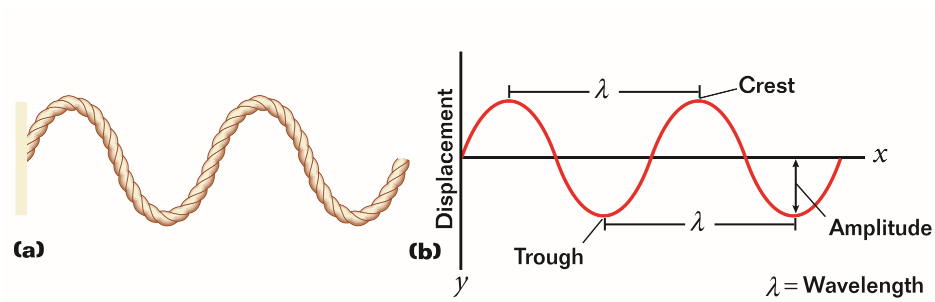

Figure 11
(a) A picture of a transverse wave at some instant t can be turned into **(b)** a graph. The x-axis represents the equilibrium position of the string. The curve shows the displacements of the string at time t.

Vibrations of a longitudinal wave are parallel to the wave motion

You can create another type of wave with a spring. Suppose that one end of the spring is fixed and that the free end is pumped back and forth along the length of the spring, as shown in **Figure 12.** This action produces compressed and stretched regions of the coil that travel along the spring. The displacement of the coils is in the direction of wave motion. In other words, the vibrations are parallel to the motion of the wave.

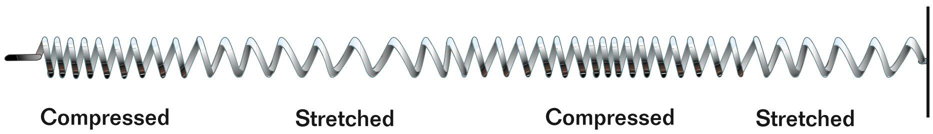

Figure 12
As this wave travels to the right, the coils of the spring are tighter in some regions and looser in others. The displacement of the coils is parallel to the direction of wave motion, so this wave is longitudinal.

When the particles of the medium vibrate parallel to the direction of wave motion, the wave is called a **longitudinal wave.** Sound waves in the air are longitudinal waves because air particles vibrate back and forth in a direction parallel to the direction of wave motion.

longitudinal wave

a wave whose particles vibrate parallel to the direction the wave is traveling

A longitudinal wave can also be described by a sine curve. Consider a longitudinal wave traveling on a spring. **Figure 13(a)** is a snapshot of the longitudinal wave at some instant *t*, and **Figure 13(b)** shows the sine curve representing the wave. The compressed regions correspond to the crests of the waveform, and the stretched regions correspond to troughs.

The type of wave represented by the curve in **Figure 13(b)** is often called a *density wave* or a *pressure wave.* The crests, where the spring coils are compressed, are regions of high density and pressure (relative to the equilibrium density or pressure of the medium). Conversely, the troughs, where the coils are stretched, are regions of low density and pressure.

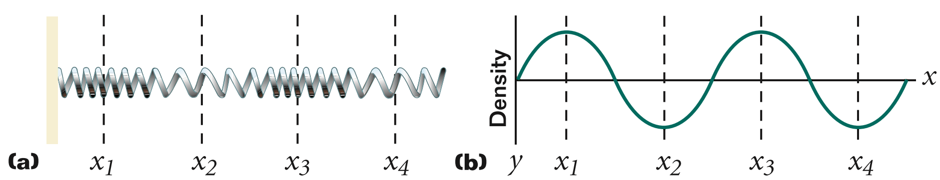

Figure 13
(a) A longitudinal wave at some instant *t* can also be represented by **(b)** a graph. The crests of this waveform correspond to compressed regions, and the troughs correspond to stretched regions.

PERIOD, FREQUENCY, AND WAVE SPEED

Sound waves may begin with the vibrations of your vocal cords, a guitar string, or a taut drumhead. In each of these cases, the source of wave motion is a vibrating object. The vibrating object that causes a sine wave always has a characteristic frequency. Because this motion is transferred to the particles of the medium, the frequency of vibration of the particles is equal to the frequency of the source. When the vibrating particles of the medium complete one full cycle, one complete wavelength passes any given point. Thus, wave frequency describes the number of waves that pass a given point in a unit of time.

The period of a wave is the time required for one complete cycle of vibration of the medium's particles. As the particles of the medium complete one full cycle of vibration at any point of the wave, one wavelength passes by that point. Thus, the period of a wave describes the time it takes for a complete wavelength to pass a given point. The relationship between period and frequency seen earlier in this chapter holds true for waves as well; the period of a wave is inversely related to its frequency.

Did you know?

The frequencies of sound waves that are audible to humans range from 20 Hz to 20 000 Hz. Electromagnetic waves, which include visible light, radio waves, and microwaves, have an even broader range of frequencies—from about 10^4 Hz and lower to 10^{25} Hz and higher.

Wave speed equals frequency times wavelength

We can now derive an expression for the speed of a wave in terms of its period or frequency. We know that speed is equal to displacement divided by the time it takes to undergo that displacement.

$$v = \frac{\Delta x}{\Delta t}$$

For waves, a displacement of one wavelength (λ) occurs in a time interval equal to one period of the vibration (T).

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

As you saw earlier in this chapter, frequency and period are inversely related.

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

Substituting this frequency relationship into the previous equation for speed gives a new equation for the speed of a wave.

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

SPEED OF A WAVE

$$v = f\lambda$$

speed of a wave = frequency × wavelength

The speed of a mechanical wave is constant for any given medium. For example, at a concert, sound waves from different instruments reach your ears at the same moment, even when the frequencies of the sound waves are different. Thus, although the frequencies and wavelengths of the sounds produced by each instrument may be different, the product of the frequency and wavelength is always the same at the same temperature. As a result, when a mechanical wave's frequency is increased, its wavelength must decrease in order for its speed to remain constant. The speed of a wave changes only when the wave moves from one medium to another or when certain properties of the medium (such as temperature) are varied.