15 Traveling Waves and Sound

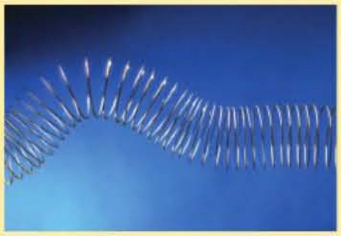
This bat's ears are much more prominent than its eyes. It would appear that hearing is a much more important sense than sight for bats. How does a bat use sound waves to locate prey?

LOOKING AHEAD ▸▸

The goal of Chapter 15 is to learn the basic properties of traveling waves.

The Wave Model

A **wave** is a disturbance traveling through a medium.



The wave propagates, but the particles of the medium don't. Here the coils of a stretched spring simply move up and back down as the wave passes.

Wave Properties

A few basic quantities can describe any type of wave.

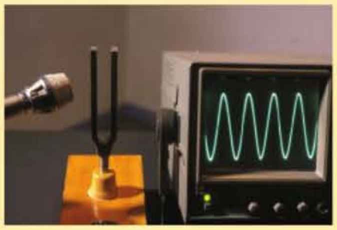
This train of ocean waves is periodic. How fast do the waves move? That's the wave **speed.** What is the distance between successive wave crests? That's the **wavelength.** How many waves strike the beach each minute? That's the **frequency.**

The description of wave motion is closely related to that of simple harmonic motion.

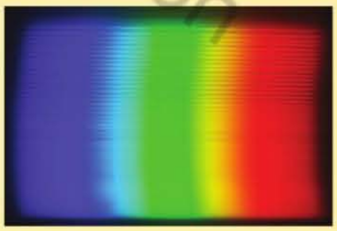
Looking Back ◂◂
Section 14.3 Description of simple harmonic motion

Types of Waves

Our model can describe any type of wave, from ocean waves to vibrating strings, but two types of waves are especially important: **sound** and **light.**



Displaying the sound waves from a tuning fork clearly shows their periodic nature.



Visible light comes in a range of wavelengths corresponding to the colors of the rainbow.

Energy and Intensity

All waves carry energy. How much? That's a question of **intensity.** Your ears are sensitive to sounds over a remarkable range of intensities, so we use the logarithmic **decibel** scale for sound intensity level.

A lens focuses sunlight onto a small area, increasing the intensity.

Doppler Effect

The frequency and wavelength of waves are shifted when there is relative motion between the source and the observer of waves. We call this the **Doppler effect.**

Radar waves shift in frequency when they reflect from a moving vehicle; the higher the speed, the bigger the shift.

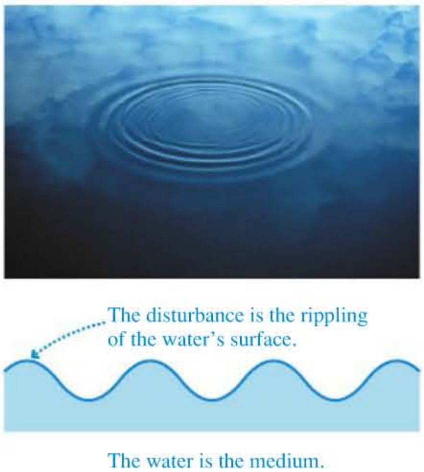
15.1 The Wave Model

The *particle model* that we have been using since Chapter 1 allowed us to simplify the treatment of motion of complex objects by considering them to be particles. Balls, cars, and rockets obviously differ from one another, but the general features of their motions are well described by treating them as particles. As we saw in Chapter 3, a ball or a rock or a car flying through the air will undergo the same motion. The particle model helps us understand this underlying simplicity.

In this chapter we will introduce the basic properties of waves with a **wave model** that emphasizes those aspects of wave behavior common to all waves. Although sound waves, water waves, and radio waves are clearly different, the wave model will allow us to understand many of the important features they share.

The wave model is built around the idea of a **traveling wave,** which is an organized disturbance that travels with a well-defined wave speed. This definition seems straightforward, but several new terms must be understood to gain a complete understanding of the concept of a traveling wave.

FIGURE 15.1 Ripples on a pond are a traveling wave.



Mechanical Waves

Mechanical waves are waves that involve the motion of a substance through which they move, the **medium.** For example, the medium of a water wave is the water, the medium of a sound wave is the air, and the medium of a wave on a stretched string is the string.

As a wave passes through a medium, the atoms that make up the medium are displaced from equilibrium, much like pulling a spring away from its equilibrium position. This is a **disturbance** of the medium. The water ripples of FIGURE 15.1 are a disturbance of the water's surface.

A wave disturbance is created by a *source.* The source of a wave might be a rock thrown into water, your hand plucking a stretched string, or an oscillating loudspeaker cone pushing on the air. Once created, the disturbance travels outward through the medium at the **wave speed** v. This is the speed with which a ripple moves across the water or a pulse travels down a string.

The disturbance propagates through the medium, and a wave does transfer *energy,* but **the medium as a whole does not travel!** The ripples on the pond (the disturbance) move outward from the splash of the rock, but there is no outward flow of water. Likewise, the particles of a string oscillate up and down but do not move in the direction of a pulse traveling along the string. **A wave transfers energy, but it does not transfer any material or substance outward from the source.**

You may have been at a sporting event in which spectators do "The Wave." The wave moves around the stadium, but the spectators (the medium, in this case) stay right where they are. This is a clear example of the principle that a wave does not transfer any material.

Electromagnetic and Matter Waves

Mechanical waves require a medium, but there are waves that do not. Two important types of such waves are electromagnetic waves and matter waves.

Electromagnetic waves are waves of an *electromagnetic field.* Electromagnetic waves are very diverse, including visible light, radio waves, microwaves, and x rays. Electromagnetic waves require no material medium and can travel through a vacuum; light can travel through space, though sound cannot. At this point, we have not defined what an "electromagnetic field" is, so we won't worry about the precise nature of what is "waving" in electromagnetic waves. The wave model can describe many of the important aspects of these waves without a detailed description of their exact nature. We'll look more closely at electromagnetic waves in Chapter 25, once we have a full understanding of electric and magnetic fields.

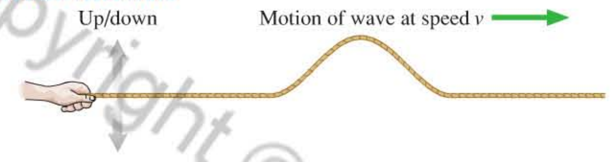
One of the most significant discoveries of the 20th century was that material particles, such as electrons and atoms, have wave-like characteristics. We will learn how a full description of matter at an atomic scale requires an understanding of such **matter waves** in Chapter 28.

Transverse and Longitudinal Waves

Most waves fall into two general classes: *transverse* and *longitudinal.* For mechanical waves, these terms describe the relationship between the motion of the particles that carry the wave and the motion of the wave itself.

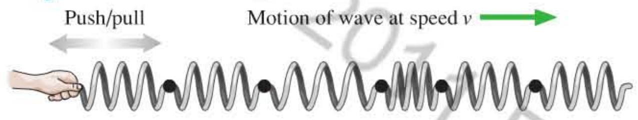
Two types of wave motion

A transverse wave



For mechanical waves, a **transverse wave** is a wave in which the particles in the medium move *perpendicular* to the direction in which the wave travels. Shaking the end of a stretched string up and down creates a wave that travels along the string in a horizontal direction while the particles that make up the string oscillate vertically.

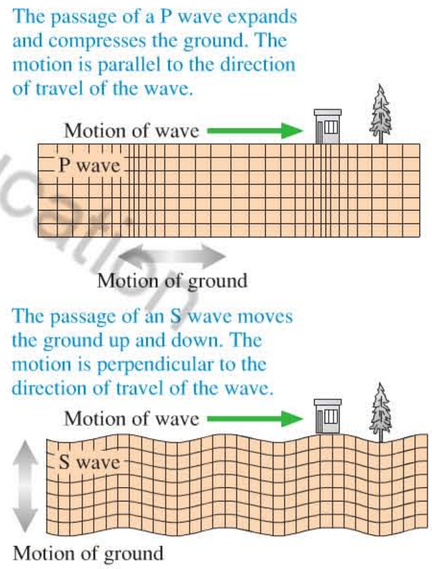
A longitudinal wave



In a **longitudinal wave,** the particles in the medium move *parallel* to the direction in which the wave travels. Here we see a chain of masses connected by springs. If you give the first mass in the chain a sharp push, a disturbance travels down the chain by compressing and expanding the springs.

The rapid motion of the earth's crust during an earthquake can produce a disturbance that travels through the earth. The two most important types of earthquake waves are S waves (which are transverse) and P waves (which are longitudinal), as shown in **FIGURE 15.2**. The longitudinal P waves are faster, but the transverse S waves are more destructive. Residents of a city a few hundred kilometers from an earthquake will feel the resulting P waves as much as a minute before the S waves, giving them a crucial early warning.

FIGURE 15.2 Different types of earthquake waves.



STOP TO THINK 15.1 Spectators at a sporting event do "The Wave," as shown in the photo on the preceding page. Is this a transverse or longitudinal wave?

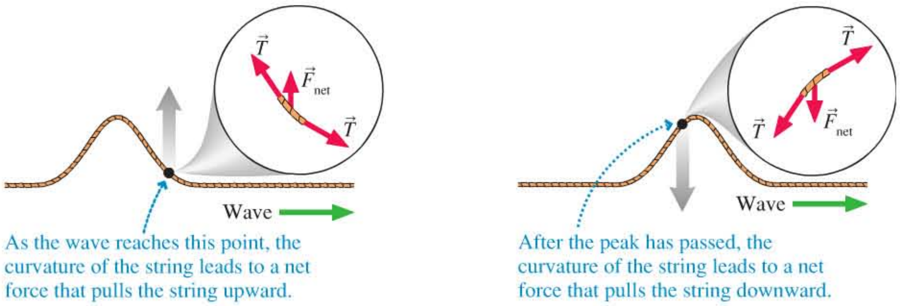
15.2 Traveling Waves

When you drop a pebble in a pond, waves travel outward. But how does this happen? How does a mechanical wave travel through a medium? In answering this question, we must be careful to distinguish the motion of the wave from the motion of the particles that make up the medium. The wave itself is not a particle, so we cannot apply Newton's laws to the wave. However, we can use Newton's laws to examine how the medium responds to a disturbance.

Waves on a String

FIGURE 15.3 shows a transverse *wave pulse* traveling to the right along a stretched string. Imagine watching a little dot on the string as a wave pulse passes by. As the pulse approaches from the left, the string near the dot begins to curve. Once the string

FIGURE 15.3 The motion of a string as a wave passes.

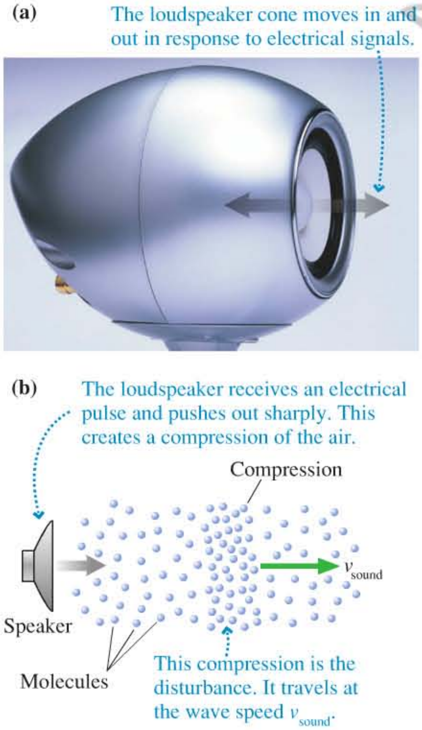


curves, the tension forces pulling on a small segment of string no longer cancel each other. As the wave passes, the curvature of the string leads to a net force that first pulls each little piece of the string up and then, after the pulse passes, back down. Each point on the string moves perpendicular to the motion of the wave, so **a wave on a string is a transverse wave.**

No new physical principles are required to understand how this wave moves. The motion of a pulse along a string is a direct consequence of the tension acting on the segments of the string. An external force may have been required to create the pulse, but **once started, the pulse continues to move because of the internal dynamics of the medium.**

Sound Waves

FIGURE 15.4 A sound wave produced by a loudspeaker.



Next, let's see how a sound wave in air is created using a loudspeaker. When the loudspeaker cone in FIGURE 15.4a moves forward, it compresses the air in front of it, as shown in FIGURE 15.4b. The *compression* is the disturbance that travels forward through the air. This is much like the sharp push on the end of the chain of springs on the preceding page, so **a sound wave is a longitudinal wave.** We usually think of sound waves as traveling in air, but sound can travel through any gas, through liquids, and even through solids. A wave similar to that in Figure 15.4b is produced if you hit the end of a metal rod with a hammer.

The motion of a wave on a string is determined by the internal dynamics of the string. Similarly, the motion of a sound wave in air is determined by the physics of gases that we explored in Chapter 12. Once created, the wave in Figure 15.4b will propagate forward; its motion is entirely determined by the properties of the air.

Wave Speed Is a Property of the Medium

The above discussions of waves on a string and sound waves in air show that the motion of these waves depends on the properties of the medium. A full analysis of these waves would lead to the important and somewhat surprising conclusion that **the wave speed does not depend on the shape or size of the pulse, how the pulse was generated, or how far it has traveled.**

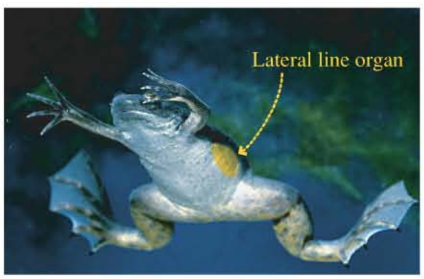
What properties of a string determine the speed of waves traveling along the string? The only likely candidates are the string's mass, length, and tension. Because a pulse doesn't travel faster on a longer and thus more massive string, neither the total mass m nor the total length L is important. Instead, the speed depends on the mass-to-length *ratio,* which is called the **linear density** μ of the string:

$$\mu = \frac{m}{L} \tag{15.1}$$

Linear density characterizes the *type* of string we are using. A fat string has a larger value of μ than a skinny string made of the same material. Similarly, a steel wire has a larger value of μ than a plastic string of the same diameter.

How does the speed of a wave on a string vary with the tension and the linear density? Using what we know about forces and motion, we can make some predictions:

- A string with a greater tension responds more rapidly, so the wave will move at a higher speed. **Wave speed increases with increasing tension.**
- A string with a greater linear density has more inertia. It will respond less rapidly, so the wave will move at a lower speed. **Wave speed decreases with increasing linear density.**



◀ **Sensing water waves** BIO The African clawed frog has a hunting strategy similar to that of many spiders: It sits and waits for prey to come to it. Like a spider, the frog detects prey animals by the vibrations they cause—not in a web, but in the water. The frog has an array of sensors called the lateral line organ on each side of its body. This organ, highlighted in the photo at left, detects oscillations of the water due to passing waves. The frog can determine where the waves come from and what type of animal made them, and thus whether a strike is called for.

A full analysis of the motion of the string leads to an expression for the speed of a wave that shows both of these trends:

$$v_{\text{string}} = \sqrt{\frac{T_s}{\mu}} \tag{15.2}$$

Wave speed on a stretched string with tension T_s and linear density μ

The subscript s on the symbol T_s for the string's tension will distinguish it from the symbol T for the *period* of oscillation.

Every point on a wave pulse travels with the speed given by Equation 15.2. You can increase the wave speed either by *increasing* the string's tension (make it tighter) or by *decreasing* the string's linear density (make it skinnier). We'll examine the implications for stringed musical instruments in Chapter 16. ActivPhysics 10.2

EXAMPLE 15.1 When does the spider sense its lunch?

All spiders are very sensitive to vibrations. An orb spider will sit at the center of its large, circular web and monitor radial threads for vibrations created when an insect lands. Assume that these threads are made of silk with a linear density of 1.0×10^{-5} kg/m under a tension of 0.40 N. If an insect lands in the web 30 cm from the spider, how long will it take for the spider to find out?

PREPARE When the insect hits the web, a wave pulse will be transmitted along the silk fibers. The speed of the wave depends on the properties of the silk.

SOLVE First, we determine the speed of the wave:

$$v = \sqrt{\frac{T_s}{\mu}} = \sqrt{\frac{0.40\ \text{N}}{1.0 \times 10^{-5}\ \text{kg/m}}} = 200\ \text{m/s}$$

The time for the wave to travel a distance $d = 30$ cm to reach the spider is

$$\Delta t = \frac{d}{v} = \frac{0.30\ \text{m}}{200\ \text{m/s}} = 1.5\ \text{ms}$$

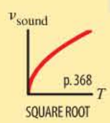
ASSESS Spider webs are made of very light strings under significant tension, so the wave speed is quite high and we expect a short travel time—important for the spider to quickly respond to prey caught in the web. Our answer makes sense.

What properties of a gas determine the speed of a sound wave traveling through the gas? It seems plausible that the speed of a sound pulse is related to the speed with which the molecules of the gas move—faster molecules should mean a faster sound wave. In Chapter 12, we found that the typical speed of an atom of mass m, the root-mean-square speed, is

$$v_{\text{rms}} = \sqrt{\frac{3k_B T}{m}}$$

where k_B is Boltzmann's constant and T the absolute temperature in kelvin. A thorough analysis finds that the sound speed is slightly less than this rms speed, but has the same dependence on the temperature and the molecular mass:

$$v_{\text{sound}} = \sqrt{\frac{\gamma k_B T}{m}} = \sqrt{\frac{\gamma R T}{M}} \tag{15.3}$$



Sound speed in a gas at temperature T

In Equation 15.3 M is the molar mass (kg per mol) and γ is a constant that depends on the gas: $\gamma = 1.67$ for monatomic gases such as helium, $\gamma = 1.40$ for diatomic ActivPhysics 10.3

TABLE 15.1 The speed of sound

Medium	Speed (m/s)
Air (0°C)	331
Air (20°C)	343
Helium (0°C)	970
Ethyl alcohol	1170
Water	1480
Human tissue (ultrasound)	1540
Lead	1200
Aluminum	5100
Granite	6000
Diamond	12,000

gases such as nitrogen and oxygen, and $\gamma \approx 1.3$ for a triatomic gas such as carbon dioxide or water vapor.

Certain trends in Equation 15.3 are worth mentioning:

- The speed of sound in air (and other gases) increases with temperature. **For calculations in this chapter, you can use the speed of sound in air at 20°C, 343 m/s, unless otherwise specified.**
- At a given temperature, the speed of sound increases as the molecular mass of the gas decreases. Thus the speed of sound in room-temperature helium is faster than that in room-temperature air.
- The speed of sound doesn't depend on the pressure or the density of the gas.

Table 15.1 lists the speeds of sound in various materials. The bonds between atoms in liquids and solids result in higher sound speeds in these phases of matter. Generally, sound waves travel faster in liquids than in gases, and faster in solids than in liquids. The speed of sound in a solid depends on its density and stiffness. Light, stiff solids (such as diamond) transmit sound at very high speeds. The sound speed is much lower in dense, soft solids such as lead.

EXAMPLE 15.2 The speed of sound on Mars

On a typical Martian morning, the very thin atmosphere (which is almost entirely carbon dioxide) is a frosty −100°C. What is the speed of sound? At what approximate temperature would the speed be double this value?

PREPARE Equation 15.3 gives the speed of sound in terms of the molar mass and the absolute temperature. If we assume that the atmosphere is composed of pure CO_2, the molar mass is the sum of the molar masses of the constituents: 12 g/mol for C and 16 g/mol for each O, giving $M = 12 + 16 + 16 = 44\text{ g/mol} = 0.044\text{ kg/mol}$. The absolute temperature is $T = 173\text{ K}$. Carbon dioxide is a triatomic gas, so $\gamma = 1.3$.

SOLVE The speed of sound with the noted conditions is

$$v_{\text{sound}} = \sqrt{\frac{\gamma RT}{M}} = \sqrt{\frac{(1.3)(8.31\text{ J/mol})(173\text{ K})}{0.044\text{ kg/mol}}} = 210\text{ m/s}$$

Rather than do a separate calculation to determine the temperature required for the higher speed, we can make an argument using proportionality. The speed is proportional to the square root of the temperature, so doubling the speed requires an increase in the temperature by a factor of 4 to about 690 K, or about 420°C.

ASSESS The speed of sound doesn't depend on pressure, so even though the atmosphere is "thin" we needn't adjust our calculation. The speed of sound is lower for heavier molecules and colder temperatures, so we expect that the speed of sound on Mars, with its cold, carbon-dioxide atmosphere, will be lower than that on earth, just as we found.

Electromagnetic waves, such as light, travel at a much higher speed than do mechanical waves. As we'll discuss in Chapter 25, all electromagnetic waves travel at the same speed in a vacuum. We call this speed the **speed of light,** which we represent with the symbol c. The value of the speed of light in a vacuum is

$$v_{\text{light}} = c = 3.00 \times 10^8\text{ m/s} \tag{15.4}$$

This is almost one million times the speed of sound in air! At this speed, light could circle the earth 7.5 times in one second.

NOTE ► The speed of electromagnetic waves is lower when they travel through a material, but this value for the speed of light in a vacuum is also good for electromagnetic waves traveling through air. ◄

EXAMPLE 15.3 How far away was the lightning?

During a thunderstorm, you see a flash from a lightning strike. 8.0 seconds later, you hear the crack of the thunder. How far away did the lightning strike?

PREPARE Two different kinds of waves are involved, with very different wave speeds. The flash of the lightning generates light waves; these will travel from the point of the strike to your position essentially instantaneously. (It takes light about 5 μs to travel

1 mile—not something you will notice.) The strike also generates sound waves that you hear as thunder; these travel much more slowly. The delay between the flash and the thunder is the time it takes for the sound wave to travel.

SOLVE We will assume that the speed of sound has its room temperature (20°C) value of 343 m/s. During the time between seeing the flash and hearing the thunder, the sound travels a distance

$$d = v\,\Delta t = (343\ \text{m/s})(8.0\ \text{s}) = 2.7 \times 10^3\ \text{m} = 2.7\ \text{km}$$

ASSESS This seems reasonable. As you know from casual observations of lightning storms, an 8-second delay between the flash of the lightning and the crack of the thunder means a strike that is close but not too close. A few km seems reasonable.

TRY IT YOURSELF

Distance to a lightning strike Sound travels approximately 1 km in 3 s, or 1 mi in 5s. When you see a lightning flash, start counting seconds. When you hear the thunder, stop counting. Divide the result by 3, and you will have the approximate distance to the lightning strike in kilometers; divide by 5 and you will have the approximate distance in miles.

STOP TO THINK 15.2 Suppose you shake the end of a stretched string to produce a wave. Which of the following actions would increase the speed of the wave down the string? There may be more than one correct answer; if so, give all that are correct.

A. Move your hand up and down more quickly as you generate the wave.
B. Move your hand up and down a greater distance as you generate the wave.
C. Use a heavier string of the same length, under the same tension.
D. Use a lighter string of the same length, under the same tension.
E. Stretch the string tighter to increase the tension.
F. Loosen the string to decrease the tension.

15.3 Graphical and Mathematical Descriptions of Waves

Now that we know a bit about waves and how they travel, it's time to develop our understanding further by describing waves with graphs and equations.

Describing waves and their motion takes a bit more thought than describing particles and their motion. Until now, we have been concerned with quantities, such as position and velocity, that depend only on time. We can write these, as we did in Chapter 14, as $x(t)$ or $v(t)$, indicating that x and v are *functions* of the time variable t. Functions of the single variable t are all right for a particle, because a particle is in only one place at a time, but a wave is not localized. It is spread out through space at each instant of time. We need a function that tells us what a wave is doing at an instant of time (when) at a particular point in space (where). We need a function that depends on *both* position and time.

NOTE ► The analysis that follows is for a wave on a string, which is easy to visualize, but the results apply to any traveling wave. ◄

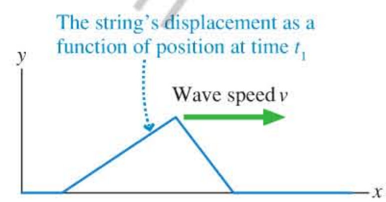


FIGURE 15.5 A snapshot graph of a wave pulse on a string.

Snapshot and History Graphs

When we considered the motion of particles, we developed a graphical description before the mathematical description. We'll follow a similar approach for waves. Consider the wave pulse shown moving along a stretched string in **FIGURE 15.5**. (We will consider somewhat artificial triangular and square-shaped wave pulses in this section to clearly show the edges of the pulse.) The graph shows the string's displacement y at a particular instant of time t_1 as a function of position x along the string. This is a "snapshot" of the wave, much like what you might make with a camera whose shutter is opened briefly at t_1. A graph that shows the wave's displacement as a function of position at a single instant of time is called a **snapshot graph**. For a wave on a string, a snapshot graph is literally a picture of the wave at this instant.

As the wave moves, we can take more snapshots. **FIGURE 15.6** shows a sequence of snapshot graphs as the wave of Figure 15.5 continues to move. These are like successive

FIGURE 15.6 A sequence of snapshot graphs shows the wave in motion.

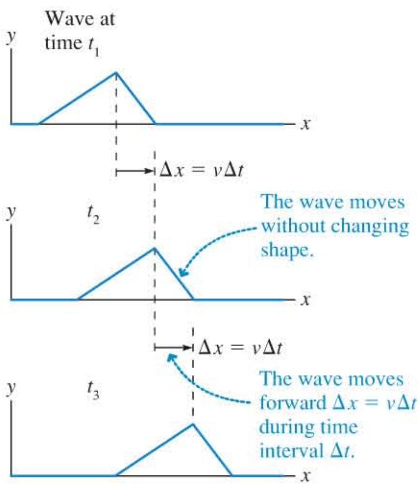
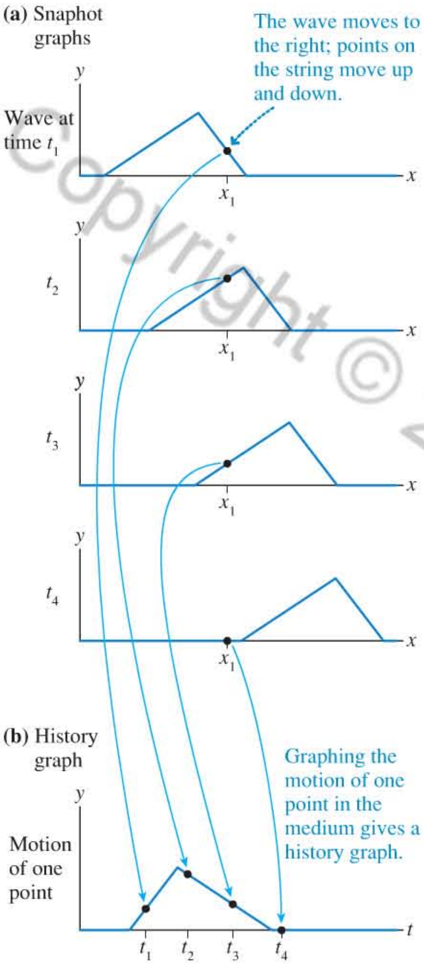


FIGURE 15.7 Constructing a history graph.



frames from a video, reminiscent of the sequences of pictures we saw in Chapter 1. The wave pulse moves forward a distance $\Delta x = v\,\Delta t$ during each time interval Δt; that is, the wave moves with constant speed.

A snapshot graph shows the motion of the *wave,* but that's only half the story. Now we want to consider the motion of the *medium*. For the wave of Figure 15.5 we can construct a different type of graph, as shown in FIGURE 15.7. Figure 15.7a shows four snapshot graphs of the wave as it travels. In each of the graphs we've placed a dot at a particular point on the string carrying the wave. As the wave travels horizontally, the dot moves vertically; this is a transverse wave. We can use information from these graphs to construct the graph in Figure 15.7b, which shows the motion of this one point on the string. We call this a **history graph** because it shows the history—the time evolution—of this particular point in the medium.

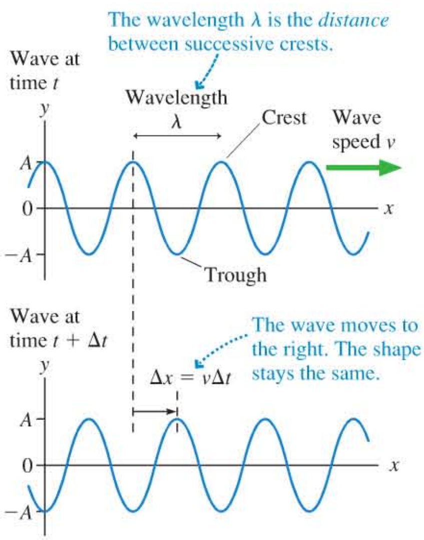
Take a close look at the history graph. The snapshot graphs show the steeper edge of the wave on the right; the history graph has the steeper edge on the left. Careful thought tells why. The history graph isn't a picture of the wave—it's a record of the motion of one point in the medium. As the wave moves toward the dot, the steep leading edge of the wave causes the dot to rise quickly. On the displacement-versus-time history graph, *earlier* times (smaller values of t) are to the *left* and *later* times (larger t) to the *right*. The rapid rise when the wave hits the dot is at an early time, and so appears on the left side of the Figure 15.7b history graph.

Sinusoidal Waves

Waves can come in many different shapes, but for the mathematical description of wave motion we will focus on a particular shape, the **sinusoidal wave.** This is the type of wave produced by a source that oscillates with simple harmonic motion. For example, a loudspeaker cone that oscillates in SHM radiates a sinusoidal sound wave. The sinusoidal electromagnetic waves broadcast by television and FM radio stations are generated by electrons oscillating back and forth in the antenna wire with SHM.

The pair of snapshot graphs in FIGURE 15.8 show two successive views of a string carrying a sinusoidal wave, revealing the motion of the wave as it moves to the right. We define the **amplitude** A of the wave to be the maximum value of the displacement. The crests of the wave—the high points—have displacement $y_{crest} = A$, and the troughs—the low points—have displacement $y_{trough} = -A$. Because the wave is produced by a source undergoing SHM, which is periodic, the wave is periodic as well. As you move from left to right along the "frozen" wave in the top snapshot graph of Figure 15.8, the disturbance repeats itself over and over. The distance spanned by one cycle of the motion is called the **wavelength** of the wave. Wavelength is symbolized by λ (lowercase Greek lambda) and, because it is a length, it is measured in units of meters. The wavelength is shown in Figure 15.8 as the distance between two crests, but it could equally well be the distance between two troughs. As time passes, the wave moves to the right; comparing the two snapshot graphs in Figure 15.8 makes this motion apparent.

FIGURE 15.8 Snapshot graphs show the motion of a sinusoidal wave.



The snapshot graphs of Figure 15.8 show that the wave, at one instant in time, is a sinusoidal function of the distance x along the wave, with wavelength λ. At the time represented by the top graph of Figure 15.8, the displacement is given by

$$y(x) = A\cos\left(2\pi\frac{x}{\lambda}\right) \tag{15.5}$$

Next, let's look at the motion of a point in the medium as this wave passes. FIGURE 15.9 shows a history graph for a point in a string as the sinusoidal wave of Figure 15.8 passes by. This graph has exactly the same shape as the snapshot graphs of Figure 15.8—it's a sinusoidal function—but the meaning of the graph is different; it shows the motion of one point in the medium. This graph is identical to the graphs you worked with in Chapter 14 because **each point in the medium oscillates with simple harmonic motion as the wave passes.** The *period* T of the wave, shown on the graph, is the time interval to complete one cycle of the motion.

NOTE ► Wavelength is the spatial analog of period. The period T is the *time* in which the disturbance at a single point in space repeats itself. The wavelength λ is the *distance* in which the disturbance at one instant of time repeats itself. ◄

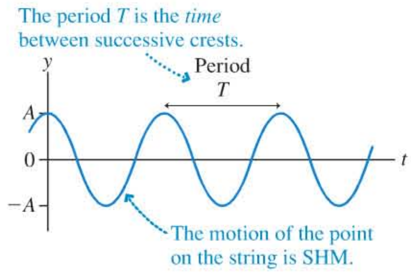


FIGURE 15.9 A history graph shows the motion of a point on a string carrying a sinusoidal wave.

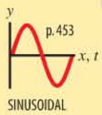
The period is related to the wave *frequency* by $T = 1/f$, exactly as in SHM. Because each point on the string oscillates up and down in SHM with period T, we can describe the motion of a point on the string with the familiar expression

$$y(t) = A\cos\left(2\pi\frac{t}{T}\right) \tag{15.6}$$

NOTE ► As in Chapter 14, the argument of the cosine function is in radians. Make sure that your calculator is in radian mode before starting a calculation with the trigonometric equations in this chapter. ◄

Equation 15.5 gives the displacement as a function of position at one instant in time, and Equation 15.6 gives the displacement as a function of time at one point in space. How can we combine these two to form a single expression that is a complete description of the wave? As we'll verify, a wave traveling to the right is described by the equation

$$y(x, t) = A\cos\left(2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right) \tag{15.7}$$



Displacement of a traveling wave moving to the right with amplitude A, wavelength λ, and period T

The notation $y(x, t)$ indicates that the displacement y is a function of the *two* variables x and t. We must specify both where (x) and when (t) before we can calculate the displacement of the wave.

We can understand why this expression describes a wave traveling to the right by looking at **FIGURE 15.10**. In the figure, we have graphed Equation 15.7 at five instants of time, each separated by one-quarter of the period T, to make five snapshot graphs. The crest marked with the arrow represents one point on the wave. As the time t increases, so does the position x of this point—the wave moves to the right. One full period has elapsed between the first graph and the last. During this time, the wave has moved by one wavelength. And, as the wave has passed, each point in the medium has undergone one complete oscillation.

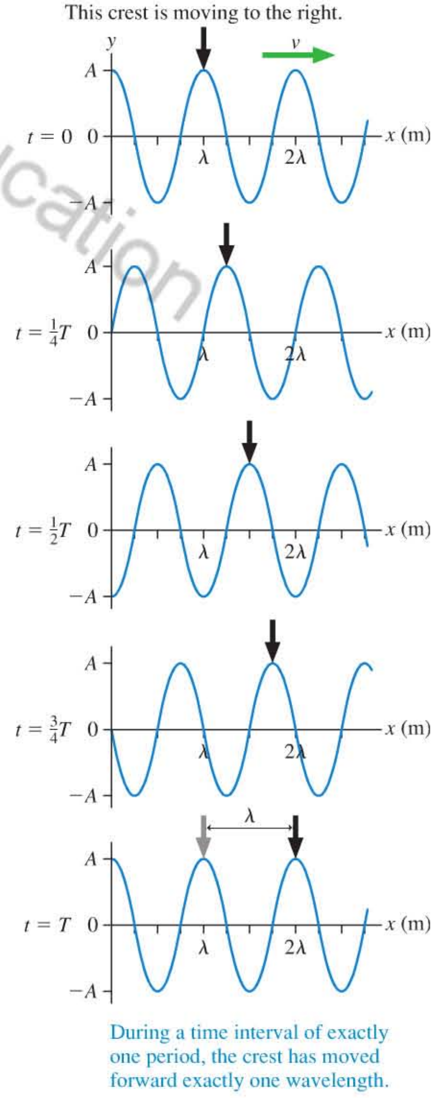
For a wave traveling to the left, we have a slightly different form:

$$y(x, t) = A\cos\left(2\pi\left(\frac{x}{\lambda} + \frac{t}{T}\right)\right) \tag{15.8}$$

Displacement of a traveling wave moving to the left

NOTE ► A wave moving to the right (the $+x$-direction) has a $-$ in the expression, while a wave moving to the left (the $-x$-direction) has a $+$. Remember that the sign is *opposite* the direction of travel. ◄

FIGURE 15.10 Equation 15.7 graphed at intervals of one-quarter of the period. This is a traveling wave moving to the right.

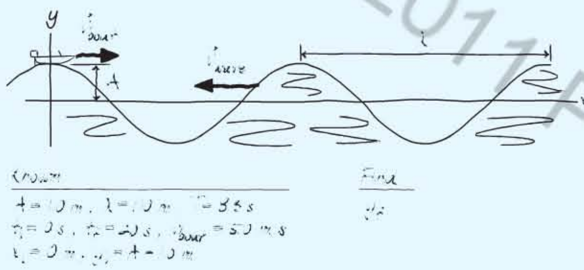


EXAMPLE 15.4 **Determining the rise and fall of a boat**

A boat is moving to the right at 5.0 m/s with respect to the water. An ocean wave is moving to the left, opposite the motion of the boat. The waves have 2.0 m between the top of the crests and the bottom of the troughs. The period of the waves is 8.3 s, and their wavelength is 110 m. At one instant, the boat sits on a crest of the wave. 20 s later, what is the vertical displacement of the boat?

PREPARE We begin with the visual overview, as in **FIGURE 15.11**. Let $t = 0$ be the instant the boat is on the crest, and draw a snapshot graph of the traveling wave at that time. Because the wave is traveling to the left, we will use Equation 15.8 to represent the wave. The boat begins at a crest of the wave, so we see that the boat can start the problem at $x = 0$.

FIGURE 15.11 Visual overview for the boat.



The distance between the high and low points of the wave is 2.0 m; the amplitude is half this, so $A = 1.0$ m. The wavelength and period are given in the problem.

SOLVE The boat is moving to the right at 5.0 m/s. At $t_f = 20$ s the boat is at position

$$x_f = (5.0 \text{ m/s})(20 \text{ s}) = 100 \text{ m}$$

We need to find the wave's displacement at this position and time. Substituting known values for amplitude, wavelength, and period into Equation 15.8, for a wave traveling to the left, we obtain the following equation for the wave:

$$y(x, t) = (1.0 \text{ m})\cos\left(2\pi\left(\frac{x}{110 \text{ m}} + \frac{t}{8.3 \text{ s}}\right)\right)$$

At $t_f = 20$ s and $x_f = 100$ m, the boat's displacement on the wave is

$$y_f = y(\text{at } 100 \text{ m}, 20 \text{ s}) = (1.0 \text{ m})\cos\left(2\pi\left(\frac{100 \text{ m}}{110 \text{ m}} + \frac{20 \text{ s}}{8.3 \text{ s}}\right)\right)$$

$$= -0.42 \text{ m}$$

ASSESS The final displacement is negative—meaning the boat is in a trough of a wave, not underwater. Don't forget that your calculator must be in radian mode when you make your final computation!

The Fundamental Relationship for Sinusoidal Waves

10.1 ActivPhysics ONLINE

In Figure 15.10, one critical observation is that the wave crest marked by the arrow has moved one full wavelength between the first graph and the last. That is, **during a time interval of exactly one period T, each crest of a sinusoidal wave travels forward a distance of exactly one wavelength λ.** Because speed is distance divided by time, the wave speed must be

$$v = \frac{\text{distance}}{\text{time}} = \frac{\lambda}{T} \tag{15.9}$$

Using $f = 1/T$, it is customary to write Equation 15.9 in the form

$$v = \lambda f \tag{15.10}$$

Relationship between velocity, wavelength, and frequency for sinusoidal waves

Although Equation 15.10 has no special name, it is *the* fundamental relationship for sinusoidal waves. When using it, keep in mind the *physical* meaning that a wave moves forward a distance of one wavelength during a time interval of one period.

We will frequently see problems in which we are given two of the variables in Equation 15.10 but we need to find the third, as in the following example.

EXAMPLE 15.5 **Writing the equation for a wave**

A sinusoidal wave with an amplitude of 1.5 cm and a frequency of 100 Hz travels at 200 m/s in the positive x-direction. Write the equation for the wave's displacement as it travels.

PREPARE The problem statement gives the following characteristics of the wave: $A = 1.5 \text{ cm} = 0.015$ m, $v = 200$ m/s, and $f = 100$ Hz.

SOLVE To write the equation for the wave, we need the amplitude, the wavelength, and the period. The amplitude was given in the problem statement. We can use the fundamental relationship for sinusoidal waves to find the wavelength:

$$\lambda = \frac{v}{f} = \frac{200 \text{ m/s}}{100 \text{ Hz}} = 2.0 \text{ m}$$

The period can be calculated from the frequency:

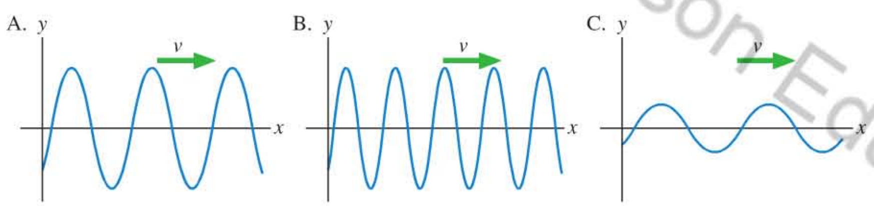
$$T = \frac{1}{f} = \frac{1}{100 \text{ Hz}} = 0.010 \text{ s}$$

With these values in hand, we can write the equation for the wave's displacement using Equation 15.7:

$$y(x, t) = (0.015 \text{ m})\cos\left(2\pi\left(\frac{x}{2.0 \text{ m}} - \frac{t}{0.010 \text{ s}}\right)\right)$$

ASSESS If the speed of a wave is known, you can use the fundamental relationship for sinusoidal waves to find the wavelength if you are given the frequency, or the frequency if you are given the wavelength. You'll often need to do this in the early stages of problems that you solve.

STOP TO THINK 15.3 Three waves travel to the right with the same speed. Which wave has the highest frequency?



15.4 Sound and Light Waves

Think about how you are experiencing the world right now. Chances are, your senses of sight and sound are hard at work, detecting and interpreting light and sound waves from the world around you. Because these waves are so important to us, we'll spend some time exploring their properties.

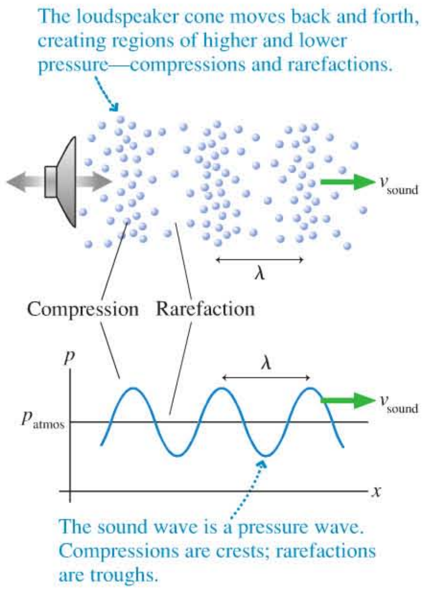
Sound Waves

We saw in Figure 15.4 how a loudspeaker creates a sound wave. If the loudspeaker cone moves with simple harmonic motion, it will create a sinusoidal sound wave, as illustrated in **FIGURE 15.12**. Each time the cone moves forward, it moves the air molecules closer together, creating a region of higher pressure. A half cycle later, as the cone moves backward, the air has room to expand and the pressure decreases. These regions of higher and lower pressure are called **compressions** and **rarefactions,** respectively.

As Figure 15.12 suggests, it is often most convenient and informative to think of a sound wave as a pressure wave. As the graph of the pressure shows, the pressure oscillates sinusoidally around the atmospheric pressure p_{atmos}. This is a snapshot graph of the wave at one instant of time, and the distance between two adjacent crests (two points of maximum compression) is the wavelength λ.

When the wave reaches your ear, the oscillating pressure causes your eardrums to vibrate. This vibration is transferred through your inner ear to the cochlea, where it is sensed, as we learned in Chapter 14. Humans with normal hearing are able to detect sinusoidal sound waves with frequencies between about 20 Hz and 20,000 Hz, or 20 kHz. Low frequencies are perceived as a "low pitch" bass note, while high frequencies are heard as a "high pitch" treble note.

FIGURE 15.12 A sound wave is a pressure wave.



EXAMPLE 15.6 Range of wavelengths of sound

What are the wavelengths of sound waves at the limits of human hearing and at the midrange frequency of 500 Hz? Notes sung by human voices are near 500 Hz, as are notes played by striking keys near the center of a piano keyboard.

PREPARE We will do our calculation at room temperature, 20°C, so we will use $v = 343$ m/s for the speed of sound.

SOLVE We can solve for the wavelengths given the fundamental relationship $v = f\lambda$:

$$f = 20\text{ Hz:}\qquad \lambda = \frac{v}{f} = \frac{343\text{ m/s}}{20\text{ Hz}} = 17\text{ m}$$

$$f = 500\text{ Hz:}\qquad \lambda = \frac{v}{f} = \frac{343\text{ m/s}}{500\text{ Hz}} = 0.69\text{ m}$$

$$f = 20\text{ kHz:}\qquad \lambda = \frac{v}{f} = \frac{343\text{ m/s}}{20\times 10^3\text{ Hz}} = 0.017\text{ m} = 1.7\text{ cm}$$

ASSESS The wavelength of a 20 kHz note is a small 1.7 cm. At the other extreme, a 20 Hz note has a huge wavelength of 17 m! A wave moves forward one wavelength during a time interval of one period, and a wave traveling at 343 m/s can move 17 m during the $\frac{1}{20}$ s period of a 20 Hz note.

TABLE 15.2 Range of hearing for animals

Animal	Range of hearing (Hz)
Elephant	<5–12,000
Owl	200–12,000
Human	20–20,000
Dog	30–45,000
Mouse	1000–90,000
Bat	2000–100,000
Porpoise	75–150,000

Short wavelengths mean sharper images Light doesn't travel very far in any but the clearest water. To navigate through and investigate their surroundings, vessels at sea can create images using sound instead of light, sending out sound waves and detecting and analyzing the reflections. This image of a shipwreck on the ocean bottom was made from the surface with 600 kHz ultrasound. This high frequency gave a very short wavelength of just under a quarter of a centimeter, making for very sharp outlines and fine details in the image.

It is well known that dogs are sensitive to high frequencies that humans cannot hear. Other animals also have quite different ranges of hearing than humans; some examples are listed in Table 15.2.

Elephants communicate over great distances with vocalizations at frequencies far too low for us to hear. These low-frequency sounds are transmitted with less energy loss than high-frequency sounds, allowing elephants to hear each other from over 6 km away—important for these social animals that may forage over very large areas.

There are animals that use frequencies well above the range of our hearing as well. High-frequency sounds are useful for *echolocation*—emitting a pulse of sound and listening for its reflection. Bats, which generally feed at night, rely much more on their hearing than their sight. They find and catch insects by echolocation, emitting loud chirps whose reflections are detected by their large, sensitive ears. The frequencies that they use are well above the range of our hearing; we call such sound **ultrasound.** Why do bats and other animals use high frequencies for this purpose?

In Chapter 19, we will look at the *resolution* of optical instruments. The finest detail that your eye—or any optical instrument—can detect is limited by the wavelength of light. Shorter wavelengths allow for the imaging of smaller details.

The same limitations apply to the acoustic image of the world made by bats. In order to sense fine details of their surroundings, bats must use sound of very short wavelength (and thus high frequency). A 50 kHz chirp from a little brown bat has a wavelength of just over half a centimeter, allowing the bat to precisely locate an insect that reflects it. Other animals that use echolocation, such as porpoises, also produce and sense high-frequency sounds.

Sound travels very well though tissues in the body, and the reflections of sound waves from different tissues can be used to create an image of the body's interior. The fine details necessary for a clinical diagnosis require the short wavelengths of ultrasound. X rays create very good images of bones; ultrasound is used for creating images of soft tissues. It is also useful in cases where the radiation exposure of x rays should be avoided. You have certainly seen ultrasound images taken during pregnancy, where the use of x rays is clearly undesirable.

EXAMPLE 15.7 Ultrasonic frequencies in medicine

To make a sufficiently detailed ultrasound image of a fetus in its mother's uterus, a physician has decided that a wavelength of 0.50 mm is needed. What frequency is required?

Computer processing of an ultrasound image shows fine detail.

PREPARE The speed of ultrasound in the body is given in Table 15.1 as 1540 m/s.

SOLVE We can use the fundamental relationship among speed, wavelength, and frequency to calculate

$$f = \frac{v}{\lambda} = \frac{1540\text{ m/s}}{0.50 \times 10^{-3}\text{ m}} = 3.1 \times 10^{6}\text{ Hz} = 3.1\text{ MHz}$$

ASSESS This is a reasonable result. Clinical ultrasound uses frequencies in the range of 1–20 MHz. Lower frequencies have greater penetration; higher frequencies (and thus shorter wavelengths) show finer detail.

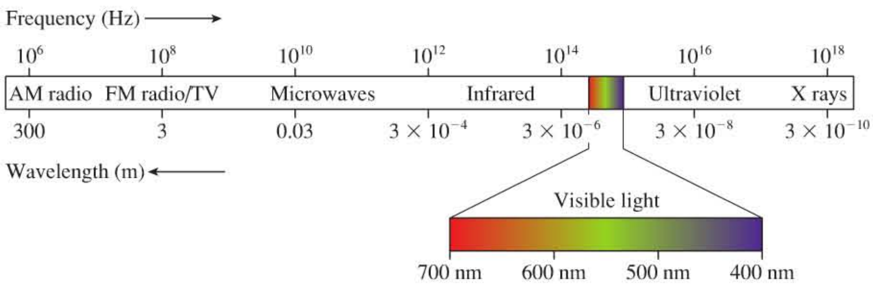
Light and Other Electromagnetic Waves

A light wave is an electromagnetic wave, an oscillation of the electromagnetic field. Other electromagnetic waves, such as radio waves, microwaves, and ultraviolet light, have the same physical characteristics as light waves even though we cannot sense them with our eyes. As we saw earlier, all electromagnetic waves, regardless of wavelength or frequency, travel through vacuum (or air) with the same speed: $c = 3.00 \times 10^8$ m/s.

The wavelengths of light are extremely short. Visible light is an electromagnetic wave with a wavelength (in air) of roughly 400 nm ($=400 \times 10^{-9}$ m) to 700 nm ($=700 \times 10^{-9}$ m). Each wavelength is perceived as a different color. Longer wavelengths, in the 600–700 nm range, are seen as orange or red light; shorter wavelengths, in the 400–500 nm range, are seen as blue or violet light.

FIGURE 15.13 shows that the visible spectrum is a small slice out of the much broader **electromagnetic spectrum**. We will have much more to say about light and the rest of the electromagnetic spectrum in future chapters.

FIGURE 15.13 The electromagnetic spectrum from 10^6 Hz to 10^{18} Hz.



EXAMPLE 15.8 Finding the frequency of microwaves

The wavelength of microwaves in a microwave oven is 12 cm. What is the frequency of the waves?

PREPARE Microwaves are electromagnetic waves, so their speed is the speed of light, $c = 3.00 \times 10^8$ m/s.

SOLVE Using the fundamental relationship for sinusoidal waves, we find

$$f = \frac{v}{\lambda} = \frac{3.00 \times 10^{8}\text{ m/s}}{0.12\text{ m}} = 2.5 \times 10^{9}\text{ Hz} = 2.5\text{ GHz}$$

ASSESS This is a high frequency, but the speed of the waves is also very high, so our result seems reasonable.

We've just used the same equation to describe ultrasound and microwaves, which brings up a remarkable point: The wave model we've been developing applies equally well to all types of waves. Features such as wavelength, frequency, and speed are characteristics of waves in general. At this point we don't yet know any details about electromagnetic fields, yet we can use the wave model to say some significant things about the properties of electromagnetic waves.

It's also interesting to note that the 2.5 GHz frequency of microwaves in an oven we found in Example 15.8 is similar to the frequencies of other devices you use each day. Many cordless phones work at a frequency of 2.4 GHz, and cell phones at just under 2.0 GHz. Although these frequencies are not very different from those of the waves that heat your food in a microwave oven, the *intensity* is much less—which brings us to the topic of the next section.

The better to hear you with BIO The great grey owl has its ears on the front of its face, hidden behind its facial feathers. Its round face works like a radar dish, collecting the energy of sound waves and "funneling" it into the ears. Collecting sound over a large area in this manner allows owls to sense very quiet sounds. Having ears on the front of the face allows them to precisely determine the source of sounds as well, an asset for a bird of prey. These owls can hear—and locate—mice moving underneath a thick blanket of snow.

15.5 Energy and Intensity

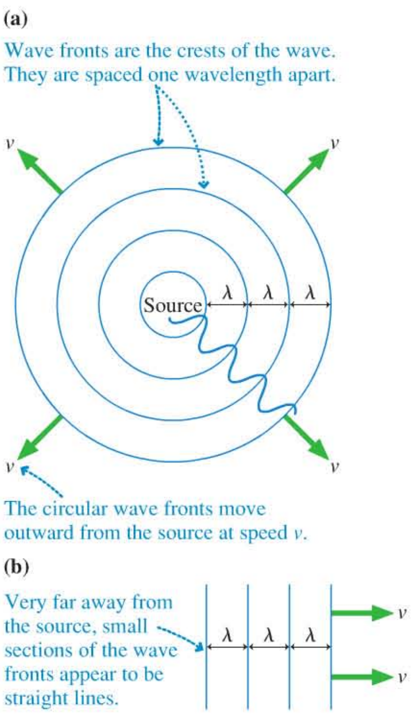
A traveling wave transfers energy from one point to another. The sound wave from a loudspeaker sets your eardrum into motion. Light waves from the sun warm the earth and, if focused with a lens, can start a fire. The *power* of a wave is the rate, in joules per second, at which the wave transfers energy. As you learned in Chapter 10, power is measured in watts. A person singing or shouting as loud as possible is emitting energy in the form of sound waves at a rate of about 1 W, or 1 J/s. A 25 W lightbulb emits about 1 W of visible light, with the other 24 W of power being emitted as heat, or infrared radiation, rather than as visible light. In this section, we will learn how to characterize the power of waves. A first step in doing so is to understand how waves change as they spread out.

Circular, Spherical, and Plane Waves

Suppose you were to take a photograph of ripples spreading on a pond. If you mark the location of the *crests* on the photo, your picture would look like FIGURE 15.14a. The lines that locate the crests are called **wave fronts,** and they are spaced precisely one wavelength apart. A wave like this is called a **circular wave.** It is a two-dimensional wave that spreads across a surface.

Although the wave fronts are circles, you would hardly notice the curvature if you observed a small section of the wave front very far away from the source. The wave fronts would appear to be parallel lines, still spaced one wavelength apart and traveling at speed v as in FIGURE 15.14b.

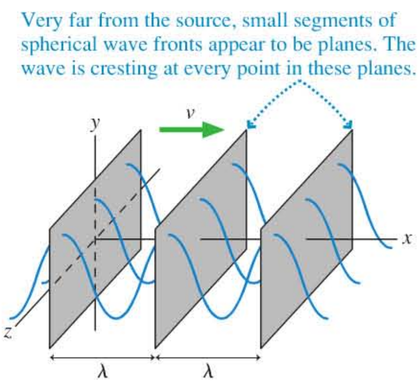
FIGURE 15.14 The wave fronts of a circular or spherical wave.



Many waves of interest, such as sound waves or light waves, move in three dimensions. For example, loudspeakers and lightbulbs emit **spherical waves.** The crests of the wave form a series of concentric, spherical shells separated by the wavelength λ. In essence, the waves are three-dimensional ripples. It will still be useful to draw wave-front diagrams such as Figure 15.14a, but now the circles are slices through the spherical shells locating the wave crests.

If you observe a spherical wave very far from its source, the small piece of the wave front that you can see is a little patch on the surface of a very large sphere. If the radius of the sphere is sufficiently large, you will not notice the curvature and this little patch of the wave front appears to be a plane. FIGURE 15.15 illustrates the idea of a **plane wave.**

FIGURE 15.15 A plane wave.



Power, Energy, and Intensity

Imagine doing two experiments with a lightbulb that emits 2 W of visible light. In the first, you hang the bulb in the center of a room and allow the light to illuminate the walls. In the second experiment, you use mirrors and lenses to "capture" the bulb's light and focus it onto a small spot on one wall. (This is what a projector does.) The energy emitted by the bulb is the same in both cases, but, as you know, the light is much brighter when focused onto a small area. We would say that the focused light is more *intense* than the diffuse light that goes in all directions. Similarly, a loudspeaker that beams its sound forward into a small area produces a louder sound in that area than a speaker of equal power that radiates the sound in all directions. Quantities such as brightness and loudness depend not only on the rate of energy transfer, or power, but also on the *area* that receives that power.

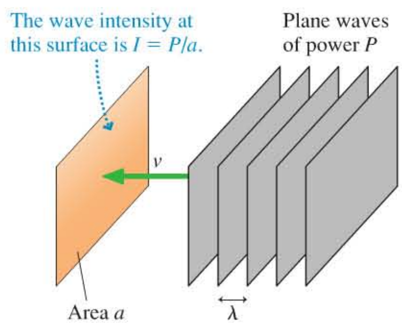
FIGURE 15.16 shows a wave impinging on a surface of area a. The surface is perpendicular to the direction in which the wave is traveling. This might be a real physical surface, such as your eardrum or a solar cell, but it could equally well be a mathematical surface in space that the wave passes right through. If the wave has power P, we define the **intensity** I of the wave as

$$I = \frac{P}{a} \qquad (15.11)$$

The SI units of intensity are W/m^2. Because intensity is a power-to-area ratio, a wave focused onto a small area has a higher intensity than a wave of equal power that is spread out over a large area.

NOTE ► In this chapter we will use a for area to avoid confusion with amplitude, for which we use the symbol A. ◄

FIGURE 15.16 Plane waves of power P impinge on area a.



EXAMPLE 15.9 The intensity of a laser beam

A bright, tightly focused laser pointer emits 1.0 mW of light power into a beam that is 1.0 mm in diameter. What is the intensity of the laser beam?

SOLVE The light waves of the laser beam pass through a circle of diameter 1.0 mm. The intensity of the laser beam is

$$I = \frac{P}{a} = \frac{P}{\pi r^2} = \frac{0.0010\ \text{W}}{\pi(0.00050\ \text{m})^2} = 1300\ \text{W/m}^2$$

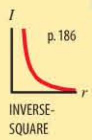
ASSESS This intensity is roughly equal to the intensity of sunlight at noon on a summer day. Such a high intensity for a low-power source may seem surprising, but the area is very small, so the energy is packed into a tiny spot. You know that the light from a laser pointer won't burn you but you don't want the beam to shine into your eye, so an intensity similar to that of sunlight seems reasonable.

Sound from a loudspeaker and light from a lightbulb become less intense as you get farther from the source. This is because spherical waves spread out to fill larger and larger volumes of space. To conserve energy, the wave's amplitude must decrease with increasing distance r.

If a source of spherical waves radiates uniformly in all directions, then, as **FIGURE 15.17** shows, the power at distance r is spread uniformly over the surface of a sphere of radius r. The surface area of a sphere is $a = 4\pi r^2$, so the intensity of a uniform spherical wave is

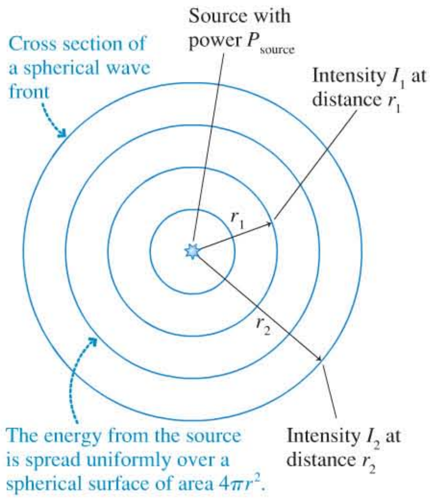
$$I = \frac{P_{\text{source}}}{4\pi r^2} \qquad (15.12)$$

Intensity at distance r of a spherical wave from a source of power P_{source}



The inverse-square dependence of r is really just a statement of energy conservation. The source emits energy at the rate of P joules per second. The energy is spread over a larger and larger area as the wave moves outward. Consequently, the *energy per area* must decrease in proportion to the surface area of a sphere.

FIGURE 15.17 A source emitting uniform spherical waves.



If the intensity at distance r_1 is $I_1 = P_{source}/4\pi r_1^2$ and the intensity at r_2 is $I_2 = P_{source}/4\pi r_2^2$, then you can see that the intensity *ratio* is

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2} \tag{15.13}$$

You can use Equation 15.13 to compare the intensities at two distances from a source without needing to know the power of the source.

NOTE ► Wave intensities are strongly affected by reflections and absorption. Equations 15.12 and 15.13 apply to situations such as the light from a star and the sound from a firework exploding high in the air. Indoor sound does *not* obey a simple inverse-square law because of the many reflecting surfaces. ◄

EXAMPLE 15.10 Intensity of sunlight on Mars

The intensity of sunlight on earth is roughly 1300 W/m^2 at noon on a summer day. Mars orbits at a distance from the sun approximately 1.5 times that of earth. Assuming similar absorption of energy by the Martian atmosphere, what would you predict for the intensity of sunlight at noon during the Martian summer?

PREPARE We aren't given the power emitted by the sun or the distances from the sun to earth and to Mars, but we can solve this problem by using the ratios of distances and intensities.

SOLVE According to Equation 15.13,

$$I_{Mars} = I_{earth}\frac{r_{earth}^2}{r_{Mars}^2} = (1300\ \text{W/m}^2)\left(\frac{1}{1.5}\right)^2 = 580\ \text{W/m}^2$$

ASSESS The intensity of sunlight is quite a bit less on Mars than on earth, as we would expect, given the much greater distance of Mars from the sun.

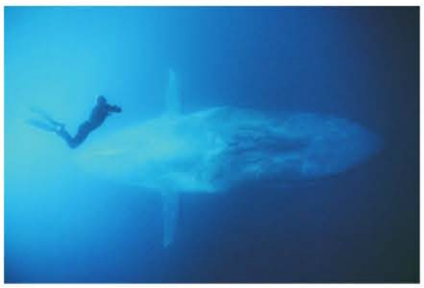
STOP TO THINK 15.4 A plane wave, a circular wave, and a spherical wave all have the same intensity. Each of the waves travels the same distance. Afterward, which wave has the highest intensity?

A. The plane wave B. The circular wave C. The spherical wave

15.6 Loudness of Sound

Ten guitars playing in unison sound only about twice as loud as one guitar. 100 trumpets playing together seem to you only four times as loud as a soloist. Generally, **increasing the sound intensity by a factor of 10 results in an increase in perceived loudness by a factor of approximately 2.** Thus your ears are sensitive over a very wide range of intensities. The difference in intensity between the quietest sound you can detect and the loudest you can safely hear is a factor of 1,000,000,000,000! A normal conversation has 10,000 times the sound intensity of a whisper, but it sounds only about 16 times as loud.

The loudness of sound is measured by a quantity called the **sound intensity level.** Because of the wide range of intensities we can hear, and the fact that the difference in perceived loudness is much less than the actual difference in intensity, the sound intensity level is measured on a *logarithmic scale*. In this section we will explain what this means. The units of sound intensity level (i.e., of loudness) are *decibels,* a word you have likely heard.



◄ **The loudest animal in the world** BIO The blue whale is the largest animal in the world, up to 30 m (about 100 ft) long, weighing 150,000 kg or more. It is also the loudest. At close range in the water, the 10–30 second calls of the blue whale would be intense enough to damage tissues in your body. Blue whales produce sound with a larynx, much as humans do, but at much lower frequencies of 10–40 Hz that can travel great distances in water. Their loud, low-frequency calls can be heard by other whales hundreds of miles away.

The Decibel Scale

There is a lower limit to the intensity of sound that a human can hear. The exact value varies among individuals and varies with frequency, but an average value for the lowest-intensity sound that can be heard in an extremely quiet room is

$$I_0 = 1.0 \times 10^{-12}\ \text{W/m}^2$$

This intensity is called the *threshold of hearing*. A sound wave can have lower intensity than this, but you won't be able to perceive it.

It's convenient and logical to place the zero of our loudness scale at the threshold of hearing. All other sounds can then be referenced to this intensity. To create a loudness scale, we define the *sound intensity level,* expressed in **decibels** (dB), as

$$\beta = (10\ \text{dB})\log_{10}\left(\frac{I}{I_0}\right) \tag{15.14}$$

Sound intensity level in decibels for a sound of intensity I

β is the lowercase Greek letter beta. The decibel is named after Alexander Graham Bell, inventor of the telephone. Sound intensity level is actually dimensionless, since it's formed from the ratio of two intensities, so decibels are actually just a *name* to remind us that we're dealing with an intensity *level* rather than a true intensity.

Equation 15.14 takes the base-10 logarithm of the intensity ratio I/I_0. As a reminder, logarithms work like this:

If you express a number as a power of 10 . . . . . . the logarithm is the exponent.

$$\log_{10}(1000) = \log_{10}(10^3) = 3$$

Right at the threshold of hearing, where $I = I_0$, the sound intensity level is

$$\beta = (10\ \text{dB})\log_{10}\left(\frac{I_0}{I_0}\right) = (10\ \text{dB})\log_{10}(1) = (10\ \text{dB})\log_{10}(10^0) = 0\ \text{dB}$$

The threshold of hearing corresponds to 0 dB, as we wanted.

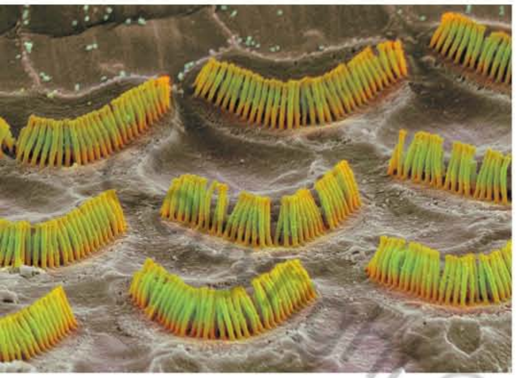
Table 15.3 lists the intensities and sound intensity levels for a number of typical sounds. Notice that the sound intensity level increases by 10 dB each time the actual intensity increases by a factor of 10. For example, the sound intensity level increases from 70 dB to 80 dB when the sound intensity increases from 10^{-5} W/m^2 to 10^{-4} W/m^2. A 20 dB increase in the sound intensity level means a factor of 100 increase in intensity; 30 dB a factor of 1000. We found earlier that sound is perceived as "twice as loud" when the intensity increases by a factor of 10. In terms of decibels, we can say that the apparent loudness of a sound doubles with each 10 dB increase in the sound intensity level.

The range of sounds in Table 15.3 is very wide; the top of the scale, 130 dB, represents 10 trillion times the intensity of the quietest sound you can hear. Vibrations of this intensity will injure the delicate sensory apparatus of the ear and cause pain. Exposure to less intense sounds also is not without risk. A fairly short exposure to 120 dB can cause damage to the hair cells in the ear, but lengthy exposure to sound intensity levels of over 85 dB can produce damage as well.

Quiet as a mouse 0 dB is the lower limit of human hearing, but other animals can hear quieter sounds. The harvest mouse has an especially well-developed sense of hearing and will detect and respond to sounds down to −10 dB, making it hard for predators to sneak up on it.

TABLE 15.3 Intensity and sound intensity levels of common environmental sounds

Sound	β (dB)	I (W/m^2)
Threshold of hearing	0	1.0×10^{-12}
Person breathing, at 3 m	10	1.0×10^{-11}
A whisper, at 1 m	20	1.0×10^{-10}
Classroom during test, no talking	30	1.0×10^{-9}
Residential street, no traffic	40	1.0×10^{-8}
Quiet restaurant	50	1.0×10^{-7}
Normal conversation, at 1 m	60	1.0×10^{-6}
Busy traffic	70	1.0×10^{-5}
Vacuum cleaner, for user	80	1.0×10^{-4}
Niagara Falls, at viewpoint	90	1.0×10^{-3}
Pneumatic hammer, at 2 m	100	0.010
Home stereo at max volume	110	0.10
Rock concert	120	1.0
Threshold of pain	130	10



◀ **Hearing hairs** BIO This electron microscope picture shows the hair cells in the cochlea of the ear that are responsible for sensing sound. Each cell has a curved row of tiny hairs, which give your ears their remarkable sensitivity. Even very tiny vibrations transmitted into the fluid of the cochlea deflect the hairs, triggering a response in the cells. Motion of the basilar membrane by as little as 0.5 nm, about 5 atomic diameters, can produce an electrical response in the hair cells. With this remarkable sensitivity, it is no wonder that loud sounds can damage these structures.

EXAMPLE 15.11 Finding the loudness of a shout

A person shouting at the top of his lungs emits about 1.0 W of energy as sound waves. What is the sound intensity level 1.0 m from such a person?

PREPARE We will assume that the shouting person emits a spherical sound wave, in which case the intensity decreases according to Equation 15.12.

SOLVE At a distance of 1.0 m, the sound intensity is

$$I = \frac{P}{4\pi r^2} = \frac{1.0\ \text{W}}{4\pi(1.0\ \text{m})^2} = 0.080\ \text{W/m}^2$$

Thus the sound intensity level is

$$\beta = (10\ \text{dB})\log_{10}\left(\frac{0.080\ \text{W/m}^2}{1.0\times10^{-12}\ \text{W/m}^2}\right) = 110\ \text{dB}$$

ASSESS This is quite loud (compare with values in Table 15.3), as you might expect.

NOTE ► In calculating the sound intensity level, be sure to use the $\log_{10}$ button on your calculator, not the natural logarithm button. On many calculators, $\log_{10}$ is labeled LOG and the natural logarithm is labeled LN. ◄

Equation 15.14 allows us to compute the sound intensity level β from the intensity I. We can do the reverse, finding an intensity from the sound intensity level, by taking the inverse of the $\log_{10}$ function. Recall, from the definition of the base-10 logarithm, that $10^{\log(x)} = x$. Applying this to Equation 15.14, we find

$$I = (1.0\times10^{-12}\ \text{W/m}^2)10^{(\beta/10\ \text{dB})} \tag{15.15}$$

EXAMPLE 15.12 How far away can you hear a conversation?

The sound intensity level 1.0 m from a person talking in a normal conversational voice is 60 dB. Suppose you are outside, 100 m from the person speaking. If it is a very quiet day with minimal background noise, will you be able to hear him or her?

PREPARE We know how sound intensity changes with distance, but not sound intensity level, so we need to break this problem into three steps. First, we will convert the sound intensity level at 1.0 m into intensity, using Equation 15.15. Second, we will compute the intensity at a distance of 100 m, using Equation 15.13. Finally, we will convert this result back to a sound intensity level, using Equation 15.14, so that we can judge the loudness.

SOLVE The sound intensity level of a normal conversation at 1.0 m is 60 dB. The intensity is

$$\begin{aligned} I(1\ \text{m}) &= (1.0\times10^{-12}\ \text{W/m}^2)10^{(60\ \text{dB}/10\ \text{dB})} \\ &= 1.0\times10^{-6}\ \text{W/m}^2 \end{aligned}$$

The intensity at 100 m can be found using Equation 15.13:

$$\frac{I(100\ \text{m})}{I(1\ \text{m})} = \frac{(1\ \text{m})^2}{(100\ \text{m})^2}$$

$$I(100\ \text{m}) = I(1\ \text{m})(1.0\times10^{-4}) = 1.0\times10^{-10}\ \text{W/m}^2$$

This intensity corresponds to a sound intensity level

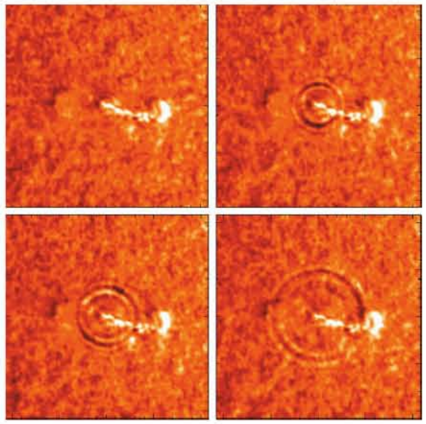
$$\beta = (10\ \text{dB})\log_{10}\left(\frac{1.0\times10^{-10}\ \text{W/m}^2}{1.0\times10^{-12}\ \text{W/m}^2}\right) = 20\ \text{dB}$$

This is above the threshold for hearing—about the level of a whisper—so it could be heard on a very quiet day.

ASSESS The sound is well within what the ear can detect. However, normal background noise is rarely less than 40 dB, which would make the conversation difficult to decipher. Our result thus seems reasonable based on experience. The sound is at a level that can theoretically be detected, but it will be much quieter than the ambient level of sound, so it's not likely to be noticed.

15.7 The Doppler Effect and Shock Waves

In this final section, we will look at sounds from moving objects and for moving observers. You've likely noticed that the pitch of an ambulance's siren drops as it goes past you. A higher pitch suddenly becomes a lower pitch. This change in frequency, which is due to the motion of the ambulance, is called the *Doppler effect.* A more dramatic effect happens when an object moves faster than the speed of sound. The crack of a whip is a *shock wave* produced when the tip moves at a *supersonic* speed. These examples—and much of this section—concern sound waves, but the phenomena we will explore apply generally to all waves.



Catching a wave on the sun SOHO (the **So**lar and **H**eliospheric **O**bservatory) is a satellite studying the sun. The instrument on the satellite responsible for images like this measures the Doppler effect of light emitted from the surface of the sun. If the surface is rising toward the satellite, the light is shifted to higher frequencies; these positions are shown darker on the image. If the surface is falling, the light is shifted to lower frequencies and is shown lighter. This series of images of the sun's surface shows a wave produced by the disruption of a solar flare. This wave is similar to the wave from an earthquake on earth, but 20 times as fast and carrying 40,000 times as much energy as a typical earthquake wave.

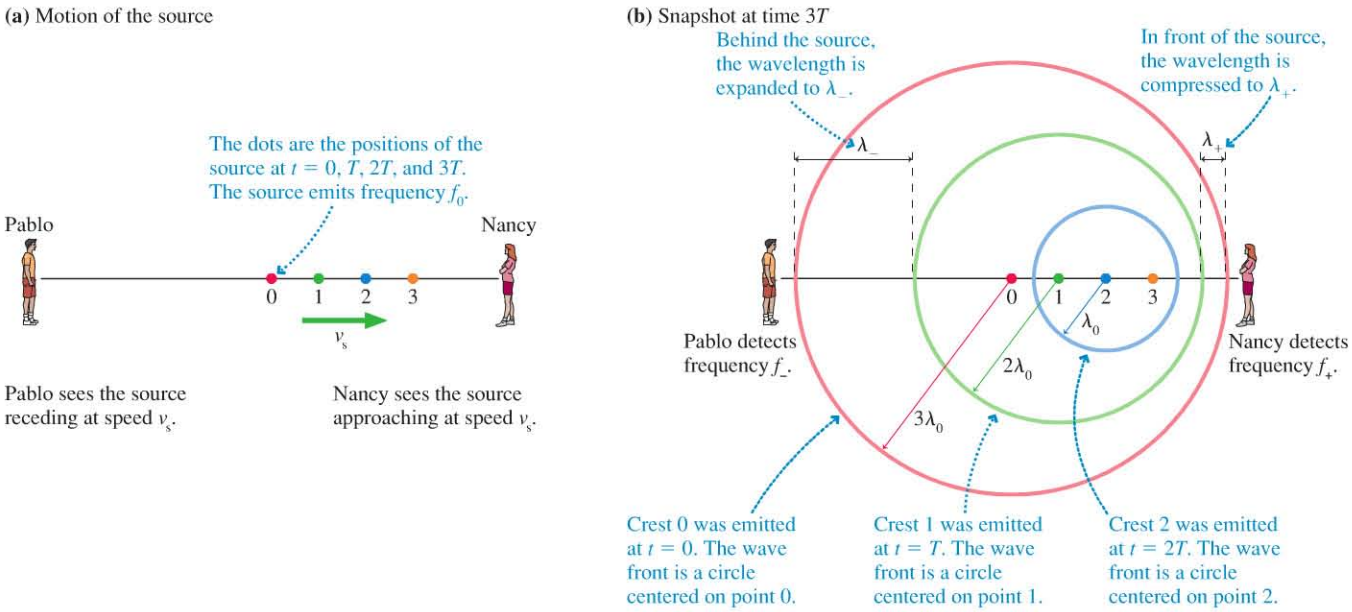
Sound Waves from a Moving Source

FIGURE 15.18a shows a source of sound waves moving away from Pablo and toward Nancy at a steady speed v_s. The subscript s indicates that this is the speed of the source, not the speed of the waves. The source is emitting sound waves of frequency f_0 as it travels. Part a of the figure is a motion diagram showing the positions of the source at times $t = 0$, T, $2T$, and $3T$, where $T = 1/f_0$ is the period of the waves.

After a wave crest leaves the source, its motion is governed by the properties of the medium. The motion of the source cannot affect a wave that has already been emitted. Thus each circular wave front in **FIGURE 15.18b** is centered on the point from which it was emitted. You can see that the wave crests are bunched up in the direction in which the source is moving and are stretched out behind it. The distance between one crest and the next is one wavelength, so the wavelength λ_+ that Nancy measures is *less* than the wavelength $\lambda_0 = v/f_0$ that would be emitted if the source were at rest. Similarly, λ_- behind the source is larger than λ_0.

These crests move through the medium at the wave speed v. Consequently, the frequency $f_+ = v/\lambda_+$ detected by the observer whom the source is approaching is *higher* than the frequency f_0 emitted by the source. Similarly, $f_- = v/\lambda_-$ detected behind the source is *lower* than frequency f_0. This change of frequency when a source moves

FIGURE 15.18 A motion diagram showing the wave fronts emitted by a source as it moves to the right at speed v_s.



10.8, 10.9 Activ Online Physics

relative to an observer is called the **Doppler effect.** A quantitative analysis based on this information would show that the frequency heard by a stationary observer depends on whether the observer sees the source approaching or receding:

$$f_+ = \frac{f_0}{1 - v_s/v}$$

Observed frequency of a wave of speed v emitted from a source approaching at speed v_s

$$f_- = \frac{f_0}{1 + v_s/v} \tag{15.16}$$

Observed frequency of a wave of speed v emitted from a source receding at speed v_s

As expected, $f_+ > f_0$ (the frequency is higher) for an approaching source because the denominator is less than 1, and $f_- < f_0$ (the frequency is lower) for a receding source.

EXAMPLE 15.13 How fast are the police driving?

A police siren has a frequency of 550 Hz as the police car approaches you, 450 Hz after it has passed you and is moving away. How fast are the police traveling?

PREPARE The siren's frequency is altered by the Doppler effect. The frequency is f_+ as the car approaches and f_- as it moves away. We can write two equations for these frequencies and solve for the speed of the police car, v_s.

SOLVE Because our goal is to find v_s, we rewrite Equations 15.16 as

$$f_0 = \left(1 + \frac{v_s}{v}\right)f_- \quad \text{and} \quad f_0 = \left(1 - \frac{v_s}{v}\right)f_+$$

Subtracting the second equation from the first, we get

$$0 = f_- - f_+ + \frac{v_s}{v}(f_- + f_+)$$

Now we can solve for the speed v_s:

$$v_s = \frac{f_+ - f_-}{f_+ + f_-}v = \frac{100\text{ Hz}}{1000\text{ Hz}}343\text{ m/s} = 34\text{ m/s}$$

ASSESS This is pretty fast (about 75 mph) but reasonable for a police car speeding with the siren on.

A Stationary Source and a Moving Observer

Suppose the police car in Example 15.13 is at rest while you drive toward it at 34 m/s. You might think that this is equivalent to having the police car move toward you at 34 m/s, but there is an important difference. Mechanical waves move through a medium, and the Doppler effect depends not just on how the source and the observer move with respect to each other but also on how they move with respect to the medium. The frequency heard by an observer moving at speed v_o relative to a stationary source emitting frequency f_0 is given by

$$f_+ = \left(1 + \frac{v_o}{v}\right)f_0$$

Doppler effect for an observer approaching a source

$$f_- = \left(1 - \frac{v_o}{v}\right)f_0 \tag{15.17}$$

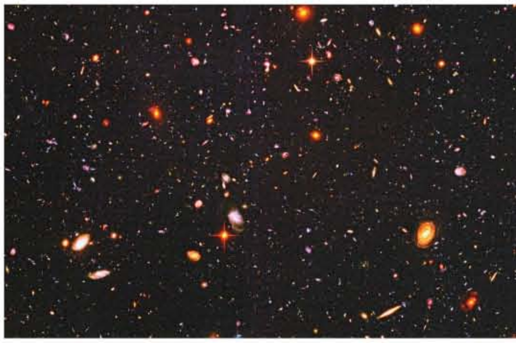
Doppler effect for an observer receding from a source

A quick calculation shows that the frequency of the police siren as you approach it at 34 m/s is 545 Hz, not the 550 Hz you heard as it approached you at 34 m/s.

The Doppler Effect for Light Waves

If a source of light waves is receding from you, the wavelength λ_- that you detect is longer than the wavelength λ_0 emitted by the source. Because the wavelength is shifted toward the red end of the visible spectrum, the longer wavelengths of light, this effect is called the **red shift.** Similarly, the light you detect from a source moving toward you is **blue shifted** to shorter wavelengths. For objects moving at normal speeds, this is a small effect; you won't see a Doppler shift of the flashing light of the police car in the above example! But for objects moving at very high speeds, the Doppler effect is significant.

In the 1920s, an analysis of the spectra of many distant galaxies showed that they *all* had a distinct red shift—all distant galaxies are moving away from us. How can we make sense of this observation? The astronomer Edwin Hubble concluded that the galaxies of the universe are *all* moving apart from each other. Extrapolating backward in time brings us to a point when all the matter of the universe—and even space itself, according to the theory of relativity—began rushing out of a primordial fireball. Many observations and measurements since have given support to the idea that the universe began in a *Big Bang* about 14 billion years ago.



The greater the distance to a galaxy, the faster it moves away from us. This photo shows galaxies at distances of up to 12 billion light years. The great distances imply large red shifts, making the light from the most distant galaxies appear distinctly red.

Frequency Shift on Reflection from a Moving Object

A wave striking a barrier or obstacle can *reflect* and travel back toward the source of the wave, a process we will examine more closely in the next chapter. For sound, the reflected wave is called an *echo*. A bat is able to determine the distance to a flying insect by measuring the time between the emission of an ultrasonic chirp and the detection of the echo from the insect. But if the bat is to catch the insect, it's just as important to know where the insect is going—its velocity. The bat can figure this out by noting the *frequency shift* in the reflected wave, another application of the Doppler effect.

Suppose a sound wave of frequency f_0 travels toward a moving object. The object would see the wave's frequency Doppler shifted to a higher frequency f_+, as given by Equation 15.17. The wave reflected back toward the sound source by the moving object is also Doppler shifted to a higher frequency because, to the source, the reflected wave is coming from a moving object. Thus the echo from a moving object is "double Doppler shifted." If the object's speed v_o is much lower than the wave speed v ($v_o \ll v$), the frequency *shift* of waves reflected from a moving object is

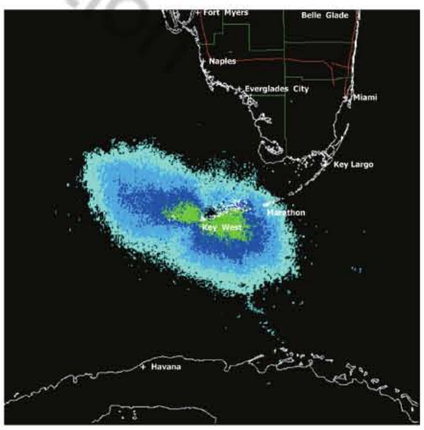
$$\Delta f = \pm 2 f_0 \frac{v_o}{v} \qquad (15.18)$$

Frequency shift of waves reflected from an object moving at speed v_o

The $+$ case is for objects moving toward the source of sound, the $-$ for objects moving away. Notice that there is no shift (i.e., the reflected wave has the same frequency as the emitted wave) when the reflecting object is at rest.

The *Doppler blood flow meter* is an important application of the frequency shift of waves reflected from moving objects. If an ultrasound emitter is pressed against the skin, the sound waves reflect off tissues in the body. In most cases, the frequency of the reflected wave is the same as that of the emitted wave. However, some of the sound waves reflect from blood cells moving through arteries toward or away from the emitter. The moving blood cells produce a frequency shift Δf in the reflected wave. By measuring Δf, doctors can determine blood flow speeds in an entirely noninvasive manner.

Frequency shift on reflection is observed for all types of waves. Radar units emit pulses of radio waves and observe the reflected waves. The time between the emission of a pulse and its return gives an object's position. The change in frequency of the returned pulse gives the object's speed. This is the principle behind the radar guns used by traffic police, as well as the Doppler radar images you have seen in weather reports.



Keeping track of wildlife with radar Doppler radar is tuned to measure only those reflected radio waves that have a frequency shift, eliminating reflections from stationary objects and showing only objects in motion. Televised Doppler radar images of storms are made using radio waves reflected from moving water droplets. But this Doppler radar image of an area off the tip of Florida was made on a clear night with no rain. The blue and green patch isn't a moving storm, it's a moving flock of birds. Migratory birds frequently move at high altitudes at night, so Doppler radar is an excellent tool for analyzing their movements.

EXAMPLE 15.14 Ultrasound frequency to measure blood flow

A biomedical engineer is designing a Doppler blood flow meter to measure blood flow in an artery where a typical flow speed is known to be 0.60 m/s. What ultrasound frequency should she use to produce a frequency shift of 1500 Hz when this flow is detected?

SOLVE We can rewrite Equation 15.18 to calculate the frequency of the emitter:

$$f_0 = \left(\frac{\Delta f}{2}\right)\left(\frac{v}{v_{\text{blood}}}\right)$$

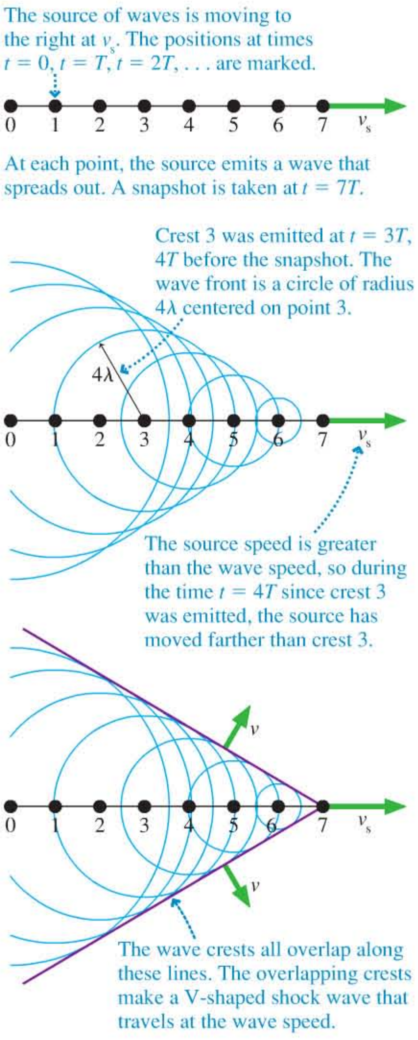
The values on the right side are all known. Thus the required ultrasound frequency is

$$f_0 = \left(\frac{1500\text{ Hz}}{2}\right)\left(\frac{1540\text{ m/s}}{0.60\text{ m/s}}\right) = 1.9\text{ MHz}$$

ASSESS Doppler units to measure blood flow in deep tissues actually work at about 2.0 MHz, so our answer is reasonable.

If we add a frequency-shift measurement to an ultrasound imaging unit, like the one in Example 15.7, we have a device—called *Doppler ultrasound*—that can show not only structure but also motion. *Doppler ultrasound* is a very valuable tool in cardiology because an image can reveal the motion of the heart muscle and the blood in the chambers of the heart in addition to the structure of the heart itself.

FIGURE 15.19 Waves emitted by a source traveling faster than the speed of the waves in a medium.



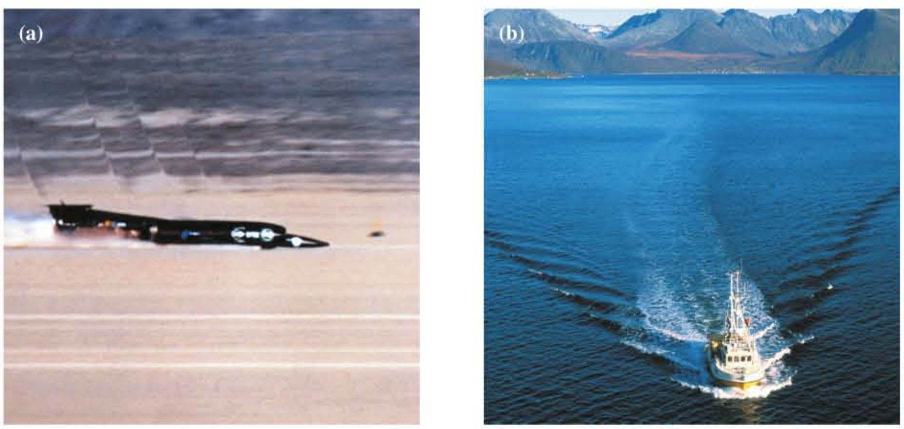
Shock Waves

When sound waves are emitted by a moving source, the frequency is shifted, as we have seen. Now, let's look at what happens when the source speed v_s exceeds the wave speed v and the source "outruns" the waves it produces.

Earlier in this section, in Figure 15.18, we looked at a motion diagram of waves emitted by a moving source. **FIGURE 15.19** is the same diagram, but in this case the source is moving faster than the waves. This motion causes the waves to overlap. (Compare Figure 15.19 to Figure 15.18.) The amplitudes of the overlapping waves add up to produce a very large amplitude wave—a **shock wave**.

Anything that moves faster than the speed of sound in air will create a shock wave. The speed of sound was broken on land in 1997 by a British team driving the Thrust SCC in Nevada's Black Rock Desert. **FIGURE 15.20a** shows the shock waves produced during a **supersonic** (faster than the speed of sound) run. You can see the distortion of the view of the landscape behind the car where the waves add to produce regions of high pressure. This shock wave travels along with the car. If the car went by you, the passing of the shock wave would produce a **sonic boom,** the distinctive loud sound you may have heard when a supersonic aircraft passes. The crack of a whip is a sonic boom as well, though on a much smaller scale.

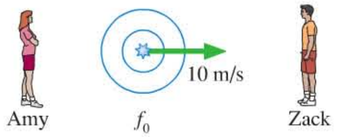
FIGURE 15.20 Extreme and everyday examples of shock waves.



Shock waves are not necessarily an extreme phenomenon. A boat (or even a duck!) can easily travel faster than the speed of the water waves it creates; the resulting wake, with its characteristic "V" shape as shown in **FIGURE 15.20b**, is really a shock wave.

STOP TO THINK 15.5 Amy and Zack are both listening to the source of sound waves that is moving to the right. Compare the frequencies each hears.

A. $f_{\text{Amy}} > f_{\text{Zack}}$
B. $f_{\text{Amy}} = f_{\text{Zack}}$
C. $f_{\text{Amy}} < f_{\text{Zack}}$

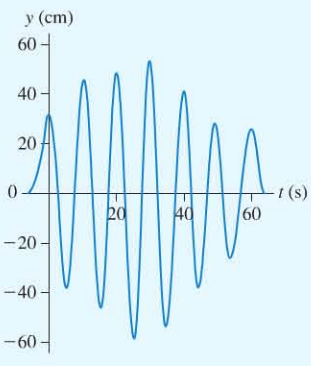


INTEGRATED EXAMPLE 15.15 Shaking the ground

Earthquakes are dramatic slips of the earth's crust. You may feel the waves generated by an earthquake even if you're some distance from the *epicenter,* the point where the slippage occurs. Earthquake waves are usually complicated, but some of the long-period waves shake the ground with motion that is approximately simple harmonic motion. **FIGURE 15.21** shows the vertical position of the ground recorded at a distant monitoring station following an earthquake that hit Japan in 2003. This particular wave traveled with a speed of 3500 m/s.

a. Was the wave transverse or longitudinal?
b. What were the wave's frequency and wavelength?
c. What were the maximum speed and the maximum acceleration of the ground during this earthquake wave?
d. Intense earthquake waves produce accelerations greater than free-fall acceleration of gravity. How does this wave compare?

FIGURE 15.21 The vertical motion of the ground during the passage of an earthquake wave.



PREPARE There are two different but related parts to the solution: analyzing the motion of the ground, and analyzing the motion of the wave. The graph in Figure 15.21 is a history graph; it's a record of the motion of one point of the medium—the ground. The graph is approximately sinusoidal, so we can model the motion of the ground as simple harmonic motion. If we look at the middle portion of the wave, we can estimate the amplitude to be 0.50 m (it varies, but this is a reasonable average over a few cycles). Because the ground was in simple harmonic motion, the traveling wave was a sinusoidal wave. Consequently, we can use the fundamental relationships for sinusoidal waves to relate the wavelength, frequency, and speed.

SOLVE

a. The graph shows the *vertical* motion of the ground. This motion of the ground—the medium—was perpendicular to the horizontal motion of the wave traveling along the ground, so this was a transverse wave.
b. We can see from the graph that 6 cycles of the oscillation took 60 seconds, so the period was $T = 10$ s. The period of the wave was the same as that of the point on the ground, 10 s; thus the frequency was $f = 1/T = 1/10\text{ s} = 0.10\text{ Hz}$. The speed of the wave was 3500 m/s, so the wavelength was

$$\lambda = \frac{v}{f} = \frac{3500\text{ m/s}}{0.10\text{ Hz}} = 35{,}000\text{ m} = 35\text{ km}$$

c. The motion of the ground was simple harmonic motion with frequency 0.10 Hz and amplitude 0.50 m. We can compute the maximum speed and acceleration using relationships from Chapter 14:

$$v_{\text{max}} = 2\pi f A = (2\pi)(0.10\text{ Hz})(0.50\text{ m}) = 0.31\text{ m/s}$$

$$a_{\text{max}} = (2\pi f)^2 A = [2\pi(0.10\text{ Hz})]^2(0.50\text{ m}) = 0.20\text{ m/s}^2$$

d. This was a reasonably gentle earthquake wave, with an acceleration of the ground quite small compared to the free-fall acceleration of gravity:

$$a_{\text{max}}(\text{in units of } g) = \frac{0.20\text{ m/s}^2}{9.8\text{ m/s}^2} = 0.020g$$

ASSESS The wavelength is quite long, as we might expect for such a fast wave with a long period. Given the relatively small amplitude and long period, it's no surprise that the maximum speed and acceleration are relatively modest. You'd certainly feel the passage of this wave, but it wouldn't knock buildings down. This value is less than the acceleration for the sway of the top of the building in Example 14.4 in Chapter 14!

SUMMARY

The goal of Chapter 15 has been to learn the basic properties of traveling waves.

GENERAL PRINCIPLES

The Wave Model

This model is based on the idea of a **traveling wave,** which is an organized disturbance traveling at a well-defined **wave speed** v.

- In **transverse waves** the particles of the medium move *perpendicular* to the direction in which the wave travels.

- In **longitudinal waves** the particles of the medium move *parallel* to the direction in which the wave travels.

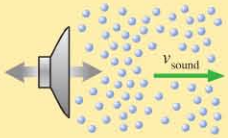
A wave transfers energy, but there is no material or substance transferred.

Mechanical waves require a material **medium.** The speed of the wave is a property of the medium, not the wave. The speed does not depend on the size or shape of the wave.

- For a **wave on a string,** the string is the medium.

$$v_{string} = \sqrt{\frac{T_s}{\mu}}$$

- A **sound wave** is a wave of compressions and rarefactions of a medium such as air.



In a gas:

$$v_{sound} = \sqrt{\frac{\gamma RT}{M}}$$

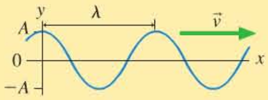
Electromagnetic waves are waves of the electromagnetic field. They do not require a medium. All electromagnetic waves travel at the same speed in a vacuum, $c = 3.00 \times 10^8$ m/s.

IMPORTANT CONCEPTS

Graphical representation of waves

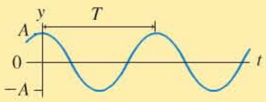
A **snapshot graph** is a picture of a wave at one instant in time. For a periodic wave, the **wavelength** λ is the distance between crests.

Fixed t:



A **history graph** is a graph of the displacement of one point in a medium versus time. For a periodic wave, the **period** T is the time between crests.

Fixed x:



Mathematical representation of waves

Sinusoidal waves are produced by a source moving with simple harmonic motion. The equation for a sinusoidal wave is a function of position and time:

$$y(x,t) = A\cos\left(2\pi\left(\frac{x}{\lambda} \pm \frac{t}{T}\right)\right)$$

$+$: wave travels to left
$-$: wave travels to right

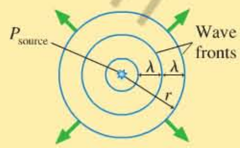
For sinusoidal and other periodic waves:

$$T = \frac{1}{f} \qquad v = f\lambda$$

The **intensity** of a wave is the ratio of the power to the area:

$$I = \frac{P}{A}$$

For a **spherical wave** the power decreases with the surface area of the spherical **wave fronts:**



$$I = \frac{P_{source}}{4\pi r^2}$$

APPLICATIONS

The loudness of a sound is given by the **sound intensity level.** This is a logarithmic function of intensity and is in units of **decibels.**

- The usual **reference level** is the quietest sound that can be heard:

$$I_0 = 1.0 \times 10^{-12}\ \text{W/m}^2$$

- The sound intensity level in dB is computed relative to this value:

$$\beta = (10\ \text{dB})\log_{10}\left(\frac{I}{I_0}\right)$$

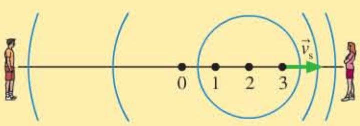
- A sound at the reference level corresponds to 0 dB.

The **Doppler effect** is a shift in frequency when there is relative motion of a wave source (frequency f_0, wave speed v) and an observer.

Moving source, stationary observer:

Receding source:

$$f_- = \frac{f_0}{1 + v_s/v}$$



Approaching source:

$$f_+ = \frac{f_0}{1 - v_s/v}$$

Moving observer, stationary source:

Approaching the source: $f_+ = \left(1 + \frac{v_o}{v}\right)f_0$

Moving away from the source: $f_- = \left(1 - \frac{v_o}{v}\right)f_0$

Reflection from a moving object:

For $v_o \ll v$, $\Delta f = \pm 2f_0\frac{v_o}{v}$

When an object moves faster than the wave speed in a medium, a **shock wave** is formed.

QUESTIONS

Conceptual Questions

1. a. In your own words, define what a *transverse wave* is.
   b. Give an example of a wave that, from your own experience, you know is a transverse wave. What observations or evidence tells you this is a transverse wave?
2. a. In your own words, define what a *longitudinal wave* is.
   b. Give an example of a wave that, from your own experience, you know is a longitudinal wave. What observations or evidence tells you this is a longitudinal wave?
3. The wave pulses shown in Figure Q15.3 travel along the same string. Rank in order, from largest to smallest, their wave speeds v_1, v_2, and v_3. Explain.

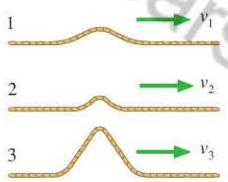


FIGURE Q15.3

4. Is it ever possible for one sound wave in air to overtake and pass another? Explain.
5. A wave pulse travels along a string at a speed of 200 cm/s. What will be the speed if:
   a. The string's tension is doubled?
   b. The string's mass is quadrupled (but its length is unchanged)?
   c. The string's length is quadrupled (but its mass is unchanged)?
   d. The string's mass and length are both quadrupled?

   Note that parts a–d are independent and refer to changes made to the original string.
6. An ultrasonic range finder sends out a pulse of ultrasound and measures the time between the emission of the pulse and the return of an echo from an object. This time is used to determine the distance to the object. To get good accuracy from the device, a user must enter the air temperature in the room. Why is this?
7. A thermostat on the wall of your house keeps track of the air temperature. This simple approach is of little use in the large volume of a covered sports stadium, but there are systems that determine an average temperature of the air in a stadium by measuring the time delay between the emission of a pulse of sound on one side of the stadium and its detection on the other. Explain how such a system works.
8. When water freezes, the density decreases and the bonds between molecules become stronger. Do you expect the speed of sound to be greater in liquid water or in water ice?
9. Figure Q15.9 shows a history graph of the motion of one point on a string as a wave traveling to the left passes by. Sketch a snapshot graph for this wave.

FIGURE Q15.9

10. Figure Q15.10 shows a history graph *and* a snapshot graph for a wave pulse on a string. They describe the same wave from two perspectives.
    a. In which direction is the wave traveling? Explain.
    b. What is the speed of this wave?

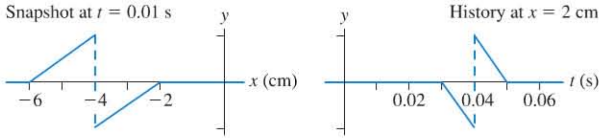


FIGURE Q15.10

11. Rank in order, from largest to smallest, the wavelengths λ_1 to λ_3 for sound waves having frequencies $f_1 = 100$ Hz, $f_2 = 1000$ Hz, and $f_3 = 10{,}000$ Hz. Explain.
12. Explain why there is a factor of 2π in Equation 15.5.
13. BIO Bottlenose dolphins use echolocation pulses with a frequency of about 100 kHz, higher than the frequencies used by most bats. Why might you expect these water-dwelling creatures to use higher echolocation frequencies than bats?

14. A laser beam has intensity I_0.
    a. What is the intensity, in terms of I_0, if a lens focuses the laser beam to 1/10 its initial diameter?
    b. What is the intensity, in terms of I_0, if a lens defocuses the laser beam to 10 times its initial diameter?
15. Sound wave A delivers 2 J of energy in 2 s. Sound wave B delivers 10 J of energy in 5 s. Sound wave C delivers 2 mJ of energy in 1 ms. Rank in order, from largest to smallest, the sound powers P_A, P_B, and P_C of these three waves. Explain.
16. When you want to "snap" a towel, the best way to wrap the towel is so that the end that you hold and shake is thick, and the far end is thin. When you shake the thick end, a wave travels down the towel. How does wrapping the towel in a tapered shape help make for a good snap?
    Hint: Think about the speed of the wave as it moves down the towel.
17. The volume control on your stereo is likely designed so that each time you turn it by one click, the loudness increases by a certain number of dB. Does each click increase the output power by a fixed amount as well?
18. A bullet can travel at a speed of over 1000 m/s. When a bullet is fired from a rifle, the actual firing makes a distinctive sound, but people at a distance may hear a second, different sound that is even louder. Explain the source of this sound.

19. You are standing at $x = 0$ m, listening to seven identical sound sources described by Figure Q15.19. At $t = 0$ s, all seven are at $x = 343$ m and moving as shown below. The sound from all seven will reach your ear at $t = 1$ s. Rank in order, from highest to lowest, the seven frequencies f_1 to f_7 that you hear at $t = 1$ s. Explain.

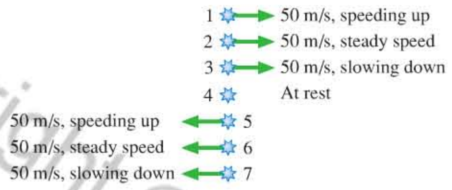


FIGURE Q15.19

Multiple-Choice Questions

20. | Denver, Colorado, has an oldies station that calls itself "KOOL 105." This means that they broadcast radio waves at a frequency of 105 MHz. Suppose that they decide to describe their station by its wavelength (in meters), instead of by its frequency. What name would they now use?
A. KOOL 0.35 B. KOOL 2.85
C. KOOL 3.5 D. KOOL 285

21. | What is the frequency of blue light with a wavelength of 400nm?
A. 1.33×10^3 Hz B. 7.50×10^{12} Hz
C. 1.33×10^{14} Hz D. 7.50×10^{14} Hz

22. | Ultrasound can be used to deliver energy to tissues for therapy. It can penetrate tissue to a depth approximately 200 times its wavelength. What is the approximate depth of penetration of ultrasound at a frequency of 5.0 MHz?
BIO
A. 0.29 mm B. 1.4 cm
C. 6.2 cm D. 17 cm

23. | A sinusoidal wave traveling on a string has a period of 0.20 s, a wavelength of 32 cm, and an amplitude of 3 cm. The speed of this wave is
A. 0.60 cm/s. B. 6.4 cm/s.
C. 15 cm/s. D. 160 cm/s.

24. || Two strings of different linear density are joined together and pulled taut. A sinusoidal wave on these strings is traveling to the right, as shown in Figure Q15.24. When the wave goes across the boundary from string 1 to string 2, the frequency is unchanged. What happens to the velocity?

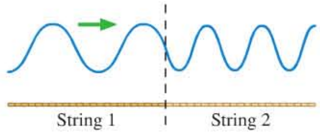


FIGURE Q15.24

A. The velocity increases.
B. The velocity stays the same.
C. The velocity decreases.

25. || You stand at $x = 0$ m, listening to a sound that is emitted at frequency f_0. Figure Q15.25 shows the frequency you hear during a four-second interval. Which of the following describes the motion of the sound source?

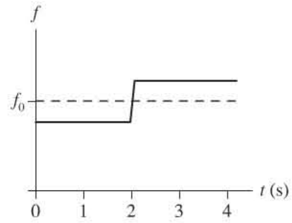


FIGURE Q15.25

A. It moves from left to right and passes you at $t = 2$ s.
B. It moves from right to left and passes you at $t = 2$ s.
C. It moves toward you but doesn't reach you. It then reverses direction at $t = 2$ s.
D. It moves away from you until $t = 2$ s. It then reverses direction and moves toward you but doesn't reach you.

PROBLEMS

Section 15.1 The Wave Model

Section 15.2 Traveling Waves

1. || The wave speed on a string under tension is 200 m/s. What is the speed if the tension is doubled?
2. || The wave speed on a string is 150 m/s when the tension is 75.0 N. What tension will give a speed of 180 m/s?
3. || A wave travels along a string at a speed of 280 m/s. What will be the speed if the string is replaced by one made of the same material and under the same tension but having twice the radius?
4. || The back wall of an auditorium is 26.0 m from the stage. If you are seated in the middle row, how much time elapses between a sound from the stage reaching your ear directly and the same sound reaching your ear after reflecting from the back wall?
5. |||| A hammer taps on the end of a 4.00-m-long metal bar at room temperature. A microphone at the other end of the bar picks up two pulses of sound, one that travels through the metal and one that travels through the air. The pulses are separated in time by 11.0 ms. What is the speed of sound in this metal?
6. || In an early test of sound propagation through the ocean, an underwater explosion of 1 pound of dynamite in the Bahamas was detected 3200 km away on the coast of Africa. How much time elapsed between the explosion and the detection?

Section 15.3 Graphical and Mathematical Descriptions of Waves

7. || Figure P15.7 is a snapshot graph of a wave at $t = 0$ s. Draw the history graph for this wave at $x = 6$ m, for $t = 0$ s to 6 s.

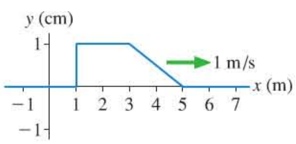


FIGURE P15.7

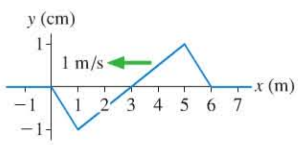


FIGURE P15.8

8. || Figure P15.8 is a snapshot graph of a wave at $t = 2$ s. Draw the history graph for this wave at $x = 0$ m, for $t = 0$ s to 8 s.

9. ||| Figure P15.9 is a history graph at $x = 0$ m of a wave moving to the right at 1 m/s. Draw a snapshot graph of this wave at $t = 1$ s.

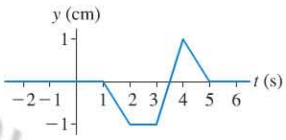


FIGURE P15.9

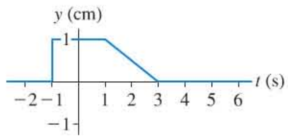


FIGURE P15.10

10. ||| Figure P15.10 is a history graph at $x = 2$ m of a wave moving to the left at 1 m/s. Draw the snapshot graph of this wave at $t = 0$ s.

11. | A sinusoidal wave has period 0.20 s and wavelength 2.0 m. What is the wave speed?

12. | A sinusoidal wave travels with speed 200 m/s. Its wavelength is 4.0 m. What is its frequency?

13. || The motion detector used in a physics lab sends and receives 40 kHz ultrasonic pulses. A pulse goes out, reflects off the object being measured, and returns to the detector. The lab temperature is 20°C.
 a. What is the wavelength of the waves emitted by the motion detector?
 b. How long does it take for a pulse that reflects off an object 2.5 m away to make a round trip?

14. | The displacement of a wave traveling in the positive x-direction is $y(x, t) = (3.5\text{ cm})\cos(2.7x - 92t)$, where x is in m and t is in s. What are the (a) frequency, (b) wavelength, and (c) speed of this wave?

15. || The displacement of a wave traveling in the negative x-direction is $y(x, t) = (5.2\text{ cm})\cos(5.5x + 72t)$, where x is in m and t is in s. What are the (a) frequency, (b) wavelength, and (c) speed of this wave?

16. ||| A traveling wave has displacement given by $y(x, t) = (2.0\text{cm}) \times \cos(2\pi x - 4\pi t)$, where x is measured in cm and t in s.
 a. Draw a snapshot graph of this wave at $t = 0$ s.
 b. On the same set of axes, use a dotted line to show the snapshot graph of the wave at $t = 1/8$ s.
 c. What is the speed of the wave?

17. | Figure P15.17 is a snapshot graph of a wave at $t = 0$ s. What are the amplitude, wavelength, and frequency of this wave?

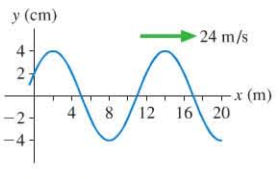


FIGURE P15.17

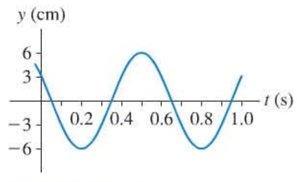


FIGURE P15.18

18. | Figure P15.18 is a history graph at $x = 0$ m of a wave moving to the right at 2 m/s. What are the amplitude, frequency, and wavelength of this wave?

19. |||| A boat is traveling at 4.0 m/s in the same direction as an ocean wave of wavelength 30 m and speed 6.8 m/s. If the boat is on the crest of a wave, how much time will elapse until the boat is next on a crest?

20. ||| In the deep ocean, a water wave with wavelength 95 m travels at 12 m/s. Suppose a small boat is at the crest of this wave, 1.2 m above the equilibrium position. What will be the vertical position of the boat 5.0 s later?

Section 15.4 Sound and Light Waves

21. | BIO A dolphin emits ultrasound at 100 kHz and uses the timing of reflections to determine the position of objects in the water. What is the wavelength of this ultrasound?

22. || a. What is the wavelength of a 2.0 MHz ultrasound wave traveling through aluminum?
 b. What frequency of electromagnetic wave would have the same wavelength as the ultrasound wave of part a?

23. | a. At 20°C, what is the frequency of a sound wave in air with a wavelength of 20 cm?
 b. What is the frequency of an electromagnetic wave with a wavelength of 20 cm?
 c. What would be the wavelength of a sound wave in water that has the same frequency as the electromagnetic wave of part b?

24. || a. What is the frequency of blue light that has a wavelength of 450 nm?
 b. What is the frequency of red light that has a wavelength of 650 nm?

25. || a. Telephone signals are often transmitted over long distances by microwaves. What is the frequency of microwave radiation with a wavelength of 3.0 cm?
 b. Microwave signals are beamed between two mountaintops 50 km apart. How long does it take a signal to travel from one mountaintop to the other?

26. || a. An FM radio station broadcasts at a frequency of 101.3 MHz. What is the wavelength?
 b. What is the frequency of a sound source that produces the same wavelength in 20°C air?

Section 15.5 Energy and Intensity

27. || BIO INT Sound is detected when a sound wave causes the eardrum to vibrate (see Figure 14.26). Typically, the diameter of the eardrum is about 8.4 mm in humans. When someone speaks to you in a normal tone of voice, the sound intensity at your ear is approximately $1.0 \times 10^{-6}\text{ W/m}^2$. How much energy is delivered to your eardrum each second?

28. ||| BIO INT At a rock concert, the sound intensity 1.0 m in front of the bank of loudspeakers is 0.10 W/m^2. A fan is 30 m from the loudspeakers. Her eardrums have a diameter of 8.4 mm. How much sound energy is transferred to each eardrum in 1.0 second?

29. ||| The intensity of electromagnetic waves from the sun is 1.4 kW/m^2 just above the earth's atmosphere. Eighty percent of this reaches the surface at noon on a clear summer day. Suppose you model your back as a 30 cm × 50 cm rectangle. How many joules of solar energy fall on your back as you work on your tan for 1.0 hr?

30. || The sun emits electromagnetic waves with a power of 4.0×10^{26} W. Determine the intensity of electromagnetic waves from the sun just outside the atmospheres of (a) Venus, (b) Mars, and (c) Saturn. Refer to the table of astronomical data inside the back cover.

31. ||| A large solar panel on a spacecraft in Earth orbit produces 1.0 kW of power when the panel is turned toward the sun. What power would the solar cell produce if the spacecraft were in orbit around Saturn, 9.5 times as far from the sun?

32. ||| Solar cells convert the energy of incoming light to electric energy; a good quality cell operates at an efficiency of 15%. Each person in the United States uses energy (for lighting, heating, transportation, etc.) at an average rate of 11 kW. Although

sunlight varies with season and time of day, solar energy falls on the United States at an average intensity of 200 W/m^2. Assuming you live in an average location, what total solar-cell area would you need to provide all of your energy needs with energy from the sun?

33. BIO LASIK eye surgery uses pulses of laser light to shave off tissue from the cornea, reshaping it. A typical LASIK laser emits a 1.0-mm-diameter laser beam with a wavelength of 193 nm. Each laser pulse lasts 15 ns and contains 1.0 mJ of light energy.
    a. What is the power of one laser pulse?
    b. During the very brief time of the pulse, what is the intensity of the light wave?

Section 15.6 Loudness of Sound

34. What is the sound intensity level of a sound with an intensity of 3.0×10^{-6} W/m^2?
35. What is the sound intensity of a whisper at a distance of 2.0 m, in W/m^2? What is the corresponding sound intensity level in dB?
36. You hear a sound at 65 dB. What is the sound intensity level if the intensity of the sound is doubled?
37. The sound intensity from a jack hammer breaking concrete is 2.0 W/m^2 at a distance of 2.0 m from the point of impact. This is sufficiently loud to cause permanent hearing damage if the operator doesn't wear ear protection. What are (a) the sound intensity and (b) the sound intensity level for a person watching from 50 m away?
38. A concert loudspeaker suspended high off the ground emits 35 W of sound power. A small microphone with a 1.0 cm^2 area is 50 m from the speaker. What are (a) the sound intensity and (b) the sound intensity level at the position of the microphone?
39. A rock band playing an outdoor concert produces sound at 120 dB 5.0 m away from their single working loudspeaker. What is the sound intensity level 35 m from the speaker?
40. BIO Your ears are sensitive to differences in pitch, but they are not very sensitive to differences in intensity. You are not capable of detecting a difference in sound intensity level of less than 1 dB. By what factor does the sound intensity increase if the sound intensity level increases from 60 dB to 61 dB?

Section 15.7 The Doppler Effect and Shock Waves

41. An opera singer in a convertible sings a note at 600 Hz while cruising down the highway at 90 km/hr. What is the frequency heard by
    a. A person standing beside the road in front of the car?
    b. A person standing beside the road behind the car?
42. BIO An osprey's call is a distinct whistle at 2200 Hz. An osprey calls while diving at you, to drive you away from her nest. You hear the call at 2300 Hz. How fast is the osprey approaching?
43. A whistle you use to call your hunting dog has a frequency of 21 kHz, but your dog is ignoring it. You suspect the whistle may not be working, but you can't hear sounds above 20 kHz. To test it, you ask a friend to blow the whistle, then you hop on your bicycle. In which direction should you ride (toward or away from your friend) and at what minimum speed to know if the whistle is working?
44. A friend of yours is loudly singing a single note at 400 Hz while driving toward you at 25.0 m/s on a day when the speed of sound is 340 m/s.
    a. What frequency do you hear?
    b. What frequency does your friend hear if you suddenly start singing at 400 Hz?
45. While anchored in the middle of a lake, you count exactly three waves hitting your boat every 10 s. You raise anchor and start motoring slowly in the same direction the waves are going. When traveling at 1.5 m/s, you notice that exactly two waves are hitting the boat from behind every 10 s. What is the speed of the waves on the lake?
46. BIO A Doppler blood flow unit emits ultrasound at 5.0 MHz. What is the frequency shift of the ultrasound reflected from blood moving in an artery at a speed of 0.20 m/s?

General Problems

47. You're watching a carpenter pound a nail. He hits the nail twice a second, but you hear the sound of the strike when his hammer is fully raised. What is the minimum distance from you to the carpenter? Assume the air temperature is 20°C.
48. A 2.50 kHz sound wave is transmitted through an aluminum rod.
    a. What is its wavelength in the aluminum?
    b. What is the sound wave's frequency when it passes into the air?
    c. What is its wavelength in air?
49. Oil explorers set off explosives to make loud sounds, then listen for the echoes from underground oil deposits. Geologists suspect that there is oil under 500-m-deep Lake Physics. It's known that Lake Physics is carved out of a granite basin. Explorers detect a weak echo 0.94 s after exploding dynamite at the lake surface. If it's really oil, how deep will they have to drill into the granite to reach it?
50. A 2.0-m-long string is under 20 N of tension. A pulse travels the length of the string in 50 ms. What is the mass of the string?
51. INT A stout cord is stretched between two fixed supports. You vigorously shake one end of the string and send a sinusoidal wave of wavelength 4.0 m along it at 16 m/s. The amplitude of the motion is 2.0 cm. What are the maximum speed and maximum acceleration of a point on the string as the wave passes?
52. BIO INT A female orb spider has a mass of 0.50 g. She is suspended from a tree branch by a 1.1 m length of 0.0020-mm-diameter silk. Spider silk has a density of 1300 kg/m^3. If you tap the branch and send a vibration down the thread, how long does it take to reach the spider?
53. INT Andy (mass 80 kg) uses a 3.0-m-long rope to pull Bob (mass 60 kg) across the floor ($\mu_k = 0.20$) at a constant speed of 1.0 m/s. Bob signals to Andy to stop by "plucking" the rope, sending a wave pulse forward along the rope. The pulse reaches Andy 150 ms later. What is the mass of the rope?
54. If a bungee cord is stretched horizontally to a length of 2.5 m, the tension in the cord is 2.1 N. A transverse pulse on the cord travels from one end to the other in 0.80 s. If the cord is stretched to a length of 3.5 m, the pulse takes the same time of 0.80 s to travel from one end to the other. What is the tension in the cord when it is stretched to this length?
55. String 1 in Figure P15.55 has linear density 2.0 g/m and string 2 has linear density 4.0 g/m. A student sends pulses in both directions by quickly pulling up on the knot, then releasing it. What should the string lengths L_1 and L_2 be if the pulses are to reach the ends of the strings simultaneously?

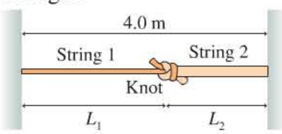


FIGURE P15.55

56. INT In 2003, an earthquake in Japan generated waves that traveled outward at 7.0 km/s. 200 km to the west, seismic instruments recorded an acceleration of 0.25g along the east-west axis at a frequency of 1.1 Hz.

a. How much time elapsed between the earthquake and the first detection of the waves?
b. Was this a transverse or a longitudinal wave?
c. What was the wavelength?
d. What was the maximum horizontal displacement of the ground as the wave passed?

57. ||| A coyote can locate a sound source with good accuracy by comparing the arrival times of a sound wave at its two ears. Suppose a coyote is listening to a bird whistling at 1000 Hz. The bird is 3.0 m away, directly in front of the coyote's right ear. The coyote's ears are 15 cm apart.
BIO
a. What is the distance between the bird and the coyote's left ear?
b. What is the difference in the arrival time of the sound at the left ear and the right ear?
c. What is the ratio of this time difference to the period of the sound wave?

Hint: You are looking for the difference between two numbers that are nearly the same. What does this near equality imply about the necessary precision during intermediate stages of the calculation?

58. || An earthquake produces longitudinal P waves that travel outward at 8000 m/s and transverse S waves that move at 4500 m/s. A seismograph at some distance from the earthquake records the arrival of the S waves 2.0 min after the arrival of the P waves. How far away was the earthquake? You can assume that the waves travel in straight lines, although actual seismic waves follow more complex routes.

59. |||| One way to monitor global warming is to measure the average temperature of the ocean. Researchers are doing this by measuring the time it takes sound pulses to travel underwater over large distances. At a depth of 1000 m, where ocean temperatures hold steady near 4°C, the average sound speed is 1480 m/s. It's known from laboratory measurements that the sound speed increases 4.0 m/s for every 1.0°C increase in temperature. In one experiment, where sounds generated near California are detected in the South Pacific, the sound waves travel 8000 km. If the smallest time change that can be reliably detected is 1.0 s, what is the smallest change in average temperature that can be measured?

60. ||| Figure P15.60 shows two snapshot graphs taken 10 ms apart, with the blue curve being the first snapshot. What are the (a) wavelength, (b) speed, (c) frequency, and (d) amplitude of this wave?

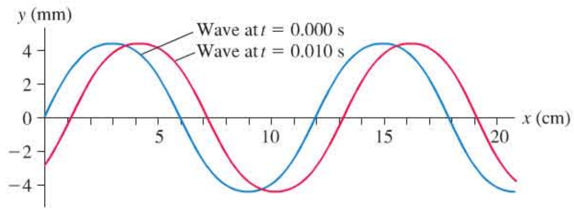


FIGURE P15.60

61. || Low-frequency vertical oscillations are one possible cause of motion sickness, with 0.3 Hz having the strongest effect. Your boat is bobbing in place at just the right frequency to cause you the maximum discomfort.
BIO
a. How much time elapses between two waves hitting the ship?
b. If the wave crests appear to be about 30 m apart, what would you estimate to be the speed of the waves?

62. ||| A wave on a string is described by $y(x, t) = (3.0\text{ cm})\times\cos[2\pi(x/(2.4\text{ m}) + t/(0.20\text{ s}))]$, where x is in m and t in s.
a. In what direction is this wave traveling?
b. What are the wave speed, frequency, and wavelength?
c. At $t = 0.50$ s, what is the displacement of the string at $x = 0.20$ m?

63. | Write the y-equation for a wave traveling in the negative x-direction with wavelength 50 cm, speed 4.0 m/s, and amplitude 5.0 cm.

64. | Write the y-equation for a wave traveling in the positive x-direction with frequency 200 Hz, speed 400 m/s, and amplitude 0.010 mm.

65. | A wave is described by the expression $y(x, t) = (3.0\text{ cm})\times\cos(1.5x - 50t)$, where x is in m and t is in s.
a. Draw an accurate snapshot graph of this wave.
b. What is the speed of the wave and in what direction is it traveling?

66. ||| A point on a string undergoes simple harmonic motion as a sinusoidal wave passes. When a sinusoidal wave with speed 24 m/s, wavelength 30 cm, and amplitude of 1.0 cm passes, what is the maximum speed of a point on the string?
INT

67. ||| A simple pendulum is made by attaching a small cup of sand with a hole in the bottom to a 1.2-m-long string. The pendulum is mounted on the back of a small motorized car. As the car drives forward, the pendulum swings from side to side and leaves a trail of sand as shown in Figure P15.67. How fast was the car moving?
INT

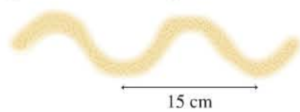


FIGURE P15.67

68. || a. A typical 100 W lightbulb produces 4.0 W of visible light. (The other 96 W are dissipated as heat and infrared radiation.) What is the light intensity on a wall 2.0 m away from the lightbulb?
b. A krypton laser produces a cylindrical red laser beam 2.0 mm in diameter with 2.0 W of power. What is the light intensity on a wall 2.0 m away from the laser?

69. || An AM radio station broadcasts with a power of 25 kW at a frequency of 920 kHz. Estimate the intensity of the radio wave at a point 10 km from the broadcast antenna.

70. ||| The earth's average distance from the sun is 1.50×10^{11} m. At this distance, the intensity of radiation from the sun is 1.38 kW/m^2. The earth's radius is 6.37×10^6 m. What is the total solar power received by the earth? (For comparison, total human power consumption is roughly 10^{13} W.)

71. || Lasers can be used to drill or cut material. One such laser generates a series of high-intensity pulses rather than a continuous beam of light. Each pulse contains 500 mJ of energy and lasts 10 ns. The laser fires 10 such pulses per second.
a. What is the *peak power* of the laser light? The peak power is the power output during one of the 10 ns pulses.
b. What is the average power output of the laser? The average power is the total energy delivered per second.
c. A lens focuses the laser beam to a 10-μm-diameter circle on the target. During a pulse, what is the light intensity on the target?
d. The intensity of sunlight at the surface of the earth at midday is about 1100 W/m^2. What is the ratio of the laser intensity on the target to the intensity of the midday sun?

72. || The quietest sound you can hear is 0 dB. Estimate the diameter of your ear canal and compute an approximate area. At 0 dB, how much sound power is "captured" by one ear? (Ignore any focusing of energy by the pinna, the external folds of your ear.)
BIO

73. The sound intensity 50 m from a wailing tornado siren is $0.10\ \text{W/m}^2$.
  a. What is the sound intensity level?
  b. In a noisy neighborhood, the weakest sound likely to be heard over background noise is 60 dB. Estimate the maximum distance at which the siren can be heard.

74. BIO A harvest mouse can detect sounds as quiet as -10 dB. Suppose you are sitting in a field on a very quiet day while a harvest mouse sits nearby at the entrance to its nest. A very gentle breeze causes a leaf 1.5 m from your head to rustle, generating a faint sound right at the limit of your ability to hear it. The sound of the rustling leaf is also right at the threshold of hearing of the harvest mouse. How far is the harvest mouse from the leaf?

75. A speaker at an open-air concert emits 600 W of sound power, radiated equally in all directions.
  a. What is the intensity of the sound 5.0 m from the speaker?
  b. What sound intensity level would you experience there if you did not have any protection for your ears?
  c. Earplugs you can buy in the drugstore have a noise reduction rating of 23 decibels. If you are wearing those earplugs but your friend Phil is not, how far from the speaker should Phil stand to experience the same loudness as you?

76. BIO A bat locates insects by emitting ultrasonic "chirps" and then listening for echoes. The lowest-frequency chirp of a big brown bat is 26 kHz. How fast would the bat have to fly, and in what direction, for you to just barely be able to hear the chirp at 20 kHz?

77. INT A physics professor demonstrates the Doppler effect by tying a 600 Hz sound generator to a 1.0-m-long rope and whirling it around her head in a horizontal circle at 100 rpm. What are the highest and lowest frequencies heard by a student in the classroom? Assume the room temperature is 20°C.

78. Ocean waves with wavelength 1.2 m and period 1.5 s are moving past a pier. A boy runs along the pier, in the direction opposite to the motion of the wave, at 3.5 m/s. How many wave crests pass the boy each second?

79. A source of sound moves toward you at speed v_s and away from Jane, who is standing on the other side of it. You hear the sound at twice the frequency as Jane. What is the speed of the source? Assume that the speed of sound is 340 m/s.

80. BIO INT When the heart pumps blood into the aorta, the *pressure gradient*—the difference between the blood pressure inside the heart and the blood pressure in the artery—is an important diagnostic measurement. A direct measurement of the pressure gradient is difficult, but an indirect determination can be made by measuring the Doppler shift of reflected ultrasound. Blood is essentially at rest in the heart; when it leaves and enters the aorta, it speeds up significantly and—according to Bernoulli's equation—the pressure must decrease. A doctor using ultrasound of 2.5 MHz measures a 6000 Hz frequency shift as the ultrasound reflects from blood ejected from the heart.
  a. What is the speed of the blood in the aorta?
  b. What is the difference in blood pressure between the inside of the heart and the aorta? Assume that the patient is lying down and that there is no difference in height as the blood moves from the heart into the aorta.

Passage Problems

Echolocation BIO

As discussed in the chapter, many species of bats find flying insects by emitting pulses of ultrasound and listening for the reflections. This technique is called **echolocation**. Bats possess several adaptations that allow them to echolocate very effectively.

81. Although we can't hear them, the ultrasonic pulses are very loud. In order not to be deafened by the sound they emit, bats can temporarily turn off their hearing. Muscles in the ear cause the bones in their middle ear to separate slightly, so that they don't transmit vibrations to the inner ear. After an ultrasound pulse ends, a bat can hear an echo from an object a minimum of 1 m away. Approximately how much time after a pulse is emitted is the bat ready to hear its echo?
  A. 0.5 ms B. 1 ms C. 3 ms D. 6 ms

82. Bats are sensitive to very small changes in frequency of the reflected waves. What information does this allow them to determine about their prey?
  A. Size B. Speed C. Distance D. Species

83. Some bats have specially shaped noses that they use to focus the ultrasound pulses in the forward direction. Why is this useful?
  A. They are not distracted by echoes from several directions.
  B. The energy of the pulse is concentrated in a smaller area, so the intensity is larger.
  C. The pulse goes forward only, so it doesn't affect the bat's hearing.

84. Some bats utilize a sound pulse with a rapidly decreasing frequency. A decreasing-frequency pulse has
  A. Decreasing wavelength.
  B. Decreasing speed.
  C. Increasing wavelength.
  D. Increasing speed.

STOP TO THINK ANSWERS

Stop to Think 15.1: Transverse. The wave moves horizontally through the crowd, but individual spectators move up and down, transverse to the motion of the wave.

Stop to Think 15.2: D, E. Shaking your hand faster or farther will change the shape of the wave, but this will not change the wave speed; the speed is a property of the medium. Changing the linear density of the string or its tension will change the wave speed. To increase the speed, you must decrease the linear density or increase the tension.

Stop to Think 15.3: B. All three waves have the same speed, so the frequency is highest for the wave that has the shortest wavelength. (Imagine the three waves moving to the right; the one with the crests closest together has the crests passing by most rapidly.)

Stop to Think 15.4: A. The plane wave does not spread out, so its intensity will be constant. The other two waves spread out, so their intensity will decrease.

Stop to Think 15.5: C. The source is moving toward Zack, so he observes a higher frequency. The source is moving away from Amy, so she observes a lower frequency.