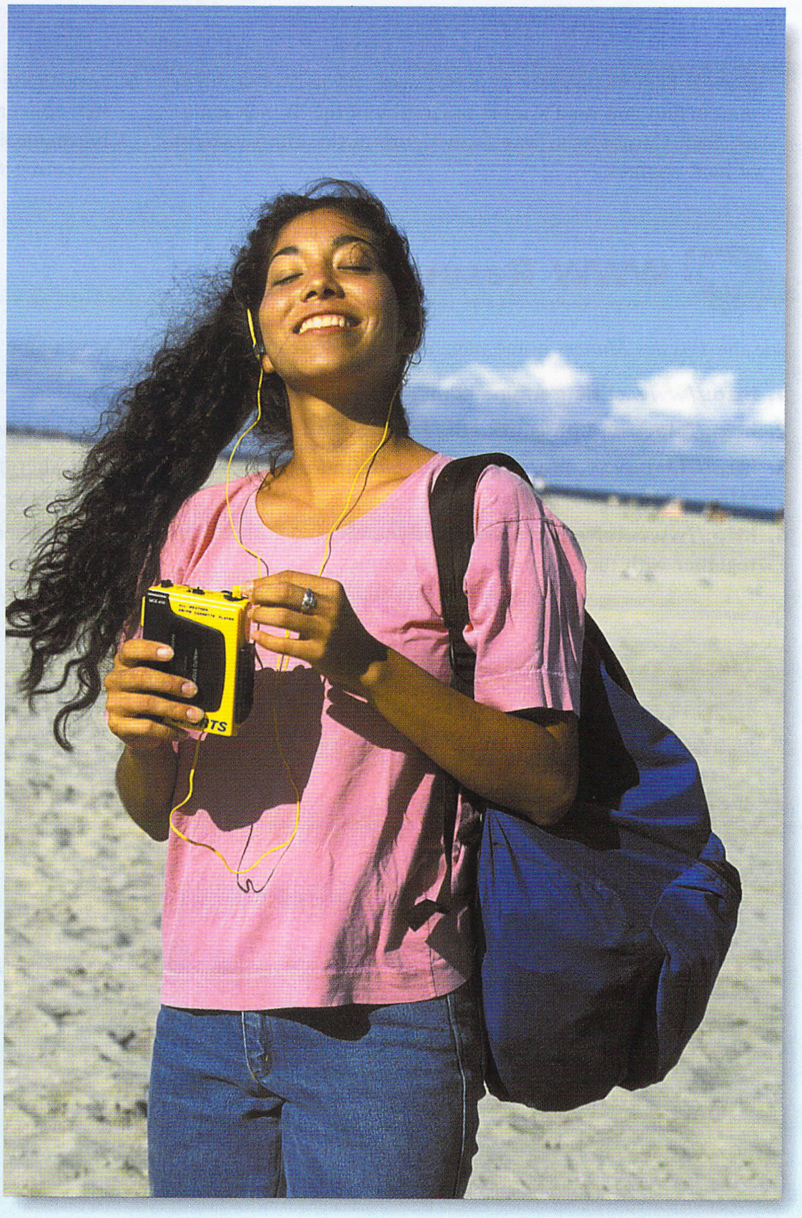
14

Vibrations and Waves

KEY IDEA

Waves carry energy from place to place without requiring matter to travel across the intervening distance.



PHYSICS AROUND US . . . A Day at the Beach

Few experiences are more relaxing than a day at the beach. The sight of waves washing ashore, the sound of good music, and the feel of the Sun's rays beating down help us forget about the pressure of exams and term papers. What might surprise you is that underlying all of these familiar experiences—ocean surf, sound, and the Sun's rays—is the phenomenon of waves.

Waves are all around us. Waves of water travel across the surface of the ocean and crash against the land. Waves of sound travel through the air when we listen to music. Some parts of the United States suffer from mighty seismic waves of rock and soil we know as "earthquakes." All of these experiences and many more are examples of waves in nature.

VIBRATIONS

The world around us is in constant motion. Ocean waves incessantly roll onto the shore, leaves flutter in the breeze, and pendulum clocks tick away the time. Even atoms and molecules wiggle constantly in their submicroscopic realm. All of these examples and countless more illustrate the phenomenon of **vibrations,** which are simply to-and-fro motions. You can watch the periodic vibrations of a child on a playground swing, feel the vibration of the ground as a train or heavy truck passes by, or hear the vibrations of a loud bell ringing the time. In all these instances, a back-and-forth motion occurs in time and space.

Vibration of a Pendulum

Have you ever watched the hypnotic swinging of a grandfather clock's pendulum? A pendulum, which is a weight suspended from a string or wire, swings back and forth with such regularity that for hundreds of years the most accurate clocks relied on their steady tick-tock motion.

The Italian physicist Galileo Galilei, who studied the behavior of falling objects (Chapter 3), also conducted pioneering experiments on pendulums. Galileo discovered that the time it takes for a pendulum to swing back and forth—its **period**—depends on its length: shorter pendulums swing faster (Figure 14-1*a*). Surprisingly, the pendulum's period does not depend on its mass or on the magnitude of the arc through which it swings (Figure 14-1*b*). You can try these experiments yourself by tying small weights to the end of a string.

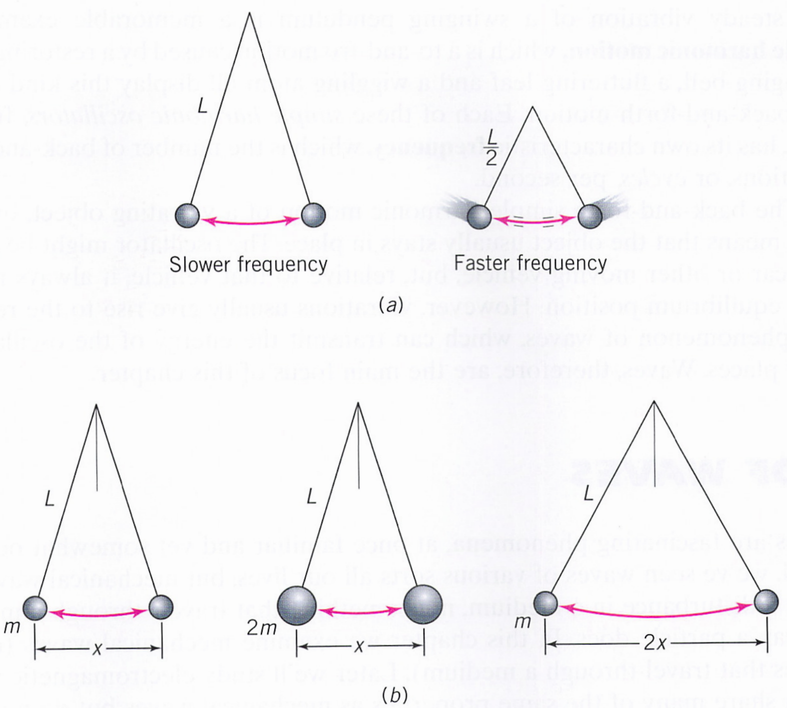


FIGURE 14-1. The periods of pendulums. (*a*) Shorter pendulums swing faster (higher frequency). (*b*) Pendulums of the same length swing at the same frequency, independent of their mass or amplitude.

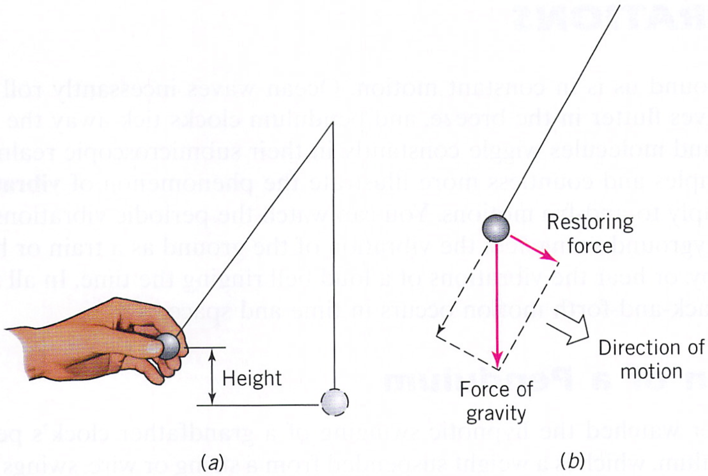


FIGURE 14-2. (*a*) Pulling a pendulum to the side increases the gravitational potential energy of the system. (*b*) Letting go of the pendulum initiates simple harmonic motion, with gravity providing the restoring force.

The steady motion of a pendulum is a consequence of gravity. You start the swinging by pushing the weight to the side, which causes it to gain gravitational potential energy (Figure 14-2*a*). When you let go, gravity acts as a *restoring force* that accelerates the weight back to swing through its central at-rest position (Figure 14-2*b*). In the absence of frictional forces, the pendulum would swing forever.

Simple Harmonic Motion

This steady vibration of a swinging pendulum is a memorable example of **simple harmonic motion,** which is a to-and-fro motion caused by a restoring force. A ringing bell, a fluttering leaf and a wiggling atom all display this kind of regular back-and-forth motion. Each of these *simple harmonic oscillators,* furthermore, has its own characteristic **frequency,** which is the number of back-and-forth vibrations, or *cycles,* per second.

The back-and-forth simple harmonic motion of a vibrating object, or oscillator, means that the object usually stays in place. The oscillator might be placed on a car or other moving vehicle, but, relative to that vehicle, it always returns to its equilibrium position. However, vibrations usually give rise to the remarkable phenomenon of waves, which can transmit the energy of the oscillator to other places. Waves, therefore, are the main focus of this chapter.

THE NATURE OF WAVES

Waves are fascinating phenomena, at once familiar and yet somewhat odd. After all, we've seen waves of various sorts all our lives, but mechanical waves are really a disturbance in a medium, not something that travels through a medium the way a particle does. In this chapter we examine mechanical waves (disturbances that travel through a medium). Later we'll study electromagnetic waves, which share many of the same properties as mechanical waves but do not need to travel in a medium. Scientists study waves by observing their distinctive behavior, particularly their unique ability to transfer energy without transferring mass. In this section we discuss some of the different properties of waves.

Energy Transfer by Waves

Energy can travel by two different carriers: the particle and the wave. For example, suppose you have a domino sitting on a table and you want to knock it over. This process requires transferring energy from you to the domino. One way to knock over the domino would be to take another domino (the "particle") and throw it. If you did this, then the muscles in your arm would impart kinetic energy to the thrown domino, which, in turn, would impart enough of that energy to the standing domino to knock it over (Figure 14-3*a*). In such a case, the energy is transferred through the motion of a solid piece of matter, as we have studied in Chapter 8.

Suppose, however, that you lined up a row of standing dominoes. If you knocked over the first domino, it would then knock over the second, which in turn would knock over the third, and so on (Figure 14-3*b*). Eventually, the falling wave of dominoes would hit the last one and you would have achieved the same result—energy has been transferred from you to the domino. In the case of the row of dominoes, however, no single object traveled from you to the most distant domino. You started a wave of falling dominoes and that wave knocked over the final one. A **wave,** then, carries energy from place to place without requiring matter to travel across the intervening distance. It's important to understand that the motion of the wave (from your hand to the final domino) is not the same as the motion of the individual dominoes in the row (which just fall over). As we shall see, these two kinds of motion—the motion of the wave and the motion of the medium—are general properties of all types of mechanical waves.

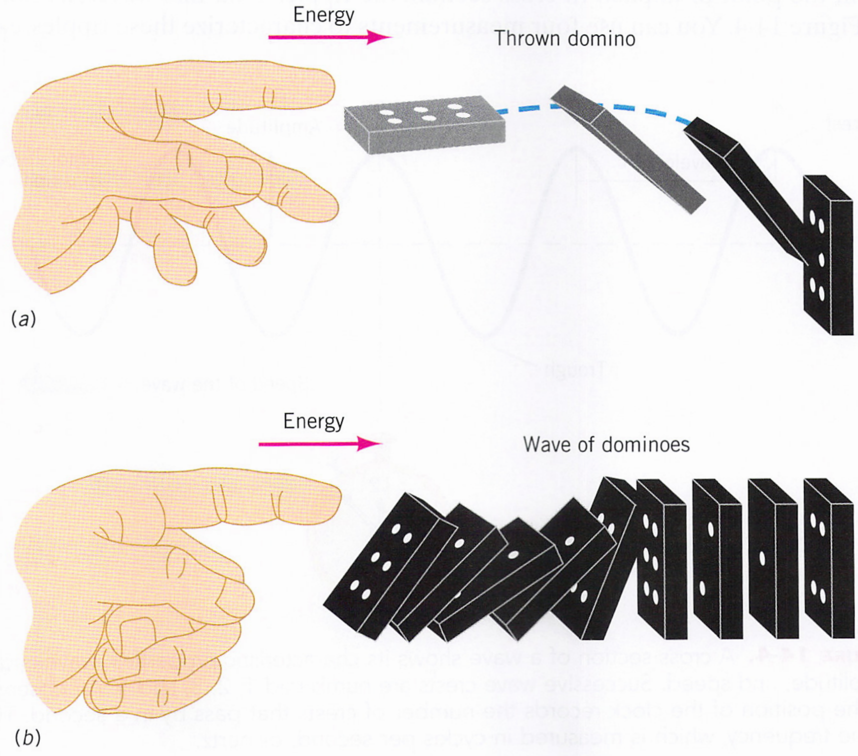


FIGURE 14-3. Two ways to knock over a domino. (*a*) You could throw another domino, thus imparting kinetic energy. (*b*) You could knock over a row of dominoes, causing a wavelike cascade.

Connection

Tsunamis

One of the most destructive waves known is the tsunami, which means "harbor wave" in Japanese. The term "tidal wave" is sometimes used, but it is a bit misleading because these waves have nothing to do with gravitationally generated tides. A tsunami is created when a geological event on the ocean floor—an undersea earthquake or a large landslide of rock off the flanks of a volcanic island—gives rise to a sudden change in the surface configuration of the sea. The effect is analogous to the wave pulse you can create by flipping one end of a rope while someone else holds the other end steady. Once the tsunami is generated, it can travel long distances—sometimes thousands of miles—and can cause great damage when it encounters land.

On April 1, 1946, this tsunami struck Hilo, Hawaii. The man in the foreground was one of 159 people killed.

A word of warning: as a tsunami approaches a shore, the water is often pulled back toward the wave. As a result, someone standing on the shore suddenly sees the ocean recede, exposing the terrain of the bottom. If you are ever on shore and see this happen, get to high ground as fast as you can—the dangerous crest of the wave won't be far away! ●

The Properties of Waves

Think about a familiar example of waves. You are standing on the banks of a quiet pond on a crisp autumn afternoon. There's no breeze and the pond in front of you is still and smooth. You pick up a rock and toss it out into the middle of the pond. As soon as the rock hits the water, a series of ripples move outward from the point of impact. In cross section, the ripples look like waves, as shown in Figure 14-4. You can use four measurements to characterize these ripples, each

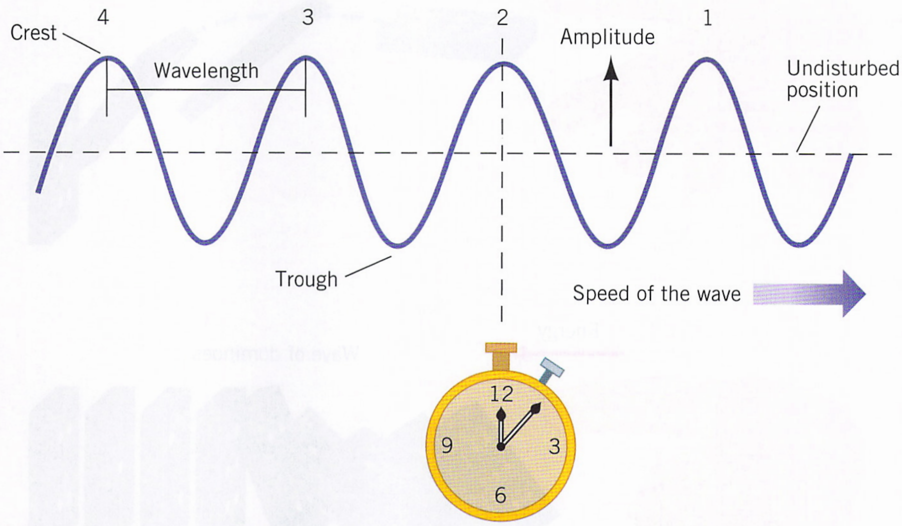


FIGURE 14-4. A cross section of a wave shows its characteristic properties: wavelength, amplitude, and speed. Successive wave crests are numbered 1, 2, 3, and 4. An observer at the position of the clock records the number of crests that pass by in a second. This is the frequency, which is measured in cycles per second, or hertz.

of which has an elevated *crest* (highest point of the wave) and a depressed *trough* (lowest point of the wave).

1. **Wavelength** is the distance between two adjacent crests—the highest points of neighboring waves. It's also the distance between two adjacent troughs or, in fact, between any two adjacent corresponding points of the wave. On a pond, the wavelength might be only a centimeter or two, while ocean waves may be tens or hundreds of meters between the crests. Wavelength is customarily represented by the Greek letter lambda (λ) and has units of distance (meters, feet, etc.).
2. The **frequency** of a wave (often represented by the letter f) is the number of wave crests that go by a given point every second. A wave that transmits one crest every second (completing one *cycle*) is said to have a frequency of 1 cycle per second or 1 **hertz** (abbreviated Hz); the units of hertz are 1/second. Small ripples on a pond might have a frequency of several hertz, while large ocean waves might arrive only once every few seconds. As with vibrations, the time for one cycle is the period of the wave, which is the reciprocal of the frequency.
3. *Velocity* is the speed and direction of the wave. Water waves typically travel a few meters per second, about the speed of walking or jogging, while sound waves travel about 340 meters (1100 feet) per second in air. (We shall see in Chapter 15 that the speed of sound can vary with temperature and altitude.)
4. **Amplitude** is the height of the wave crest above the undisturbed surface, such as the level of the calm pond before you tossed in the rock. In general terms, the amplitude is the maximum displacement of the wave from the undisturbed state of the medium, a definition that applies to all kinds of waves.

The Relationship Among Wavelength, Frequency, and Speed

A simple relationship exists among three fundamental wave measurements: wavelength, frequency, and speed. If we know any two of the three measurements, we can calculate the third using a simple equation.

1. In words:

   The speed of a wave is equal to the wavelength of the wave times the number of waves that pass by each second (frequency).

2. In an equation with words:

   Wave speed (in m/s) = Wavelength (in m) × Frequency (in Hz)

3. In an equation with symbols:

   $$v = f \times \lambda$$

   where λ and f are the common symbols for wavelength and frequency.

This simple equation holds for all kinds of waves. In fact, it is not really a new formula but just the definition of *speed* (Speed = Distance divided by Time) applied to a wave.

FIGURE 14-5. Waves passing a sailboat reveal how wavelength, speed, and frequency are related. If you know the distance between wave crests (the wavelength) and the number of crests that pass each second (the frequency), then you can calculate the wave's speed.

To understand this relationship, think about waves on the water. Suppose you are sitting on a small sailboat, as shown in Figure 14-5, watching a series of wave crests passing by. You can count the number of wave crests going by every second (the frequency) and measure the distance between the crests (the wavelength). From these two numbers, you can calculate the speed of the wave. For example, if one wave crest arrives every 2 seconds (the period is 2, so the frequency is $\frac{1}{2}$) and the wave crests are 6 meters apart (the wavelength), then the waves must be traveling 6 meters every 2 seconds, which is a speed of $6 \times \frac{1}{2} = 3$ meters per second. You might look out across the water and see a particularly large wave crest that will arrive at the boat after four intervening smaller waves. You could then predict that the big wave is 30 meters away (five times the wavelength) and that it will arrive in 10 seconds (five times the period). That kind of information can be very helpful if you are plotting the best course for an America's Cup yacht race or estimating the path of potentially destructive ocean waves.

EXAMPLE 14-1

Seismic Waves

Earthquakes usually start from disturbances in Earth's crust, as huge landmasses bang up against one another. The kind of mechanical wave generated by an earthquake is called a *seismic wave,* and it plays a major role in how we study the structure of Earth's deep interior (see Thinking More About Waves at the end of this chapter). Suppose a seismic wave is detected passing through rock at a speed of 6 kilometers per second and a frequency of 2 crests per second. What is the wavelength of this wave?

REASONING AND SOLUTION: The relationship among wavelength, frequency, and speed applies to all waves. We know that

$$\text{Wave speed (in m/s)} = \text{Wavelength (in m)} \times \text{Frequency (in Hz)}$$

In this case, the speed is 6 kilometers per second, which equals 6000 meters per second, and the frequency is 2 cycles per second, which equals 2 hertz. We can rearrange the equation to solve for wavelength:

$$\begin{aligned}\text{Wavelength (in m)} &= \frac{\text{Speed (in m/s)}}{\text{Frequency (in Hz)}}\\ &= \frac{6000 \text{ m/s}}{2 \text{ Hz}}\\ &= 3000 \text{ m}\end{aligned}$$

These seismic waves, therefore, have a long wavelength—3 kilometers or about 1.8 miles. Nevertheless, they're much shorter than Earth's diameter and thus travel many times their wavelength before they die out. ●

KINDS OF WAVES

Waves can be classified according to the different motions of the medium through which the wave passes. The most common and important kinds of waves are transverse and longitudinal waves.

Transverse Waves

Imagine that a chip of bark or a piece of grass is lying on the surface of a pond when you throw in a rock. When the ripples go by, that floating object and the water around it move up and down, but they do not move to a different spot. At the same time, however, the wave crest moves in a direction parallel to the surface of the water. This means that the motion of the wave is different from the motion of the medium on which the wave moves—a point we made earlier about the wave in the row of dominoes. A wave like that on water, in which the motion of the medium (water in this case) is perpendicular to the direction of the wave, is called a *transverse wave.* Another example of a transverse wave is a wave transmitted along a stretched rope, string, or Slinky (Figure 14-6*a*).

You can observe (and participate in) this phenomenon if you ever go to a sporting event in a crowded stadium where fans "do the wave." Each individual simply stands up and sits down, but the visual effect is of a giant sweeping motion around the entire stadium. In this way, waves can move great distances, even though individual pieces of the transmitting medium hardly move at all.

Longitudinal Waves

Not all waves are transverse waves, like those on a rope. Sound is another form of wave, a wave that moves through the air and other media. When you talk, for example, your vocal cords move air molecules back and forth. The vibrations of these air molecules set the adjacent molecules in motion, which set the next group of molecules in motion, and so forth. A spherical sound wave moves out from your mouth, consisting of molecules of the air in motion, producing regions of alternately higher pressure (or compression) and lower pressure (or rarefaction). If you could see this wave, it would look very much like the ripples on a pond. The only difference is that in the air the wave crest that is moving out is not a raised portion of a water surface, but a denser region of air molecules. As a sound wave moves through the air, gas molecules vibrate forward and back in the same direction as (along) the wave. Sound, therefore, is a *longitudinal wave* (Figure 14-6*b*).

We explore more properties of sound waves in the next chapter. Suffice it to say that this longitudinal motion is very different from the transverse wave of a ripple in water, in which the water molecules move perpendicular to the direction of the waves. Note that in either longitudinal or transverse waves, the energy always moves in the direction of the wave, whether along a line like a rope, across a surface like a pond, or in all directions like a sound wave from your mouth. What is different is the direction of motion of the particles of the medium.

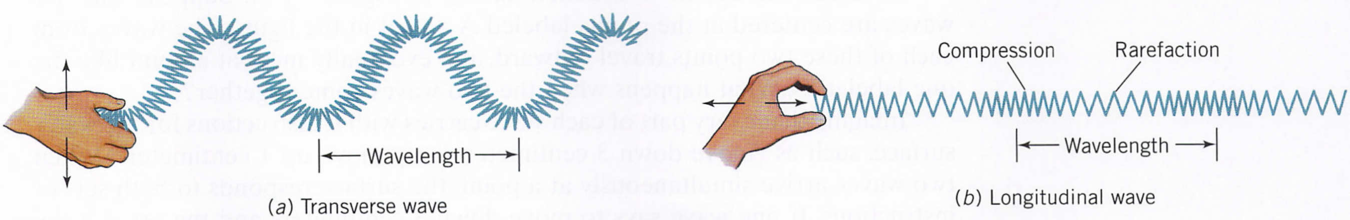


FIGURE 14-6. Two different kinds of waves. (*a*) in a transverse wave, the medium moves perpendicular to the direction of the wave. (*b*) In a longitudinal wave, the medium moves in the same direction as the wave.

Develop Your Intuition: Doing the Wave

Let's look again at the "wave" that fans in a large stadium sometimes do during ball games. Watching from a distance, you see a steady motion around and around the entire stadium. In this transverse wave, the individual people are the particles of the medium that move up and down, while the wave moves round and round. But think for a moment. Could fans in a stadium ever produce a longitudinal wave?

In a longitudinal wave, the fans (the transmitting medium in this case) would have to move in the same direction as the wave. One way to accomplish this would be to have everyone lean quickly to the right as the wave crest arrives, then slowly straighten up again. It might not look as impressive as the usual "wave," but it would be longitudinal.

INTERACTIONS OF TWO OR MORE WAVES

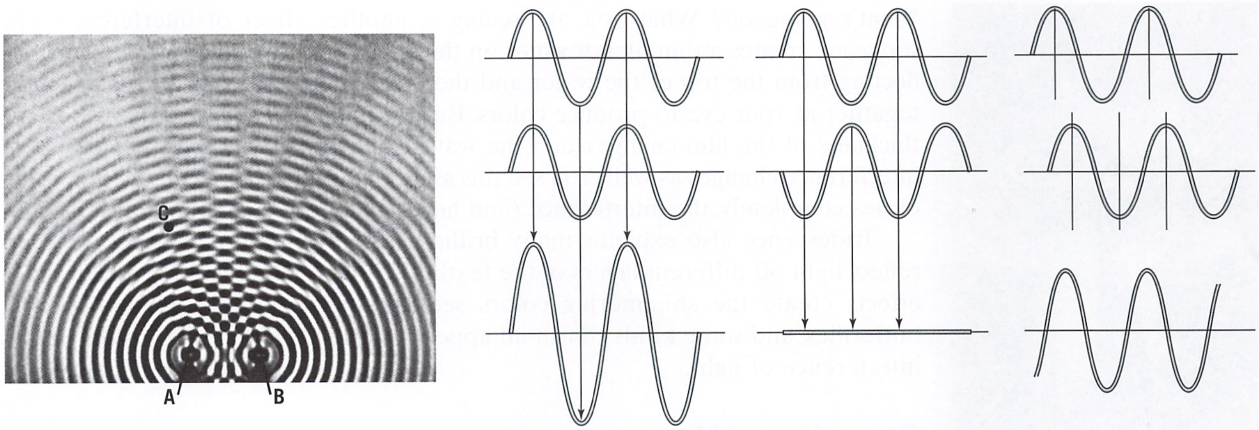
Have you ever noticed how many different sources of sound you can hear at one time? For example, you can be driving in your car with the radio on and talking to your friends in the back seat at the same time, while still hearing the sounds of traffic outside. All of these different sound waves reach your ears at the same time, but you can recognize each one individually. How does that happen? To understand how our ears can perform this seemingly miraculous task, we need to consider how waves interact with one another.

Interference

One of the most striking features of waves occurs when waves from different sources overlap each other. This phenomenon, called **interference,** describes what happens when waves from two different sources come together at a single point. For instance, imagine that in our example of the pond, you throw two pebbles instead of one. In this case, two sets of ripples move out over the surface of the pond. One set is centered at the spot where the first pebble fell, while the other is centered where the second pebble fell. When the ripples overlap, we have two waves coming together from different sources. In this case each wave interferes with the other, and the height of the observed wave at every point is the sum of the heights (positive or negative) of the interfering waves.

Consider the common situation shown in Figure 14-7*a*. Suppose the two waves are centered at the points labeled A and B in the figure. The waves from each of these two points travel outward, and eventually meet at a point like the one labeled C. What happens when the two waves come together?

Imagine that every part of each wave carries with it instructions for the water surface, such as "move down 3 centimeters," or "move up 1 centimeter." When two waves arrive simultaneously at a point, the surface responds to both sets of instructions. If one wave says to move down 3 centimeters and the other wave says to move up 1 centimeter, the result is that the water surface moves down 2 centimeters.



(*a*) (*b*) Constructive interference (*c*) Destructive interference (*d*) Complex interference

FIGURE 14-7. Examples of interference. (*a*) Two ripples start at points A and B; waves travel outward and eventually meet at a point like the one labeled C. The results can be (*b*) constructive interference, (*c*) destructive interference, or (*d*) more complex interference.

Each point on the surface of the water, then, moves a different distance up or down, depending on the instructions that are brought to it by the waves from point A and point B. One possible situation is shown in Figure 14-7*b*. Two waves, each carrying the command "go up 1 centimeter," arrive at a point together. The two waves act together to lift the water surface to the highest possible height it can have. This is a phenomenon called "constructive interference," or reinforcement. On the other hand, you could have the situation shown in Figure 14-7*c*, in which the two waves arrive at the point in such a way that one is giving the instruction to go up 1 centimeter and the other to go down 1 centimeter. In this case, the water surface does not move at all. This situation is called "destructive interference," or cancellation.

Intermediate cases, in which the two waves arrive with the crest of one displaced from the crest of the other, as in Figure 14-7*d*, result in a wave whose height at each point is somewhere between the sum of the crests and zero. Thus, there is a smooth transition between constructive and destructive interference.

Iridescence

A beautiful consequence of interference can be seen on paved roads on sunny afternoons. If you look carefully at the oil slicks on the pavement, you often see a phenomenon called "iridescence"—a rainbow of colors on the dark oil surface. In this case, two light waves are interfering with one another. One wave is the sunlight that bounces off the top of the oil film. The other wave is the sunlight that goes through the oil film and bounces off the bottom. These two waves may interfere constructively or destructively. As we see later, different wavelengths of light correspond to different colors. Light from different parts of the oil slick, then, produces different colors and creates the iridescent rainbow display.

Example of iridescence in soap bubbles.

When you clean the windows of your car on a warm sunny day, you often see a similar colorful phenomenon. As you wipe the squeegee along the glass, an iridescent sheen of colors appears. The colors seem to move around and then fade.

Example of iridescence in a peacock's tail feathers.

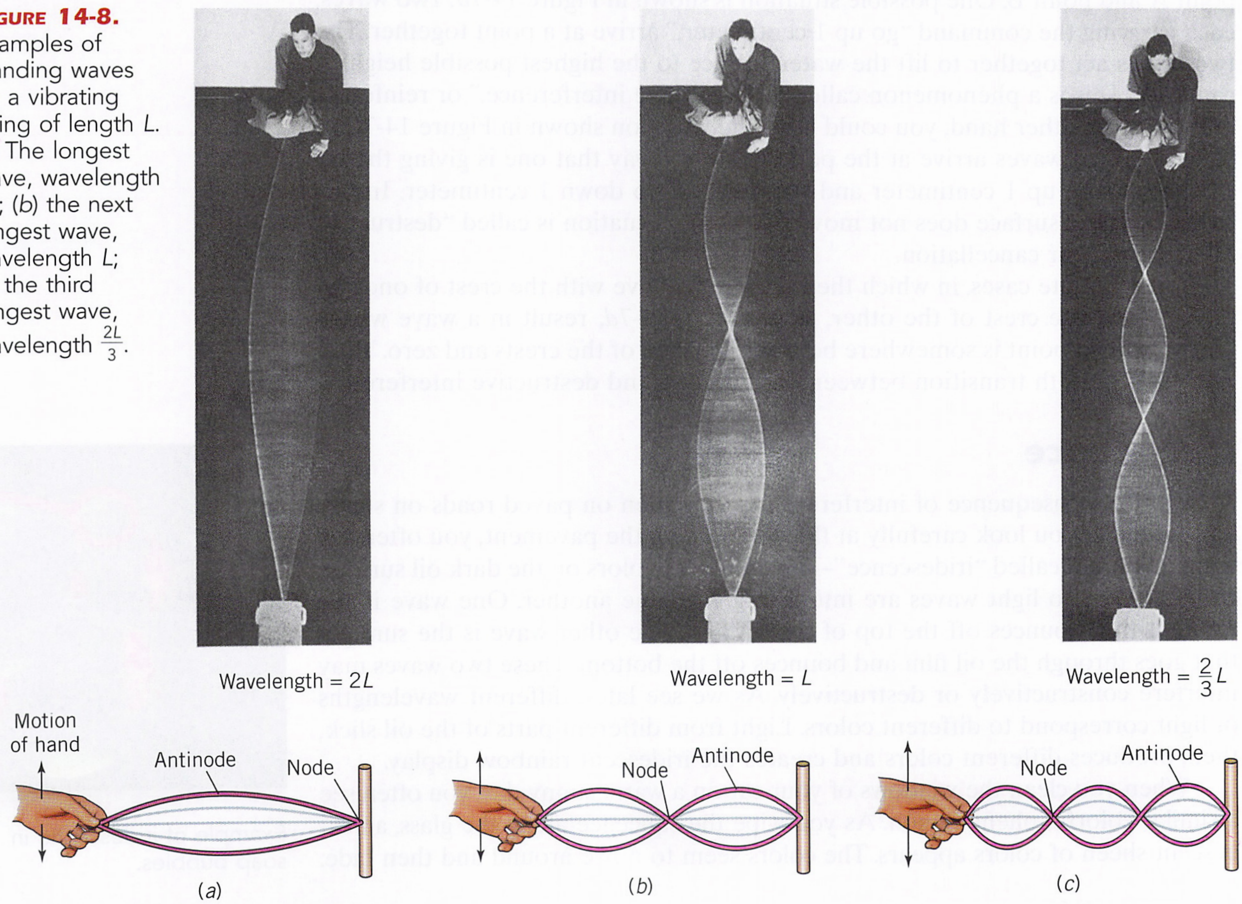
What's going on? What you are seeing is another effect of interference. The squeegee creates a thin film of water on the windshield. Two light waves—one reflecting from the top of the water and the other reflected from the glass—come together at your eye to produce colors. But as the Sun evaporates the water, the thickness of the film changes, and the wavelength corresponding to constructive interference changes as well. You see this as a change in color. When the film evaporates completely, the interference (and hence the display of colors) disappears.

Iridescence also explains many brilliant colors in nature. Peacock feathers reflect light off different layers of the feather structure; the resulting interference effects create the shimmering colors seen in the male bird. Hummingbirds, butterflies, and some kinds of fish all appear in bright, shimmering colors due to interference of light.

Standing Waves

A special kind of wave interaction, called a standing wave, plays an important role in many phenomena, from producing the musical note of a trumpet or organ to explaining the nature of the atom. The easiest way to understand the mechanics of a standing wave is to think about starting one on a rope attached to a tree. You hold the rope in your hand and shake it up and down. As a result, a wave pulse travels down the rope to where it is tied to the tree. At that point, the wave is reflected and moves back down the rope toward your hand. If, in the

FIGURE 14-8. Examples of standing waves on a vibrating string of length L. (a) The longest wave, wavelength $2L$; (b) the next longest wave, wavelength L; (c) the third longest wave, wavelength $\frac{2L}{3}$.



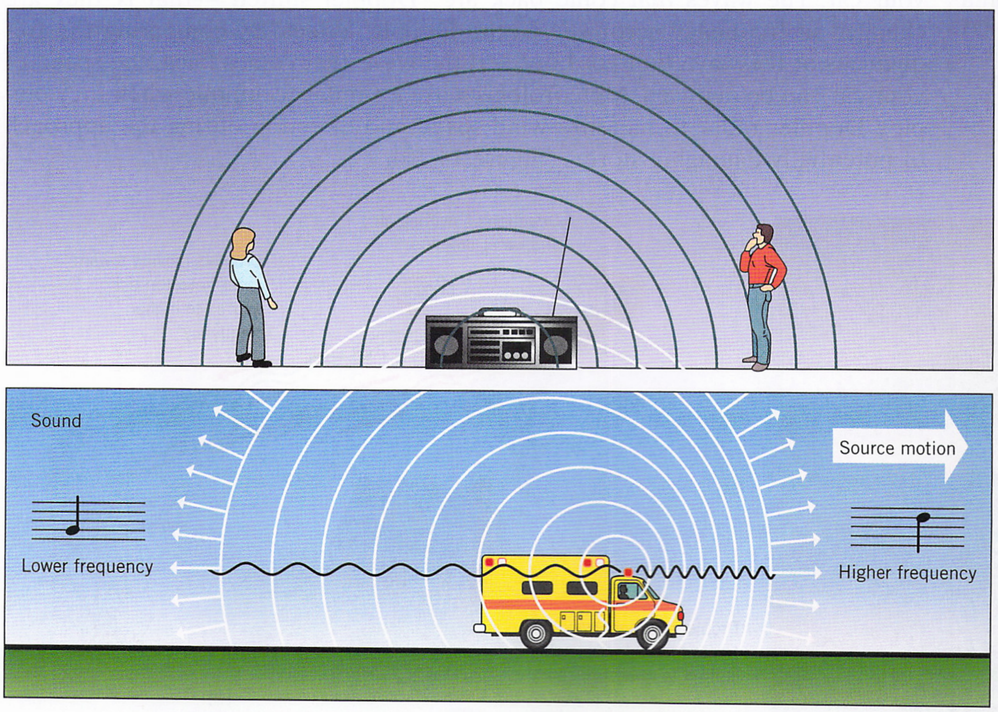
meantime, you keep shaking your hand and sending waves down the rope, those waves start to interfere with the waves coming back. If you time your hand movement just right, you can create a characteristic pattern of oscillation on the rope, as shown in Figure 14-8. This distinctive pattern is called a *standing wave* because the pattern does not move along the rope, but appears to simply stand in place.

Figure 14-8*a* shows the longest standing wavelength that can be sustained on the rope. If the length of the rope is L, the wavelength of this standing wave is $2L$. This is not, however, the only standing wave you can create. If you shake your hand faster (exactly twice as fast, in fact), you can get a pattern such as that shown in Figure 14-8*b*. If you shake the rope faster still, you can get the pattern shown in Figure 14-8*c*. In the last two patterns, there are places on the rope called *nodes* that do not move at all. The places where the rope moves the maximum distance are called *antinodes*. The wavelengths of the waves shown are L and $\frac{2}{3}L$, respectively. These types of standing waves play an important role in producing musical tones, as we see in Chapter 15.

THE DOPPLER EFFECT

Once waves have been generated, their motion is independent of the source. It doesn't matter what kind of rock produces a wave in a pond; once produced, all such waves behave exactly the same way. This statement has an important consequence that was analyzed in 1842 by Austrian physicist Christian Johann Doppler (1803–1853). This consequence is called the Doppler effect in his honor. The **Doppler effect** describes the way the frequency of a wave appears to change if there is relative motion between the wave source and the observer.

Let's take sound as an example. Figure 14-9*a* shows the way a sound wave looks when the source is stationary relative to a listener—when you listen to your radio, for example. In this case everything sounds "normal."



(*a*)

(*b*)

Figure 14-9. The Doppler effect is illustrated by comparing (*a*) a stationary source of sound and (*b*) a moving source of sound.

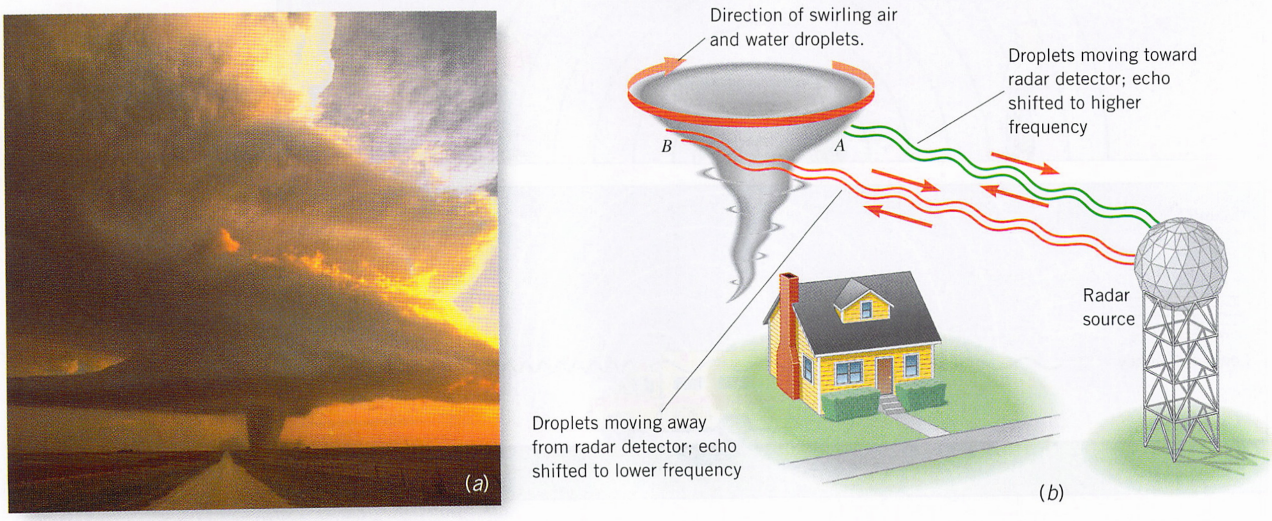
However, if the source of sound—a speeding ambulance, for example—is moving relative to the listener, a different situation occurs (Figure 14-9*b*). Periodically, a pulse of high pressure (the sound wave) moves away from the moving source of the sound wave and travels outward in a sphere, centered on the spot where the source was located when that particular pulse was emitted. By the time the source is ready to emit other pulses, it has moved. Thus the second sound-wave sphere emitted is centered at the new source location. As the source continues to move, it emits sound waves centered farther and farther from the original source—to the right in the figure—producing a characteristic pattern as shown.

To an observer standing in front of the source, the wave crests appear to be bunched up. To this observer, the frequency of the wave is higher than it would be from the same source if it were stationary—a classic example of the Doppler effect. In the case of a sound wave, this means that the sound is higher-pitched. On the other hand, if you are standing behind the moving source, the distance between crests is stretched out and it appears to you as if the wave has a lower frequency. If the wave is sound, then the pitch of the sound is lower.

You probably have heard the Doppler effect. Think of standing on a highway while cars go by at high speeds. Engine noise appears very high-pitched as a car approaches and drops in pitch as the car passes. This effect is particularly striking at automobile races, where cars are moving at very high speed. This sort of change of pitch was, in fact, the first example of the Doppler effect to be studied. Scientists hired a band of trumpeters to sit on an open railroad car and blast a single long, loud note as the train whizzed by at a carefully controlled speed. Musicians on the ground determined the pitches they heard as the train approached and as it receded, and they compared those pitches to the actual note the musicians were playing. The same sort of bunching up and stretching out of crests can happen for any wave, including light.

The Doppler effect also has practical applications. For example, police radar units send out a pulse of electromagnetic waves that is reflected by the metal in your car. The waves that come back are "Doppler shifted"—that is, they are changed in frequency according to the Doppler effect. By comparing the frequencies of the wave that goes out and the wave that comes back, the speed of your car can be deduced. Meteorologists use a similar technique when they employ Doppler radar to measure wind speed and direction during the approach of potentially damaging storms (Figure 14-10).

FIGURE 14-10. Doppler radar can measure the speed of water droplets in a tornado, moving toward the radar receiver on one side of the rotating funnel and away on the other side. In this way, the radar can determine wind speed.



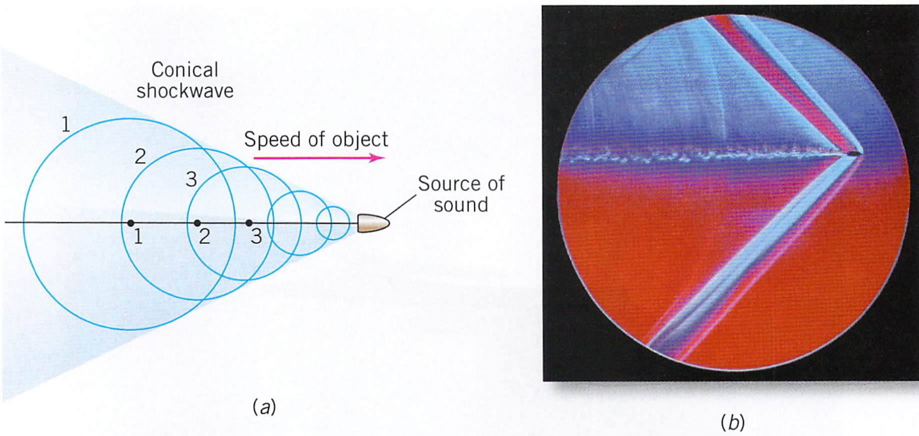


FIGURE 14-11. (*a*) When the speed of a sound source is greater than the speed of the sound waves, then the crests pile up on one another, forming a cone with the source at its apex. The edge of this cone is a region of high pressure (a shock wave) that is built up from the sound waves emitted by the speeding object. (*b*) A high-speed bullet that moves faster than the speed of sound creates a sonic boom.

Connection

Shock Waves and the Sound Barrier

According to the Doppler-effect relationship, the faster a source of sound is moving toward an observer, the higher the observed frequency of the source. But what happens when the source is moving so fast that its speed equals or even exceeds the speed of sound itself?

If you look back at Figure 14-9, you'll see that the crests of the emitted waves get closer together in the direction that the sound's source is moving. The faster the source moves, the closer together these crests become. When the speed of the source is the same as the speed of the sound waves, the crests pile up on one another, forming a cone with the source at its apex (Figure 14-11*a*). The edge of this cone is a region of high pressure, built up from the sound waves emitted by the speeding object. If the source is moving faster than the speed of sound, we call this edge a "shock wave." When a jet plane moves faster than the speed of sound, it creates a shock wave that moves along with the plane, extending down to the ground itself. We hear this high-pressure wave as it passes, causing the loud noise known as a "sonic boom." All objects that move faster than the speed of sound—supersonic aircraft, high-speed bullets, and even the tip of a bullwhip—create this boom (Figure 14-11*b*).

When experimental jet planes that could approach the speed of sound were first being built, they often shook from their own shock waves. Several attempts to go faster than sound were tragically unsuccessful because planes went out of control from this shaking. Pilots referred to a "sound barrier" that had to be broken for the plane to go faster than sound. There is indeed a force pushing against a plane as it approaches the speed of sound. As the plane pushes sound waves ahead of it, forming the shock wave, the waves push back against the plane by Newton's third law. The high-pressure shock wave causes water droplets in the air to condense suddenly, forming a fog behind the plane. Photos sometimes show planes emerging from this fog as if they were in fact breaking through some kind

FIGURE 14-12. When a plane exceeds the speed of sound, a high-pressure shock wave causes water droplets in the air to condense suddenly, forming a fog behind the plane. Photos sometimes show planes emerging from this fog as if they were breaking through some kind of physical barrier.

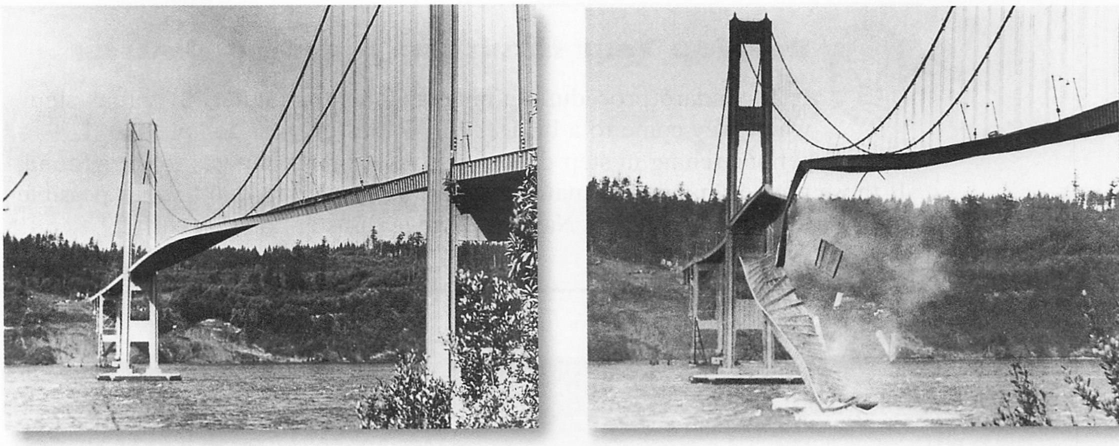
of physical barrier (Figure 14-12). But the sound barrier is simply the reaction force of the shock wave.

INTERACTIONS OF WAVES WITH MATTER: RESONANCE

Because waves carry energy, they are capable of affecting any matter with which they interact. We know that waves crashing into the shore eventually wear away the hardest rocks. Similar transfers of wave energy occur when light waves from lasers cut through solid metal or when a piercing sound shatters glass. The examples of water and light waves are fairly straightforward, involving little more than the wave having its effect through the brute-force delivery of energy. The example of a high-pitched sound breaking a wine glass, however, involves a more interesting process, one that physicists call **resonance.**

Imagine that you are pushing a child on a swing, and you are exhorted to "go higher." You know from experience that the way to increase the amplitude of the swing is to time your pushes so that you are pushing (thus delivering energy to the swing) just when the swing is at the highest point of its backward arc. By carefully timing your pushing, you can get the swing to go high enough to satisfy the most demanding child. In the language of physics, we say that you are timing your pushes to coincide with the *resonant frequency* of the swing.

Every physical system has one or more characteristic times or periods with which it interacts with outside influences. In the case of the swing, the characteristic time it takes for the swing to return to the high point of its arc is perhaps one swing every 3 or 4 seconds. In solid materials, the time it takes for atoms to vibrate back and forth in response to an outside force is typically less than a



The collapse of the Tacoma Narrows Bridge on November 7, 1940. The main span, 2800 feet long and 39 feet wide, began to oscillate on a day with strong, sustained winds.

millionth of a second. The *resonant frequency of the system* is defined to be 1 divided by the characteristic time during which the system responds.

The lesson of the swing, then, is that if energy is delivered to a system at the resonant frequency, the system is able to absorb large amounts of that energy. In the case of the swing, that means that the amplitude of the arc increases. In the case of a glass, if the crests of the sound wave arrive at just the right times, the glass experiences bigger and bigger oscillations until it shatters.

Perhaps the most famous example of the power of resonance took place in the state of Washington in 1940. The Tacoma Narrows Bridge had been completed and had been in operation for just four months when a strong wind came up that just happened to amplify the bridge's natural resonant frequency. The bridge had not been built with enough support to keep the roadway steady in such a wind. The bridge first began to sway and then to move in surges of ever increasing amplitude until it broke apart in spectacular fashion. The Tacoma Narrows Bridge has become a cautionary tale told to every beginning engineering student.

One of the authors (JT) remembers how those engineering majors would turn pale at football games at the University of Illinois. Students sat on an upper deck in the stadium, and, at crucial points in the game, they would start clapping and stamping their feet in unison. At these junctures, you could see the railing at the front of the upper deck begin to move rhythmically up and down. The engineering students were probably remembering those classroom films of the Tacoma Narrows Bridge collapse.

Resonance is not always destructive. For example, radio tuners are designed to have a variable resonant frequency. When you tune in a radio station, you're setting the tuner to allow one particular frequency of radio waves to be resonant. The radio electronics amplify that frequency so you can hear it while the electronics block out all other frequencies. When you turn to a different station's frequency, the new frequency becomes the resonant frequency. This is how the tuner selects just the frequency you want to hear from among all the radio waves broadcast in your listening area.

Develop Your Intuition: Avoiding Disaster

It is standard procedure in military units for soldiers to "break step" when they come to a bridge. Why is this practice followed?

Soldiers marching in step deliver precisely timed impacts to the ground. If those impacts happen to match a bridge's resonant frequency, it is possible that a repeat of the Tacoma Narrows Bridge disaster could occur.

Better safe than sorry!

THINKING MORE ABOUT

Waves: Seismic Waves and Earth's Interior

Scientists have tried for hundreds of years to learn the causes and behaviors of earthquakes, which have caused death and destruction throughout recorded human history. Today we have a pretty good understanding of why and how they occur. However, along the way, scientists found that you can't study earthquakes without first understanding waves, and the study of waves in the Earth led to our first glimpses of Earth's interior structure.

As we discussed in Example 14-1, earthquakes generate seismic waves, which are waves that travel through the Earth. Instruments to detect these waves and measure their properties are called seismographs. Using these instruments, geologists of the nineteenth century found that there are two different kinds of seismic waves (Figure 14-13). Those that reach the seismograph soonest after an earthquake are called primary waves, or P waves. P waves are longitudinal waves, like sound waves, and can travel through solid or liquid rock. Seismographs also detect other waves, called secondary waves or S waves. These events are transverse waves, like ripples on the surface

This damage was caused by a strong earthquake that struck Kobe, Japan, in January 1995.

FIGURE 14-13. Two different kinds of seismic waves, longitudinal P waves and transverse S waves, travel through Earth. Geologists use a seismograph to detect these waves.

of a pond. S waves can travel through solid rock, but not molten rock.

Scientists observed the pattern of seismic waves that were detected by seismographs around the world. Then they correlated their observations with the location of the initiating earthquake (called the earthquake's "epicenter"). After some years, they noted that S waves were never detected in a broad zone on the side of the Earth opposite from the location of the earthquake (Figure 14-14). In contrast, P waves were detected on the side of Earth opposite the earthquake, but not in either of two zones located at particular angles from the earthquake's location.

The Croatian Andrija Mohorovicic and the German Beno Gutenberg first worked out the explanation for these patterns of wave propagation through the Earth in the early twentieth century. Mohorovicic showed that all seismic waves are dispersed in a regular fashion when they encounter a boundary between Earth's outer crust and an inner layer of dense rock (the "mantle"), about 20 miles below Earth's surface—a boundary now known as the "Moho discontinuity." Gutenberg created a series of mathematical models of the Earth to see which model could best explain the observed pattern of wave detection. It turned out that the observed pattern fit a model of the Earth with a dense solid inner core surrounded by a molten outer core, all centered within the mantle. The S waves cannot travel through this molten part of the Earth, so they never reach the far side; in effect, the outer core casts a shadow for the S waves. The P waves can travel through the liquid outer core, but bend when they enter the core and again when they leave it. These bends in their path keep them from penetrating to the zones shown in the figure.

Better instrumentation has allowed succeeding generations of geophysicists to refine this model of Earth's deep interior and to determine the depth of boundaries between inner core, outer core, and mantle. But Gutenberg's basic model, deduced by trial and error, is still correct. How does this trial and error approach fit into the scientific method described in Chapter 1? Is it essential for a scientist to have a fully formed hypothesis in order to make important discoveries?

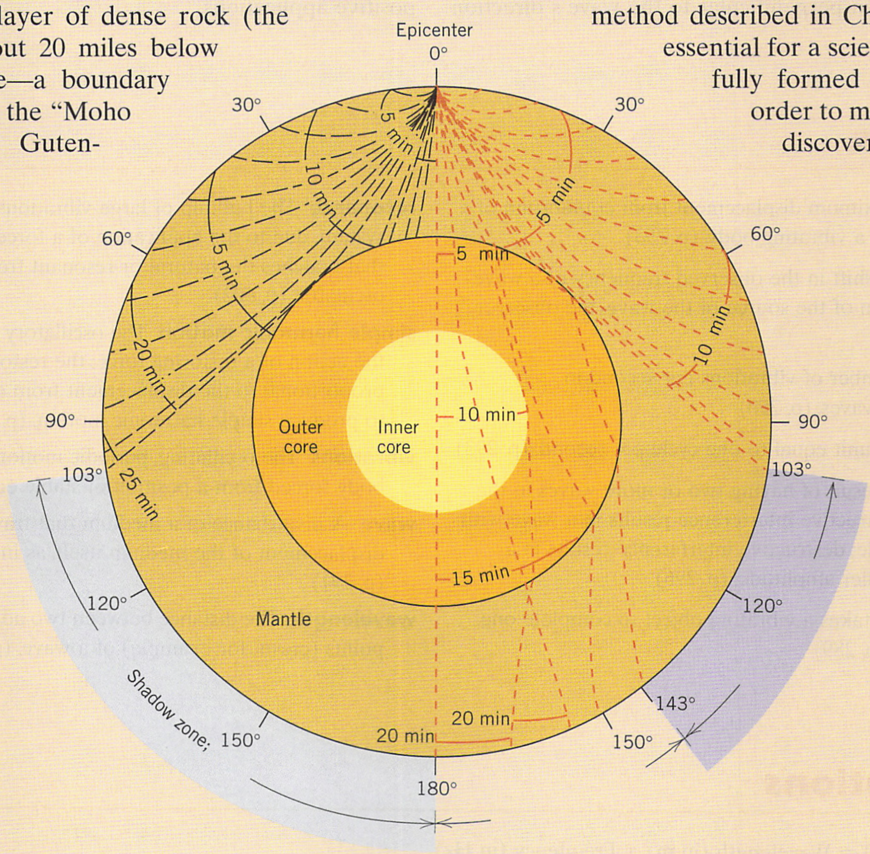


FIGURE 14-14. Seismic waves passing through Earth take a variety of paths. The speeds of P (longitudinal) and S (transverse) waves differ depending on the type of rock, its temperature, and the pressure. Also, S waves cannot travel through regions of molten rock.

Summary

Vibrations are back-and-forth motions of an object in time and space. The time required for a single oscillation is the **period.** A steadily swinging pendulum is an example of **simple harmonic motion,** which is a to-and-fro motion caused by a restoring force.

Waves, caused by vibrations, are a means of transferring energy across a distance. Mechanical waves move in a medium, but the movement of the wave is not the same as the movement of the medium. Waves are characterized by several quantities: **wavelength** (the distance between crests of the wave), **frequency** (the number of waves that go by a point each second), **amplitude** (the maximum height of the wave), and speed. Frequency is measured in a unit called the **hertz** (Hz); 1 Hz corresponds to one crest passing a point each second. These quantities are related by the equation:

$$\text{Speed} = \text{Frequency} \times \text{Wavelength}$$

Waves can be transverse (in which case the medium moves in a direction perpendicular to the wave's direction of motion) or longitudinal (in which case the medium moves in the same direction as the wave).

When two waves arrive simultaneously at a point, they interfere. The resulting disturbance is the sum of the disturbances from each wave by itself. **Interference** can be constructive (in which case the waves reinforce one another) or destructive (in which case they cancel one another out). Standing waves are disturbances that exist in a medium but do not travel. Standing waves can be thought of as the result of interference between outgoing and reflected waves.

Waves emitted by a moving source appear to have a higher frequency if the source is moving toward the observer and a lower frequency if it is moving away—a phenomenon known as the **Doppler effect.**

When waves strike an object, they can have a large effect if the wave crests arrive at intervals corresponding to the object's internal resonant frequency. This **resonance** effect can cause severe damage to structures but also has many positive applications.

Key Terms

amplitude The maximum displacement from equilibrium of a wave medium or a vibrating body. (p. 293)

Doppler effect A shift in the observed frequency of a wave due to the motion of the source of the wave, the observer, or both. (p. 299)

frequency The number of vibrations per second in oscillations and waves. (p. 290)

hertz The physical unit equal to one cycle per second. (p. 293)

interference The result of having two or more waves in the same place; constructive interference results in a wave with a larger amplitude; destructive interference results in a wave with a smaller amplitude. (p. 296)

period The time it takes a vibrating object to complete one full oscillation. (p. 289)

resonance The buildup of large vibrations in an oscillating system, due to the application of a force with a frequency that matches the natural or resonant frequency of the oscillator. (p. 302)

simple harmonic motion The oscillatory motion caused by the action of a restoring force; the restoring force must be proportional to the displacement from equilibrium in order to produce simple harmonic motion. (p. 290)

vibrations The oscillating, periodic motions of a medium or body forced from a position of stable equilibrium. (p. 289)

wave A disturbance of a medium that travels without a net displacement of the medium itself, as in a sound wave. (p. 291)

wavelength The distance between two adjacent corresponding points (crests, for example) of a wave. (p. 293)

Key Equations

$$\text{Wave speed (in m/s)} = \text{Wavelength (in m)} \times \text{Frequency (in Hz)}$$

$$\text{Wavelength (in m)} = \frac{\text{Speed (in m/s)}}{\text{Frequency (in Hz)}}$$

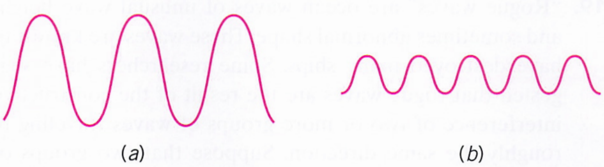
$$1 \text{ hertz} = 1 \text{ cycle/second}$$

Review

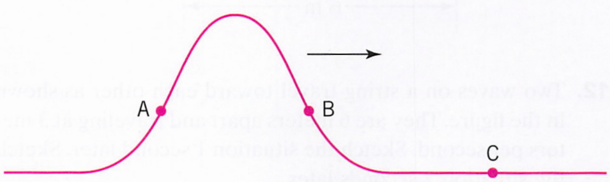
1. What is a wave?
2. How can a wave carry energy? Give an example.
3. What is meant by simple harmonic motion? Explain how a weight on a spring or a pendulum represents this. How is this like a wave?
4. What is meant by the crest of a wave? What is meant by the trough?
5. What is the wavelength of a wave? What is its amplitude?
6. What is the frequency of a wave or harmonic oscillator? What is the period? How are these two quantities/concepts related to one another?
7. What is the commonly used unit of frequency? What are its units?
8. What is the velocity of a wave? How is it related to the frequency?
9. What is a transverse wave? Give an example.
10. What is a longitudinal wave? Give an example.
11. How would you measure the wavelength of a longitudinal wave on a stretched spring? In terms of the motion of a single coil of the spring, what are the period, frequency, and amplitude of the wave?
12. What does it mean to say that two waves interfere?
13. What is the difference between constructive and destructive interference?
14. What happens when two waves completely interfere with one another destructively? Constructively? Explain in terms of an ocean wave.
15. What is meant by a standing wave?
16. What is a node? What is an antinode?
17. How many nodes are there in a standing wave that is two wavelengths long? Three wavelengths? One wavelength?
18. What is the Doppler effect? Give an everyday example.
19. How does a police or fire siren sound as it approaches you? As it leaves you? What is happening to the wavelength and frequency of the sound waves as this occurs?
20. What is resonance? How could it contribute to the shattering of a glass or the destruction of a bridge?
21. What is the difference between resonance and interference?
22. If there were an earthquake off the coast of Alaska of a very large magnitude, how could that energy be transferred over very large distances? What type of waves in what different mediums might be involved?

Questions

1. Jim and Gina are swinging on adjacent, equal length swings at the school playground. Jim weighs about twice as much as Gina. Who, if either, will take less time to swing back and forth? What, if anything, will change if Jim swings while standing on the seat of his swing?
2. The magnitude of the arc through which a pendulum swings does not affect its period. If this were not true, the construction of a pendulum clock would be much more difficult. Why?
3. Two waves that travel through the same medium are sketched in the figure. Which one has the longer wavelength? Which one has the smaller amplitude? Which one has the higher frequency? Which one has the shorter period?



4. Two waves have the same speed. The first has twice the frequency of the second. Compare the wavelengths of the two waves.
5. A single wave pulse on a string is created by wiggling the end up and down once. The wave travels to the right (see figure). What kind of wave is this: transverse or longitudinal? What direction is the string moving at points A, B, and C in the figure? (*Hint:* Think about what the wave would look like a short time later.)



6. What happens to a piece of driftwood in a lake with waves? In what direction should it move as a result of the waves? Given this, how is energy transferred by a wave?
7. "Doing the wave" is a common activity in large football stadiums. Is the "wave" an example of a transverse or longitudinal wave? Explain.
8. **A.** In the elementary grades, some teachers illustrate a wave with the following activity. The students stand in a straight line side by side, shoulder to shoulder, with their hands at their sides. When the first student is

tapped on the shoulder by the teacher, that student then touches the next student at her side, who in turn then touches the next student down the line until the final student is touched.

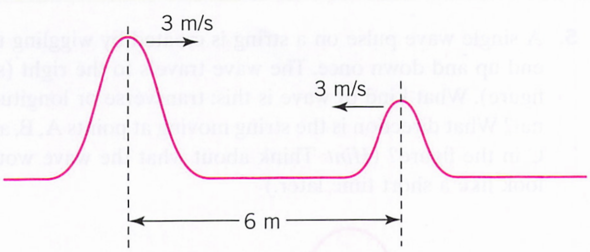
a. This is an example of which type of wave? Explain.
b. If the pupils were holding hands, would the time for the wave to reach the last student be longer or shorter than in the first example? Why?
c. If the students were standing at arm's length, instead of side by side, would the time it takes for the wave to reach the last student be shorter or longer than in the first example? Why?
d. Using this information, can you relate the speed of a longitudinal wave to the density of the medium?

B. Instead of touching, suppose that the students jump up off the floor and that the next pupil cannot jump until the previous student is on the floor again. In this case, which type of wave do you have? Explain.

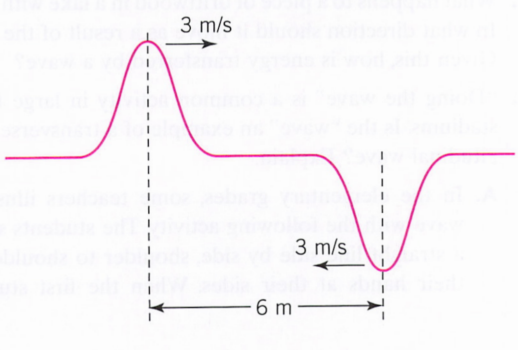
9. Why do waves break as they approach the shore?

10. What effect does the medium through which a wave moves have on the speed of transmission?

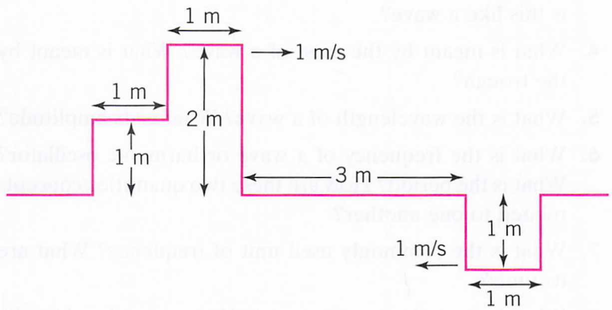
11. Two waves on a string travel toward each other as shown in the figure. They are 6 meters apart and traveling at 3 meters per second. Sketch the situation 1 second later. Sketch the situation 2 seconds later.



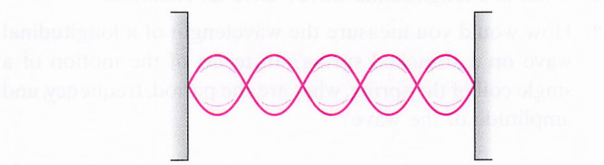
12. Two waves on a string travel toward each other as shown in the figure. They are 6 meters apart and traveling at 3 meters per second. Sketch the situation 1 second later. Sketch the situation 2 seconds later.



13. Two wave pulses travel toward each other as shown in the figure. (These pulse shapes are unrealistic for waves on a string but that does not matter for this problem.) They are moving at 1 meter per second. Sketch the situation 2 seconds later. Sketch the situation 3 seconds later. Sketch the situation 5 seconds later.



14. How many nodes and antinodes are there in the standing wave pattern shown?



15. A police siren emits a 500-Hz tone. If the police car is chasing you, but catching up, how does that affect the sound you hear? What if you are pulling away?

16. What type of unique information might a Doppler radar give you that ordinary radar would not?

17. Suppose your car desperately needs shock absorbers, so that the coil or leaf springs are essentially supporting the weight of the car. You are driving down a long stretch of road that has equally spaced bumps in it. At one particular speed, but not others, your car bounces violently in reaction to driving over the bumps. What is happening?

18. If the speed of a wave doubles while the wavelength remains the same, what happens to the frequency?

19. "Rogue waves" are ocean waves of unusual wave height and sometimes abnormal shape. These waves are known to have destroyed many ships. Some researchers have suggested that rogue waves are the result of the constructive interference of two or more groups of waves traveling in roughly the same direction. Suppose that two groups of waves have wave heights of 15 feet and 25 feet, respectively, and are traveling in the same direction. A rogue wave near these groups of waves is observed to have a height of 50 feet. Does this support the theory that rogue waves are created by interference?

Problem-Solving Example

EXAMPLE 14-2

Standing Waves

Suppose the speed of a wave on a given piece of rope is 6 m/s and the rope is 3 m long. How often do you have to move your hand to produce each of the three standing waves shown in Figure 14-8?

REASONING AND SOLUTION: The frequency with which you shake your hand is the frequency of the wave you send out. To solve this problem we have to remember that for any wave the wavelength, frequency, and speed are related by

$$\text{Speed} = \text{Frequency} \times \text{Wavelength}$$

Since we know the speed of the wave (6 m/s) as well as the wavelengths of the three waves ($2L$, L, and $\frac{2}{3}L$, where $L = 3$ m), it's simply a matter of using this equation. For the longest wave, the wavelength is 6 m (twice the length of the 3-meter rope), so that

$$6 \text{ m/s} = \text{Frequency} \times 6 \text{ m}$$

$$\text{Frequency} = \frac{6 \text{ m/s}}{6 \text{ m}}$$

$$= 1/\text{s or } 1 \text{ Hz}$$

In other words, to obtain the longest possible standing wave, you have to shake your hand once a second. For the other two standing waves, the wavelengths are 3 and 2 m, respectively, so the frequencies are $\frac{6}{3} = 2$ Hz and $\frac{6}{2} = 3$ Hz. ●

Problems

1. You are pushing your little sister on a swing and in 1.5 minutes you make 45 pushes. What is the frequency (in hertz) of your swing pushing efforts?
2. Andrea was watching her brother in the ocean and noticed that the waves were coming in on the beach at a frequency of 0.33 Hz. How many waves hit the beach in 15 s?
3. Andrea asked her brother to take a 6-ft floating raft out of the water near the wave-swept shore. Using this raft as a measuring tool, she estimated that the wavelengths of these particular ocean waves were about 9 ft. How fast are these surface ocean waves if the frequency remains 0.33 Hz?
4. If an ocean wave passes a stationary point every 3 seconds and has a velocity of 12 m/s, what is the wavelength of the wave? Can you tell what the amplitude of the wave is from this information?
5. A standing wave on a rope 2-m long has two nodes.
   a. How many wavelengths does it have? If it has three nodes? If it has five nodes?
   b. Draw the standing waves in part (a) with two, three, and five nodes. Label the nodes and wavelengths.
   c. What wavelengths can create standing waves?

Investigations

1. Investigate how energy travels through Earth in an earthquake. What exactly is a seismic wave? Trace the development of seismography through history.
2. Write down a list of different phenomena in the physical world that can be represented by waves. Can anything with a simple, periodic, repeating characteristic be modeled with and described by waves? How about any object that moves in a circle at a constant speed through time? A pendulum? Something that just vibrates back and forth?
3. Next time you are near a lake or large body of water, stop and examine the waves. Can you estimate the amplitude and wavelength of the waves that day? Write down some notes on what might have caused these waves. Is there any debris floating in the waves? If so, how does it move? Investigate as many of the wave phenomena discussed in this chapter as you can. Organize your observations into a notebook, noting consistencies and inconsistencies with what you have learned in this chapter.
4. If you have access to a wave tank (usually a small tank or old aquarium) use it to further explore the nature of waves. Pay special attention to wave interference and the reflection of waves off the side of the tank.
5. Explore the history of tsunamis, or tidal waves. How often and where do they strike? What would be the effect of an impact of a large asteroid in the middle of the ocean in terms of these waves? Have popular film and the media overexaggerated this possible occurrence?
6. Investigate further just how engineers take resonance into account when designing structures. What specifically is done to avoid problems like the collapse of the Tacoma Narrows bridge?
7. Locate an old-fashioned Slinky, a coiled spring that has been used mostly as a child's toy. Use it to generate transverse and longitudinal waves and investigate as many of the wave phenomena discussed in this chapter as possible.

8. Investigate the design and use of atomic clocks, which rely on the precise and regular vibrations of individual atoms to measure time. What atoms are used in such a clock? How is the time unit of 1 second defined?
9. Investigate the technology of laser interferometry, which relies on waves of light energy that bounce off a surface. How is this technique used to measure extremely short distances?
10. Modern seismometers can measure ground vibrations as small as a footstep. Investigate the design of such an instrument. How are tiny motions of the ground amplified?

WWW Resources

See the *Physics Matters* home page at **www.wiley.com/college/trefil** for valuable web links.

1. **http://www.falstad.com/ripple/** A Java applet simulation of a ripple tank, allowing all kinds of 2-D wave experiments and demonstrations with reflectors, lenses, etc.
2. **http://www.phy.ntnu.edu.tw/java/waveSuperposition/waveSuperposition.html** An animated Java demonstration of superposition of waves.
3. **http://users.erols.com/renau/harmonics.html** A very nice standing waves applet.