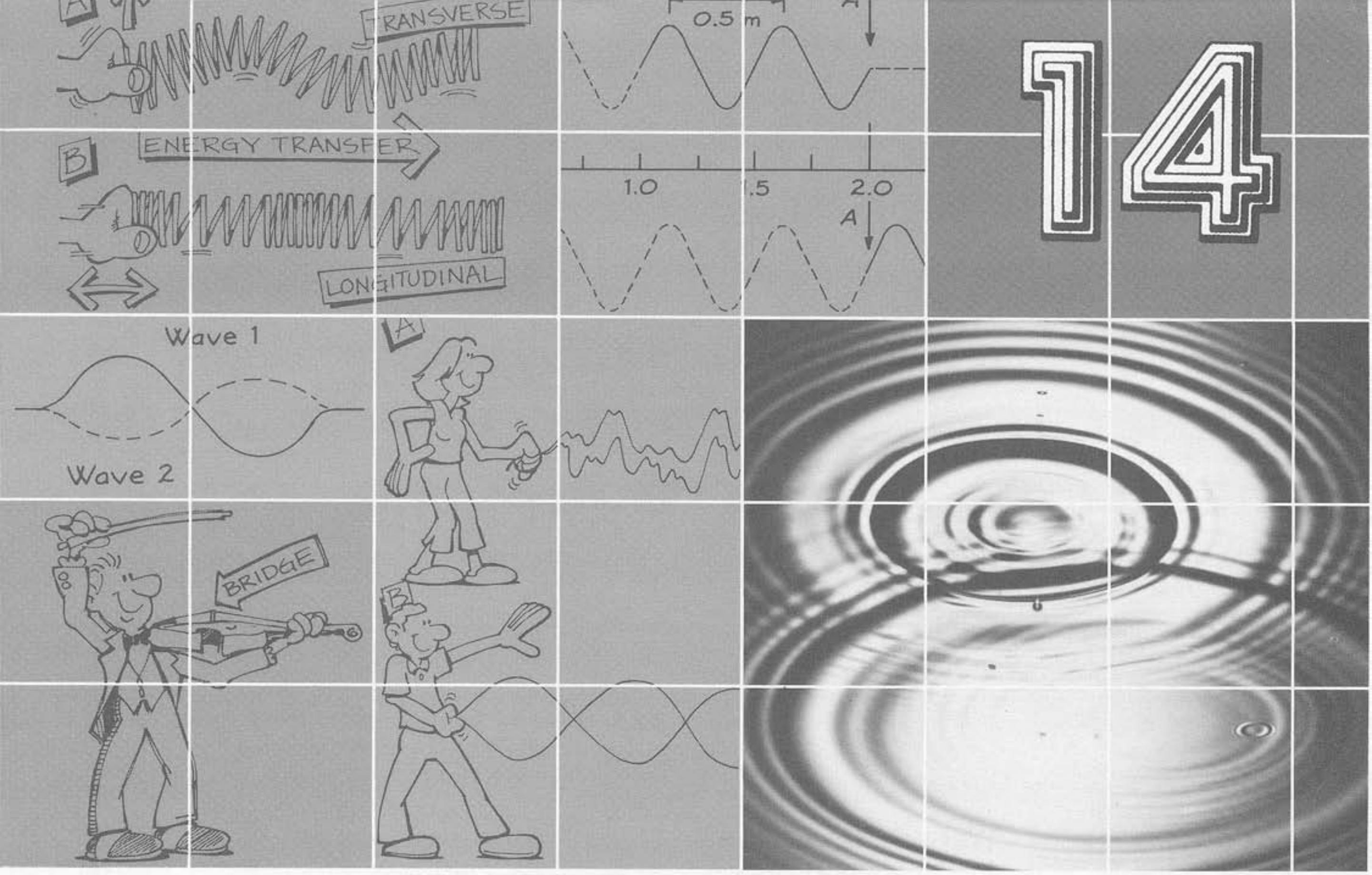


Making Waves

A friend lies asleep in a boat on the far side of a lake. A sound sleeper, he has not responded to any of your shouts. How can you get the message across? One way might be to toss a stone and try to hit him. The message travels with the stone. Another way would be to take a board and move it up and down at the water's surface, creating water waves that travel across and rock the boat. No object moves from you to your friend; instead the wave carries your message.

Stones and waves illustrate the ways we expect to contact or be contacted by life in outer space. While we have not yet received messages (either objects or waves) from extraterrestrial intelligence, science fiction writers freely imagine both methods of encounter. In the 1982 motion picture *E.T.*, the title character arrived on earth in a spaceship. Like the stone, E.T. carried his message with him. Finding that he was stranded on earth, E.T. contacted his ship with radio signals—sending waves, not himself.

Both methods—throwing stones and making waves—are used in real life as well. Objects have always carried messages. Using waves to carry messages is also nothing new—people have always communicated by means of sound. And for thousands of years people have used fires, lanterns, and lighthouses to signal each other by means of light. Light and sound, like radio signals, transmit messages in the form of waves.

Getting the message across requires the transfer of energy. Thus far, we have described how objects transfer energy. In this chapter we examine how waves transfer energy. Intuitively, our model of wave motion comes from experiences with the visible waves found in water and springs. Wave characteristics, like *amplitude, frequency, wavelength,* and *wave speed,* describe the differences we see among waves. How waves appear to us depend on whether we are moving relative to the wave source. Called *Doppler effects,* these differences remind us of how much our measurements depend on the reference frame we are in. Waves can interact with themselves and with matter. When waves meet waves, they combine according to the *principle of superposition.* When waves meet other matter, they can be *reflected, refracted,* or *absorbed.* In this chapter we use the visible waves found in water and springs to examine these and other wave concepts. In the next chapter we see how successfully the wave model explains the behavior of sound and light.

WAVE MOTION

Raindrops fall softly in a warm summer rain, causing ripples as they strike the surface of a puddle. You throw a stone into a pond. Plunk! A small wave moves outward from the point where the stone hits the water. As you stand on the beach on a windy day you see bigger waves—waves that gradually wear away the soil and rock along the shore. Deep in the ocean floor an earthquake occurs, giving rise to a giant wave called a tidal wave, or *tsunami.* Traveling at enormous speeds, the tsunami carries enough energy to destroy homes and lives.

While different in their destructive potential, these waves are similar in at least three respects. Each is created by a disturbance of the water. Each carries energy along the water's surface from the original disturbance to other locations. And, each transfers energy over distances much greater than those traveled by the individual water molecules. This last characteristic, the transfer of energy but not matter, makes wave motion an intriguing phenomenon.

Transferring Energy But Not Matter

Waves transfer energy but not matter. This can be hard to understand when we talk about something as continuous as water. An analogy with distinct objects makes the process clearer. Suppose you set up a line of dominoes from your finger to a bell (Figure 14-1). When you push one domino over, it pushes

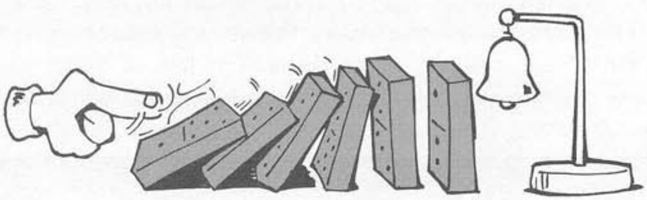


Figure 14-1
Energy is transferred from your finger to the bell, but no single domino moves the entire distance.

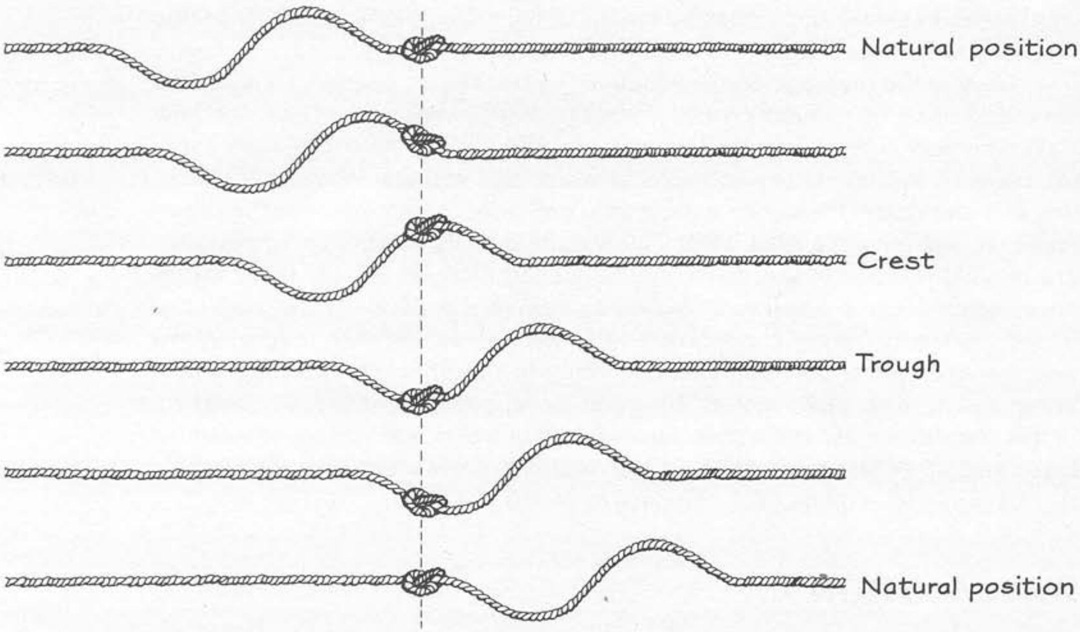


Figure 14-2

If we watch just one segment of the medium, it moves up and down about its central location as the disturbance passes through. One complete vibration occurs when the segment moves from its natural position to a crest, back to its natural position, to a trough, and back to its natural position again. The wave moves from left to right, but each segment of the medium returns to its original location.

the next one, which pushes the next, and so forth. Finally, the last domino falls over and rings the bell. Energy is transferred from your finger to the bell, but no single domino moves the entire distance. Likewise, when you drop a stone into a pond, energy is transferred from you to the shore, although individual water molecules do not travel the entire distance. A disturbance like that shown in Figure 14-2 travels from left to right while each section of the material simply vibrates up and down about a central location.

Like any energy-transfer process, wave motion requires an energy source and an energy receiver. The energy source creates a disturbance, which travels to the energy receiver. In the domino analogy, your finger acts as the energy source and the bell as the energy receiver. The raindrops, the stone, the wind, and the earthquake all act as energy sources in our examples of water waves. Soil and rock at the water's edge act as the energy receivers.

To our energy-source–energy-receiver model we must now add a third component. The disturbance created by the energy source must be transmitted through something, called the **medium.** The line of dominoes acts as the medium for the domino wave. Water is the medium for water waves. Matter transmits sound waves. Rock, soil, and water transmit the shock waves created by earthquakes. In each example, the medium transmits energy from a source to a receiver.

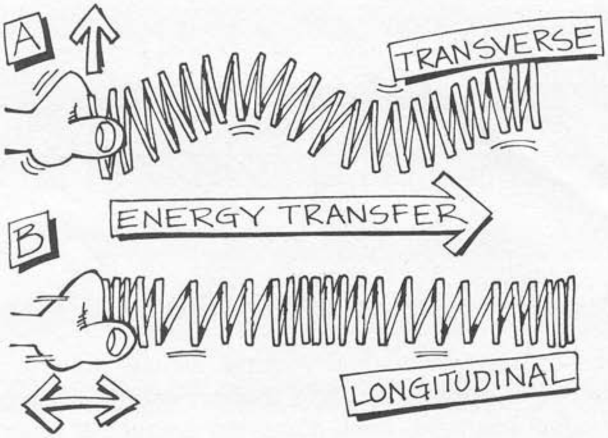


Figure 14-3
Both waves transfer energy from left to right. **(a)** To produce transverse waves, you move your hand up and down. **(b)** To produce longitudinal waves, you move the coils to the left and right.

Longitudinal and Transverse Waves

While the medium does not actually move from the energy source to the energy receiver, it does vibrate as it transmits the disturbance. The direction in which it vibrates leads to the definition of two different types of waves.

You can produce the two types of waves using a stretched spring attached to a wall, as shown in Figure 14-3. First shake your hand up and down, producing the wave shown in Figure 14-3(a). This wave distorts the linear shape of the spring as it moves from left to right. Now, while stretching the spring with one hand, use the other hand to compress several coils, then let go. Figure 14-3(b) shows the wave that results. The spring's linear shape is maintained, but its coils are compressed or pulled apart as the wave moves along its length.

We can describe the differences between these two kinds of waves by comparing the direction in which the energy travels with the direction in which the coils in the spring vibrate. In Figure 14-3(a), the energy moves from left to right, but the coils vibrate up and down. A wave in which the medium vibrates perpendicular to the direction of energy transfer is called a **transverse wave.** Waves along the surface of water are transverse. In Figure 14-3(b), the energy moves from left to right and the coils also vibrate from left to right. In **longitudinal waves,** the medium vibrates parallel to the direction of energy transfer. Sound waves are longitudinal waves.

While a spring can transmit both transverse and longitudinal waves, many media cannot. In order to transmit a wave, a medium must be able to mimic the motion of the energy source and then return to its original shape. Matter in any state—solid, liquid, or gas—will transmit longitudinal waves. Sound waves, for example, can be transmitted by air, water, even solid walls—as you have no doubt noticed if your neighbors enjoy loud parties. Solids and surfaces of liquids transmit transverse waves because both have strong molecular bonds defining a shape that can be restored once the disturbance moves on. If you place your finger near a plucked guitar string, you can feel the transverse vibrations of the stretched string. Liquids and gases, however, have no definite shape and cannot transmit transverse waves through their interior.

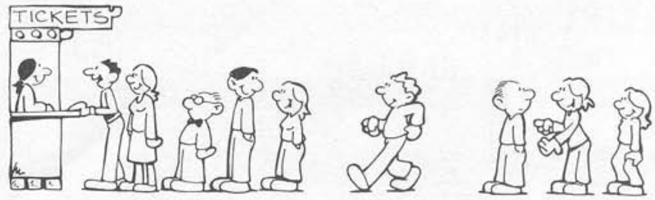


Figure 14-4
People transmit waves too! Is this "people wave" transverse or longitudinal?

CHARACTERISTICS OF WAVES

Ripples and tsunamis are both transverse waves, but the similarities end there. Compared to ripples, tsunamis transfer enormous amounts of energy. In a more modest example, think about the amount of energy you transfer when you shake the end of a spring. The distance you move the spring up and down, the rate at which you shake the end of the spring, and even the type of spring itself affect the nature of the transverse wave and the energy it transfers. To describe the differences among waves and the energy they transfer, we need to introduce some terms.

Amplitude, Frequency, and Wavelength

Varying the *distance* we move the spring up and down produces the differences in height between waves A and B in Figure 14-5. The **amplitude** of a wave is the maximum distance the parts of the medium move from their natural positions (Figure 14-6). Since we move the end of the spring up and down farther in B than in A, wave B has a greater amplitude than wave A. More energy is required to move the end of the spring farther. Tsunamis transfer more energy than ripples.

Varying the *rate* at which we shake the end of the spring produces the differences between waves A and C (Figure 14-5). These two waves have the same amplitude, but those in A seem squeezed together more than those in C. Two terms—*frequency* and *wavelength* —are used to describe this difference. Frequency describes the difference in terms of time; wavelength describes the difference in terms of space.

Frequency describes the rate at which we shake the end of the spring and, consequently, the rate at which each segment of the spring vibrates up and down. We measure this rate by watching one segment of the medium and counting the number of vibrations or cycles completed during a convenient time interval. As shown in Figure 14-2, a segment completes one cycle when it moves from its normal position to a crest, back to the normal position, to a trough, and finally back to its normal position. The **frequency** of a wave is the number of complete cycles divided by the time interval in which they occur.

$$\text{Frequency} = \frac{\text{number of complete cycles}}{\text{time interval}}$$

For example, if a segment completes 10 cycles in 5 seconds (s), then the frequency is 10 cycles divided by 5 s or 2 cycles per second. The units cycles per

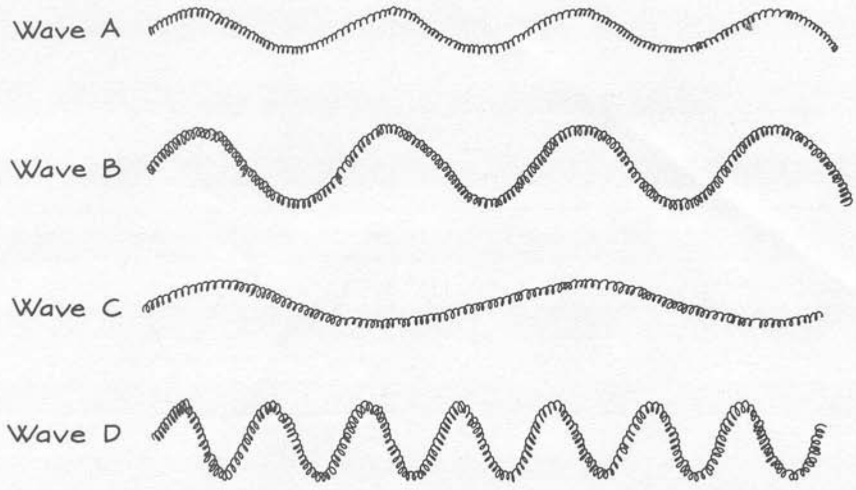


Figure 14-5
Waves A and B differ in amplitude. Waves A and C differ in frequency and wavelength. How does wave D differ from the others?

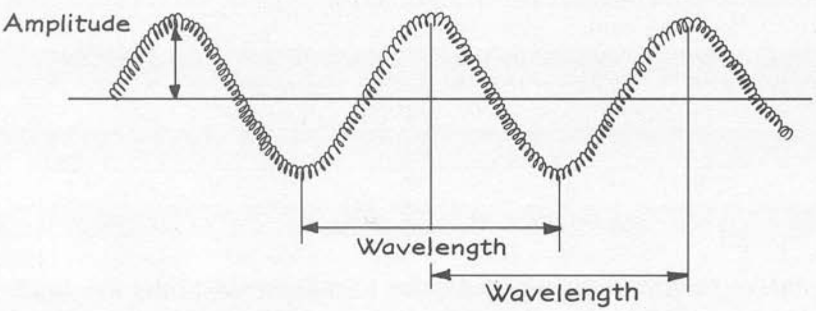


Figure 14-6
The distance covered by each unit is called the wavelength of the wave.

second are called hertz (Hz). A higher frequency means that pulses are occurring more frequently and results in waves that are more closely spaced. The frequency of the waves in A is greater than those in C. Since each cycle transfers energy along the spring, increasing the frequency increases the rate at which you transfer energy.

The frequency at which a wave medium vibrates is the same as the rate at which the energy source vibrates. Sound waves vibrate at rates from a few hertz to tens of thousands of hertz. Our ears respond only to waves in the range of 20 Hz to around 20,000 Hz. Tides, ocean waves, and earthquake waves are generally a few hertz. Light waves vibrate at much higher rates, about 10^{14} Hz.

Frequency describes differences between waves A and C in terms of time. These differences can be described in terms of space as well. If you look closely at the two wave patterns, you can see that they are composed of repetitions of a single unit (Figure 14-6). Each unit consists of a crest, the maximum displacement above normal, and a trough, the maximum displacement below normal. The length of this basic unit is called the **wavelength** of a wave. The wavelength of A is less than that of C; consequently, the waves in A are more closely spaced. Wavelength is measured in meters (m). The wavelength of visible light is extraordinarily tiny—10^{-7} m. The wavelength of tsunamis can be enormous—5×10^5 m.

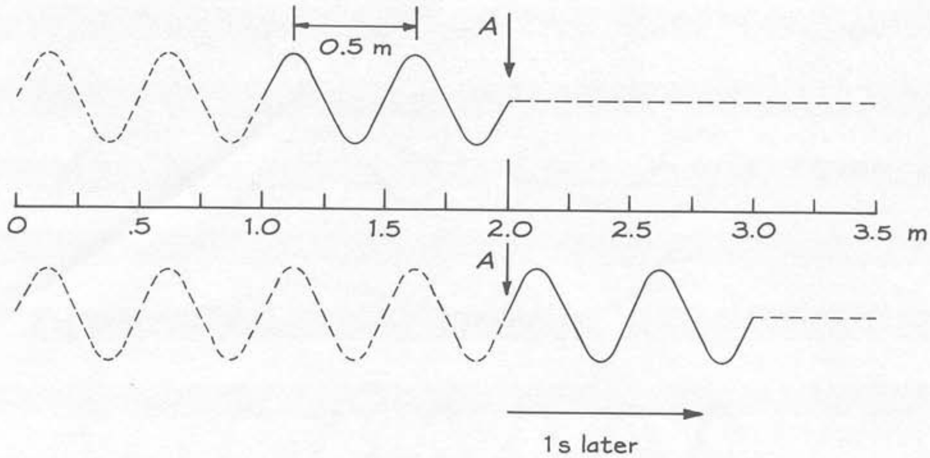


Figure 14-7
When 1 second has elapsed, a wave at A will have moved two complete wavelengths to the right. The wave speed is two wavelengths per second, or 1.0 meters per second.

SELF-CHECK 14A

Use the terms *amplitude, frequency,* and *wavelength* to describe how waves A, B, and C differ from wave D in Figure 14-5.

Wave Speed

Moving the end of the spring up and down farther increases the amplitude of the waves produced. Moving the end of the spring faster increases their frequency. Stretching the spring or getting an entirely new spring will affect the speed at which the waves move. Wave speed depends on the medium chosen.

Wave speed is the distance traveled by a disturbance divided by the time required for it to travel that distance. This speed can be described in terms of a wave's frequency and wavelength. To see how, we focus our attention on one segment of the wave medium, point A in Figure 14-7. A frequency of 2 Hz tells us that two complete waves pass point A each second. When one second has elapsed, a wave at point A will have moved a distance of two wavelengths. Its speed, then, is two wavelengths per second. If each wavelength is 0.5 m, then the wave speed is two wavelengths times 0.5 m per wavelength, or 1.0 m/s. The wave speed of a wave can be determined from the product of its wave frequency and wavelength:

Wave speed

Wavelength

$$v = f\lambda$$

Frequency

$$\text{Wave speed} = \text{frequency} \times \text{wavelength}$$

In general, the speed at which waves travel depends on the medium through which the disturbance moves. Sound waves, for example, travel at speeds of about 330 m/s in air. If we compare the frequencies and wavelengths produced by a variety of musical instruments (Table 14-1), the product of the two quantities is always the same—330 m/s. You do not hear a

Table 14-1 Sound Waves

Frequency (Hz)	Wavelength (m)	Wave Speed (m/s)
162	2.04	330
262	1.26	330
440	0.75	330
524	0.63	330

piccolo before you hear a trombone. All the sounds of the orchestra reach you at the same time. For a given medium, frequency and wavelength vary inversely so that the wave speed remains constant.

In a sense, wave speed describes how quickly the energy supplied by the energy source can be handed off from one part of the medium to another, from one coil in the spring to the next. The speed with which this occurs depends on the physical characteristics of the medium (how tightly the spring is stretched or whether the medium is a solid, liquid, or gas), on the substance from which the medium is made, and on the type of wave (transverse or longitudinal) being transmitted. The range of speeds is enormous. Sound waves travel through air at about 330 m/s, while light waves travel through space more than a million times faster, 3×10^8 m/s. This difference in speed produces the time delay between seeing lightning and hearing the thunder produced in distant storms.

SELF-CHECK 14B

A tuning fork vibrates at a frequency of 440 Hz. If the waves it produces have a wavelength of 3 m underwater, what is the speed of sound in water? How does this compare to the speed of sound in air?

Seeing the Earth's Interior

Wave speed has provided geologists with a valuable tool for building models of the earth's interior. Earthquakes, dynamite blasts, and nuclear tests all produce transverse and longitudinal waves that are transmitted through the earth's interior. By measuring the travel time of these waves to reporting stations located around the world, geologists have been able to estimate average speeds at various depths below the earth's surface. Since the speed of

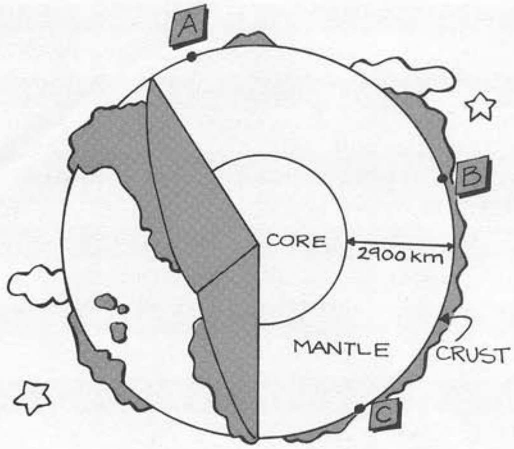


Figure 14-8
Geologists believe that the abrupt changes in wave speed identify the boundary between the earth's crust and mantle and between the mantle and a liquid or semi-liquid core.

both transverse and longitudinal waves depends on the medium through which they travel, changes in speed tell us that there are changes in the materials found in the earth's interior.

As shown in Table 14-2, the speed of longitudinal waves increases gradually with increasing depth. Two exceptions stand out. An abrupt increase in speed occurs at a depth of 35 kilometers (km). An abrupt decrease in speed occurs at a depth of 2900 km. Geologists believe that these sudden changes in speed locate boundaries between distinct regions of the earth's interior.

Our model of the earth's interior now includes concentric layers called the crust, mantle, and core (Figure 14-8). The abrupt increase in speed shown in Table 14-2 marks the boundary between the earth's crust and mantle. Similar increases in speed have been measured throughout the world, though

Table 14-2 Speeds of Longitudinal Waves Below the Earth's Surface

Depth (km)	Wave Speed (m/s)	Depth (km)	Wave Speed (m/s)
0	5,000	2,900	13,500
16	6,000		8,000
29	6,720	3,000	8,100
35	7,200	4,000	9,500
	8,320	5,000	10,500
1,000	12,000	6,000	11,500
2,000	13,000		

at depths that range from 5 km beneath the ocean floor to 60 km in mountainous regions. The earth's crust does not appear to be uniformly thick. Geologists believe that the increase in speed that occurs as waves leave the earth's crust and enter the mantle is due to a sudden increase in the presence of iron compounds in the mantle's rock layers. The abrupt decrease in speed that occurs at 2900 km marks the boundary between the earth's mantle and core. Since longitudinal waves travel more slowly in liquids than in solids, geologists believe that the earth's core is either liquid or semiliquid. We will never see the core or mantle directly, yet each longitudinal or transverse wave that passes through the earth's interior gives us a glimpse of what might lie beneath.

Figure 14-9
If you tap the surface of the water at a constant rate, a pattern of concentric circles moves outward from the boat.

MOVING SOURCES AND RECEIVERS

When an earthquake occurs, the wave source and receiver are stationary relative to one another. The frequency and wavelength of the wave emitted by the source are the same as that received by the receiver. Observers at both locations would describe the waves as being the same. However, in other examples of wave phenomena, either the source or receiver can be moving relative to the other. While the wave speed remains constant regardless of this motion, the frequency and wavelength of the waves change. The extent of these changes describes the relative motion between the source and the receiver.

A Moving Boat

Suppose you are sitting in a motionless boat on a lake. You tap the surface of the water and a wave moves outward in all directions. If you tap your finger repeatedly, say once per second, you will see the pattern of concentric circles shown in Figure 14-9. As the waves travel away from you, they pass people sitting in boats at points X and Y. By measuring the time between consecutive crests—1 s—these people can determine the rate at which you are tapping the water.

Now suppose your boat is moving toward X at a constant speed as you tap the water. At the end of the first second, the wave produced by the first tap will have spread out as shown in Figure 14-10(a). The boat moves during this time, so the wave produced by the second tap originates from a different place than the wave produced by the first tap. At the end of 2 s, the pattern we see is that shown in Figure 14-10(b). While the wave produced by each tap is circular, the waves are no longer concentric. The crests crowd together on one side and spread apart on the other side. As more waves are produced, the pattern in Figure 14-10(c) is created.

Observers at X and Y now report different time intervals between crests. Though you are still producing wave crests at a rate of one per second, observers at X report that crests arrive more often than once per second. Observers at Y, on the other hand, see waves arriving less often than once

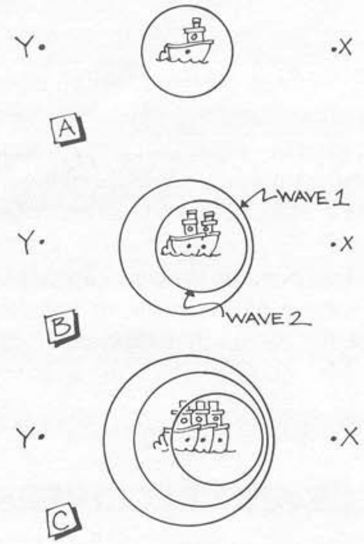


Figure 14-10

As the wave source moves, the waves no longer remain concentric. The crests crowd together on the right and spread apart on the left.

per second. The frequency at which the waves arrive at X and Y no longer matches the frequency at which the waves are produced, nor do they agree with each other. These differences arise from the motion of your boat—the source of the waves.

The Doppler Effect

A change in the observed frequency of waves caused by the motion of the source is called the **Doppler effect.** The frequency of waves received by the observers increases as the boat moves toward them and decreases as the boat moves away from them. The extent of the frequency shift depends upon the speed of the boat.

The Doppler effect is usually described in terms of the change in frequency. In our example, this change is the difference between the frequency of the waves emitted at the boat and the frequency of the waves received by observers at X or Y. As the relative speed between the wave source and receiver increases, the change in frequency increases. Police radar uses this relationship to measure the speeds at which cars travel.

While we have described the Doppler effect in terms of a moving wave source, the same changes occur when a wave source is stationary and the receiver is moving. In fact, both the source and the receiver can be moving simultaneously. The relative speed between the source and the receiver determines the extent of the change in frequency.

SELF-CHECK 14C

Suppose we stop moving the boat and observers at Y begin moving toward us. If we continue to tap the water at a frequency of 1 Hz, what do the observers at Y report? What do the observers at X report?

A STEP FURTHER—MATH

USING DOPPLER SHIFTS TO MEASURE SPEED

In most applications of the Doppler effect, the change in frequency, called the **Doppler shift,** is used to measure the speed of a moving object. Police determine the speed of a car by measuring the Doppler shift in reflected radar waves. Medical technicians use the Doppler shift in ultrasonic waves reflected by red blood cells to determine the speed at which blood flows. A Doppler shift in the light emitted by moving galaxies enables astronomers to estimate the speeds at which these galaxies move away from us. All these measurements require a quantitative description of the relationship between the Doppler shift and the relative speed between the wave source and receiver.

Two speeds are required to describe the Doppler shift—wave speed (the speed at which the waves travel from source to receiver) and the relative speed between the wave source and receiver. When the wave speed is much greater than the relative speed between source and receiver, the change in frequency due to the Doppler effect is given by:

$$\text{Change in frequency} = \frac{\text{relative speed}}{\text{wave speed}} \times (\text{frequency of source})$$

Change in frequency

Relative speed between source and receiver

$$\Delta f = \frac{v_r}{v_w} f_s$$

Frequency emitted by source

Wave speed

When the relative speed and wave speed are both expressed in the same units, such as meters per second, the change in frequency is expressed in the same units as the frequency of the wave source, usually Hz. The change in frequency is positive when the wave source and receiver move toward one another; negative when they move apart from one another.

To see how to apply this equation, let's return to the boat example. While sitting in the boat you produce water waves with a frequency of 1.00 Hz, one wave each second. Typically, water waves move at a wave speed of 0.100 m/s. If your boat moves at a speed of 0.005 m/s toward X, a stationary observer at X will report a Doppler shift of

$$\text{Change in frequency} = \frac{\text{relative speed}}{\text{wave speed}} \times (\text{frequency of source})$$

$$= \frac{0.005\ \text{m/s}}{0.100\ \text{m/s}} \times 1\ \text{Hz}$$

$$= 0.05\ \text{Hz}$$

Since the wave source is moving toward the wave receiver, the change in frequency is positive. An observer at X reports a change in frequency of +0.05 Hz. Under the same circumstances, the observer at Y reports a change in frequency of −0.05 Hz.

The police officer, medical technician, and astronomer rearrange the Doppler relationship to determine the relative speed in terms of the change in frequency, wave speed, and frequency of the source:

$$\text{Relative speed} = \frac{\text{change in frequency}}{\text{frequency of source}} \times (\text{wave speed})$$

$$v_r = \frac{\Delta f}{f_s} v_w$$

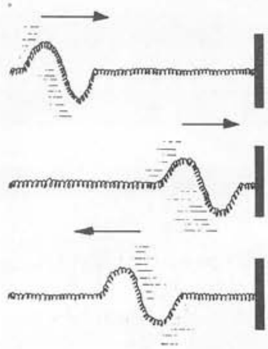


Figure 14-11
A wave can be reflected when it reaches a rigid boundary, such as the wall.

Suppose you are driving along an interstate highway (speed limit of about 25 m/s.) A stationary police radar unit emits radar waves that move at a wave speed of 3×10^8 m/s and have a frequency of 1×10^{10} Hz. When these waves are reflected by your car, their Doppler shift is 100 (1×10^2) Hz. Will you get a ticket?

WAVES MEET MATTER

Waves do not move through a single medium. Earthquake waves, for example, move through a variety of rock layers, each of which has a slightly different composition and is under different pressures from the rock above it. When the change in the medium is gradual, waves gradually change speed and direction. When the change in the medium is abrupt, waves can also change direction or stop traveling altogether. They can be reflected, refracted, or absorbed.

Reflection

Light waves striking the surface of a mirror do not travel on through. They travel back in the general direction from which they came. Sound waves striking the smooth walls of a long corridor travel back to you as an echo. A transverse wave transmitted along a spring reverses direction when it reaches the wall (Figure 14-11). In many situations, waves remain in some initial medium rather than enter a new medium. These waves are said to be **reflected.**

Waves are reflected when the new medium offers a significantly more difficult path for the energy to travel. Since there are many possible media, the extent to which waves are reflected varies. A wall, for example, provides a very rigid medium compared to a spring. Consequently, the wave energy is transmitted back along the spring rather than into the wall. These waves are said to be *totally reflected.* If we were to replace the wall with a less rigid

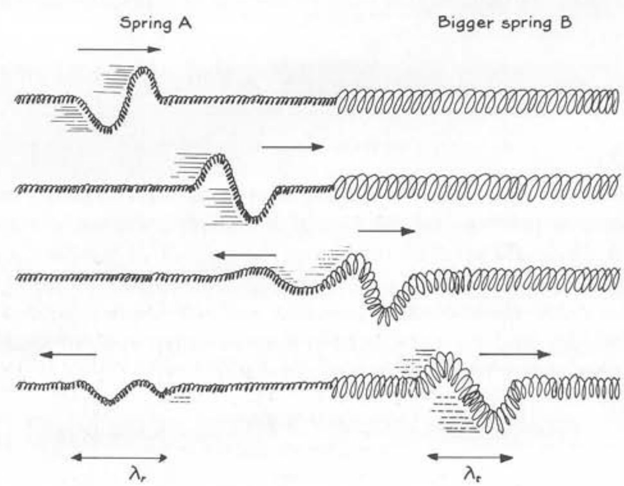


Figure 14-12
A wave can be both reflected and transmitted when it reaches the boundary between two media.

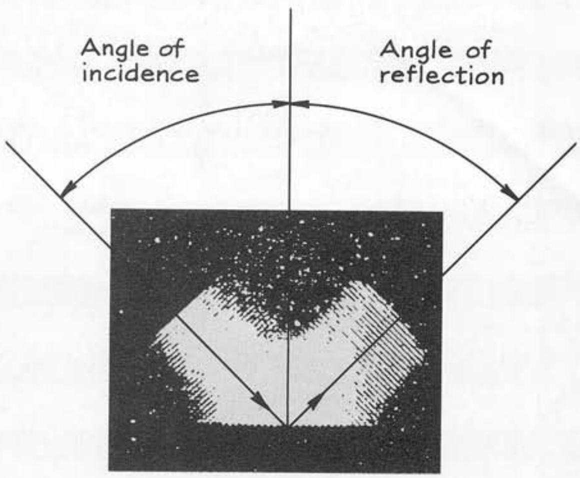


Figure 14-13
Waves are reflected such that the angle of reflection equals the angle of incidence.

medium, like the spring shown in Figure 14-12, some energy would be transmitted into the new medium. Some would still be reflected. These waves are said to be *partially reflected.*

In one dimension, reflected waves simply travel back in the direction from which they came. In two dimensions, waves are reflected from a boundary in a slightly more complex manner. If we compare the direction of motion for incoming and reflected waves, we see a pattern. Rays describe the direction in which incoming and reflected waves move. As shown in Figure 14-13, incoming rays and reflected rays make equal angles with a line perpendicular to the boundary. The angle made by the incoming ray and the perpendicular, called the **angle of incidence,** is equal to the angle made by the reflected ray and the perpendicular, called the **angle of reflection.** This relationship is called the **law of reflection:**

$$\text{Angle of incidence} = \text{angle of reflection}$$

Waves reflected from a boundary are always reflected such that the angle of incidence equals the angle of reflection. The law of reflection describes the behavior of both partially reflected and totally reflected waves.

SELF-CHECK 14D

Transverse waves are reflected at the boundary between the earth's mantle and core, shown in Figure 14-8. Use the law of reflection to determine whether seismic stations at *B* or *C* would report transverse waves received from an earthquake at *A*.

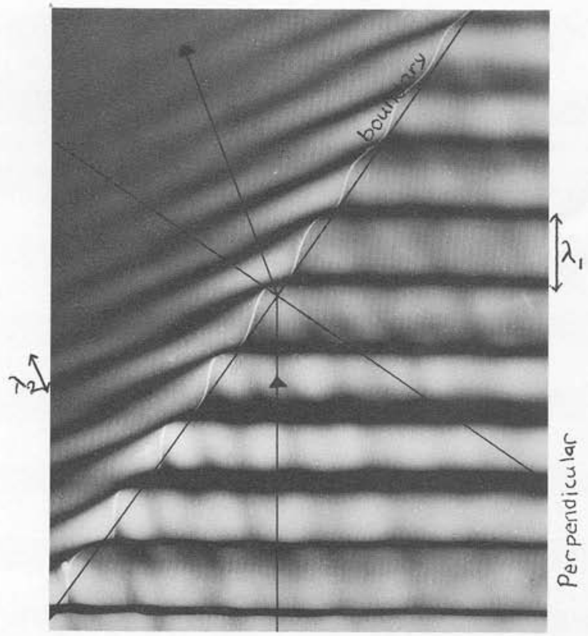


Figure 14-14
Water waves are refracted as they move from deep to shallow water. The wavelength decreases and the angle of refraction is less than the angle of incidence.

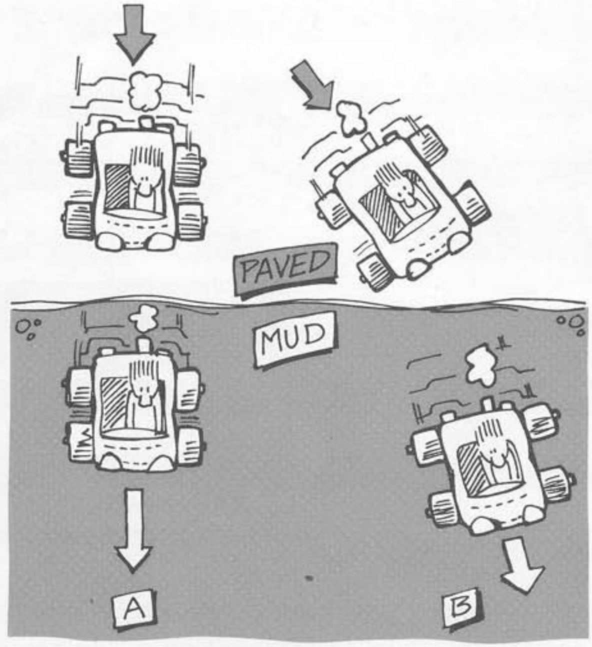


Figure 14-15
Waves are refracted in much the same fashion that a cart turns as it crosses the boundary between a paved surface and mud.

Refraction

Waves that strike a boundary between two media are sometimes transmitted rather than reflected. Light travels through water. Sound travels through walls. The transverse wave shown in Figure 14-12 is partially transmitted into the new medium. The waves transmitted into the new medium are not identical to the waves in the original medium. The change in speed that occurs as the waves change media affects both the wavelength and direction of the transmitted waves.

The change in wavelength that occurs as waves are transmitted into new media is particularly noticeable in Figure 14-12. The wavelength of the transmitted wave is shorter than the wavelength of the original wave. This change can be explained in terms of the change in speed. Waves travel more quickly in medium A than in medium B. Since the frequency of the wave motion is always constant, the wavelength must change when the speed of the wave changes. If the wave speeds up, the wavelength increases. If the wave slows down, the wavelength decreases. In Figure 14-12, the wavelength of the transmitted wave is shorter because the wave slows down as it enters medium B.

Water waves offer a striking example of the change in direction that often accompanies the change in wavelength when waves enter a new me-

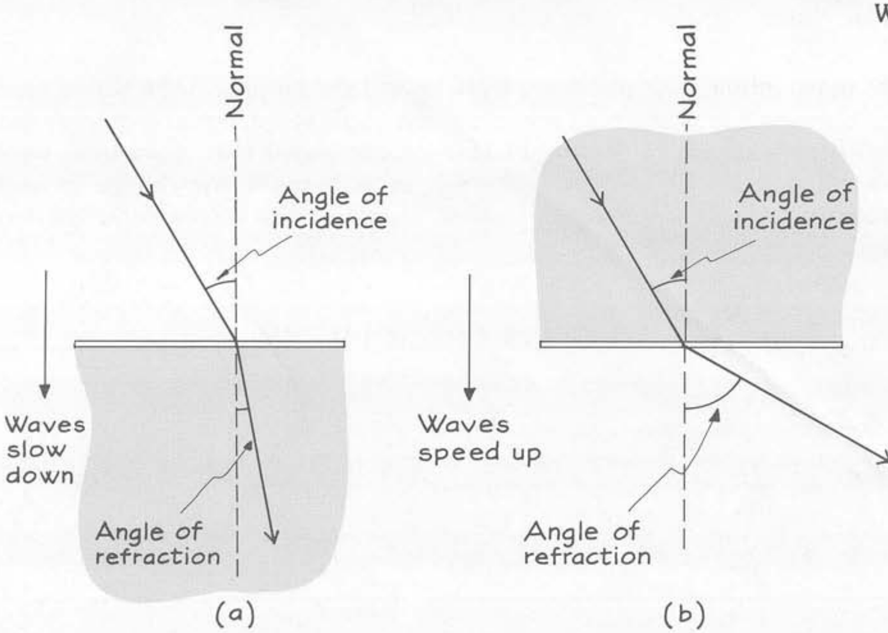


Figure 14-16
(a) When waves slow down, the angle of refraction is less than the angle of incidence. **(b)** When waves speed up, the angle of refraction is greater than the angle of incidence.

dium. Water waves travel at different speeds in water at different depths. A new depth constitutes, in effect, a new medium. When waves move from deeper water to shallower water, we find that they change direction as well as wavelength (Figure 14-14). This change in direction can be explained by the change in speed that occurs as the waves enter the shallower water.

We can understand how a change in wave speed leads to a change in direction with the help of an analogy. Figure 14-15 shows a cart moving from a paved surface to a muddy surface. Naturally, the cart moves at a slower speed in the mud than on the pavement. When the cart moves straight toward the boundary, the wheels on the left and right sides enter the mud at the same time and the cart simply slows down. When the cart moves toward the boundary at an angle, however, one side enters the mud before the other. In Figure 14-15(b) the wheels on the left enter the mud before the wheels on the right. Consequently, the left side of the cart moves more slowly than the right side and the cart turns. Its direction of motion has changed. The water waves in Figure 14-14 behaved in much the same fashion—one side of the wave entered the shallower water before the other side did. Therefore, the wave turned.

Refraction is the term for the change in direction and change in wavelength that occur as waves are transmitted from one medium into another. To measure the change in wavelength, we compare the wavelengths in the new and old media. To measure the change in direction, we compare angles relative to a line perpendicular to the boundary separating the two media. The **angle of incidence** is the angle between the incoming ray and the perpendicular. The **angle of refraction** is the angle between the outgoing, or transmitted, ray and the perpendicular. Waves that travel along the perpendicular, so that the angle of incidence is $0°$, do not change direction. The angle of refraction is also $0°$. At any other angle of incidence, however, waves are refracted such that the angle of incidence does not equal the angle of refraction. If the waves move into a medium in which they slow down, the angle of refraction is less than the angle of incidence (Figure 14-16(a)). Light waves that move into a glass prism are bent toward the normal. If the waves move into a medium in which they speed up, the angle of refraction is greater than the angle of incidence (Figure 14-16(b)). Light waves that move from water to air are bent away from the normal. In both cases, the change in angle depends on the change in speed that occurs as the waves enter the new medium.

SELF-CHECK 14E

Longitudinal waves are transmitted from the earth's mantle into its core, but the waves slow down substantially (see Table 14-2). Sketch the path of the longitudinal waves produced by an earthquake at point A in Figure 14-8.

Absorption

Light can be completely absorbed by a black surface. Sound can be absorbed by the panels added to soundproof an office or room. In some situations, waves are neither reflected nor refracted. They simply appear to fade away. This is called **absorption.**

While the wave itself can disappear, the energy the wave transmits cannot. Conservation of energy does not allow it. Generally, the energy carried by the wave is converted into the thermal energy of the absorbing medium. The black surface becomes hot. Sound panels become warmer than the surrounding air. The wave energy is converted into the thermal energy of a medium's atoms and molecules.

WAVES MEET WAVES

Drop two stones in a pond at the same time. Each stone creates a series of circular waves. As the waves created by one stone move outward, they meet those created by the other stone. The familiar pattern shown in Figure 14-17 arises when wave meets wave.

Wave Interference

Figure 14-18 shows a series of drawings made of two wave crests as they move toward one another, meet in the center, and finally move away from one another. If we compare (a) and (e), the two crests seem to have passed through one another essentially unchanged. The drawing in (c), however, shows a completely new wave, which is a combination of the two crests. When waves interact, they combine according to the superposition principle.

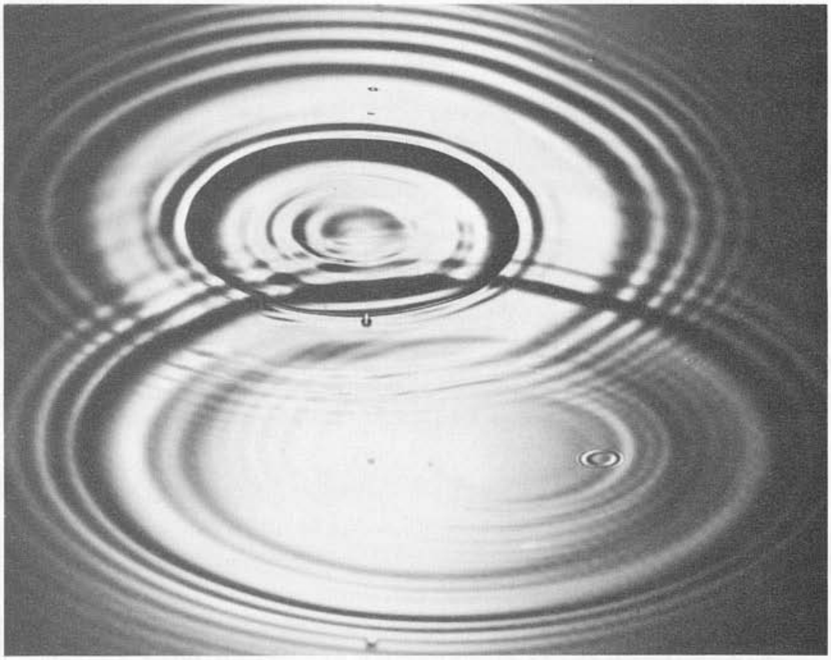


Figure 14-17
Waves produced by each stone travel outward, overlapping to produce complex patterns.

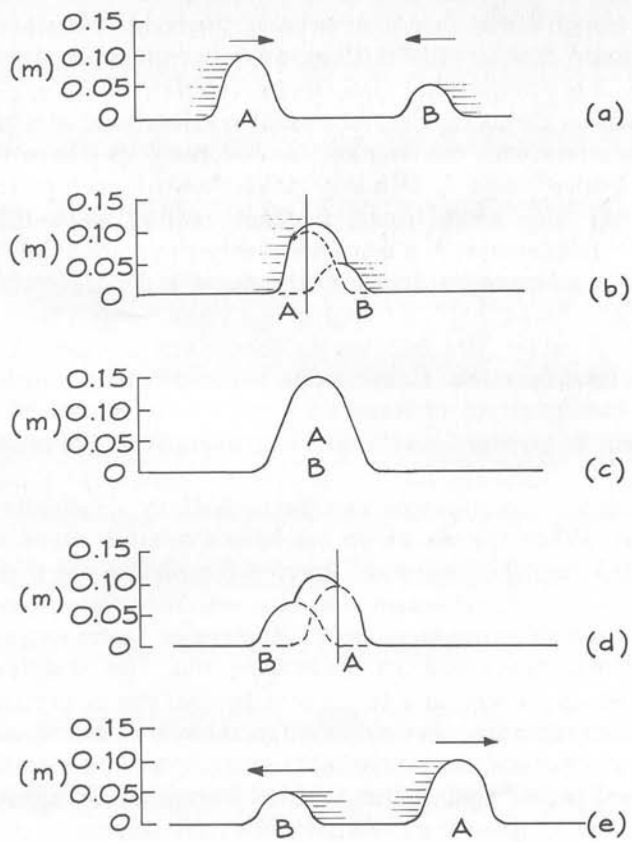


Figure 14-18
The two waves meet, combine briefly to form a new wave and then move on essentially unchanged.

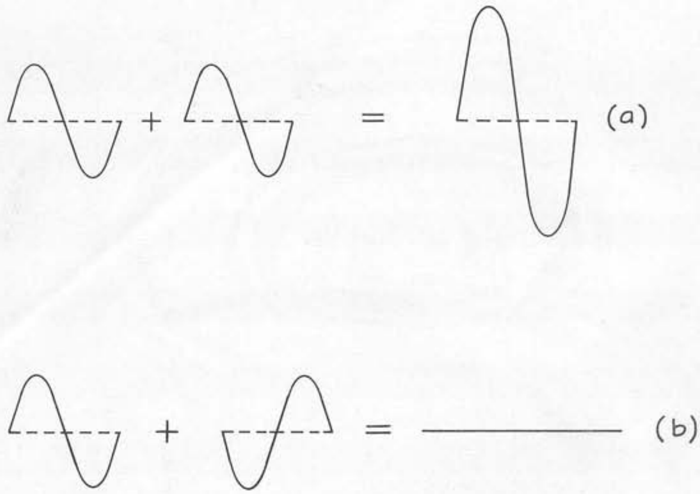


Figure 14-19
(a) Constructive interference. **(b)** Destructive interference.

The **superposition principle** states that when waves meet in space, their effects on the medium add. The total displacement of the medium is the sum of the displacements caused by each wave separately. We can apply this principle to the interaction sketched in Figure 14-18. Wave A has an amplitude of 0.10 m. Wave B has an amplitude of 0.05 m. When the two crests combine in (c), the amplitude is 0.10 m + 0.05 m, or 0.15 m. Had wave B been a wave trough rather than a wave crest, the combined wave would have had an amplitude of 0.10 m − 0.05 m, or 0.05 m. Amplitudes in the same direction add; those in opposite directions subtract.

When waves combine, they are said to **interfere** with one another. Waves can interfere with one another constructively or destructively. When two identical waves meet in such a way that each wave crest matches another wave crest and each wave trough matches another wave trough (Figure 14-19(a)), their combination is a wave with twice the amplitude of each single wave. This is called **constructive interference.** In Figure 14-19(b), the two identical waves meet so that the trough of one wave meets a crest of the other wave, and vice versa. The two waves cancel one another. This is called **destructive interference.** Constructive and destructive interference demonstrate the two extremes of wave addition. The amplitude of a combined wave can never be greater than the sum of the amplitudes of the waves which interact.

The superposition principle can be applied to all situations in which waves interact. When the waves do not have the same shape or the same wavelength, the combined wave can have a complex shape that bears little resemblance to the original waves that interact. You can imagine how complex the combined wave produced by a 100-piece orchestra might be. Still the principle governing wave interactions is the same. The complex wave that reaches our ears is the sum of a series of individual waves produced by each instrument. Each separate wave exists independently of the others and keeps its individual characteristics. Remarkably enough, we learn to separate out these individual waves against the complex background, following only the melodic line or picking out the parts played by the woodwinds.

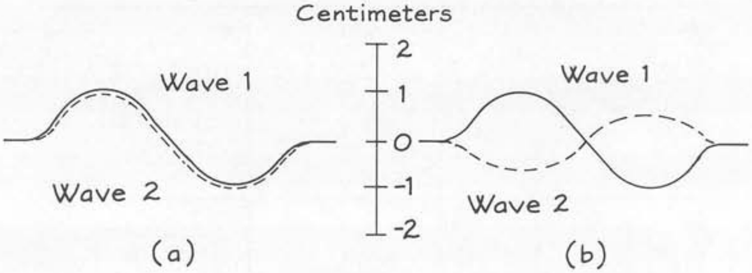


Figure 14-20

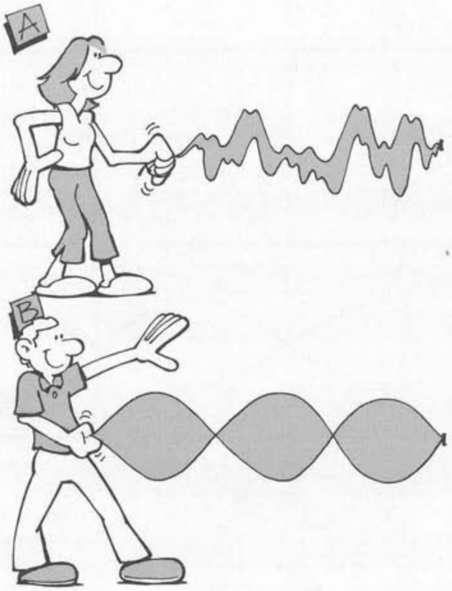


Figure 14-21
(a) At most frequencies, we see a jumble. **(b)** At a few frequencies we see a stationary wave pattern called a standing wave.

SELF-CHECK 14F

Sketch the shape of the combined waves shown in Figure 14-20.

Standing Waves

Suppose you are vibrating a spring that is attached to a wall. You produce continuous and identical waves by moving the spring up and down at a constant rate. As they travel back along the spring, the reflected waves interact continuously with identical incoming waves. At most frequencies, these interactions produce a jumble like that shown in Figure 14-21(a). However, at a few frequencies they produce patterns like those in Figure 14-21(b)—waves that move up and down but do not appear to travel along the spring. These stationary wave patterns are called **standing waves.**

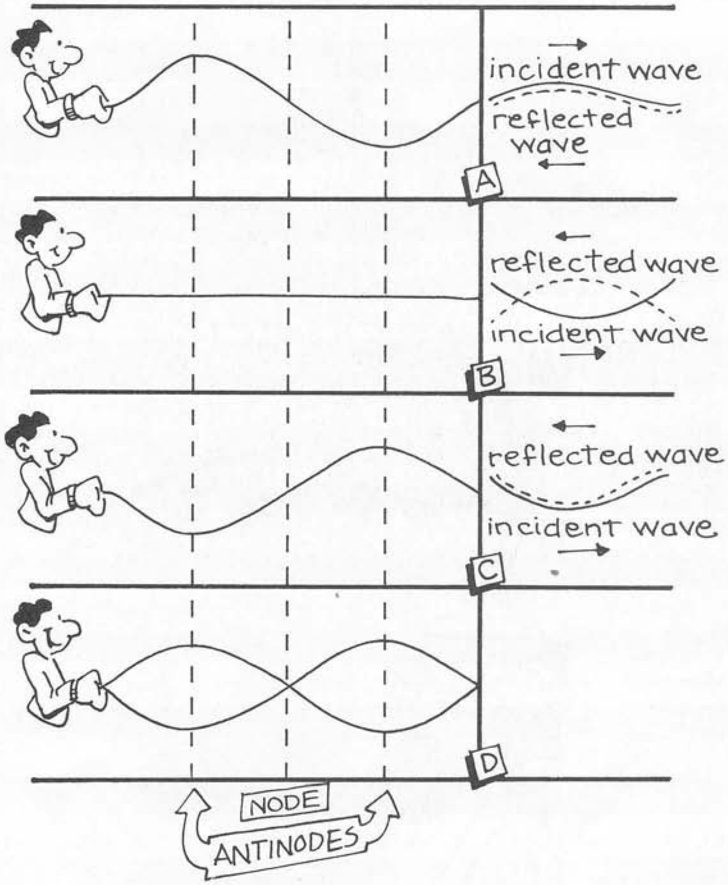


Figure 14-22
A standing wave is produced as the reflected and incoming waves alternate between constructive and destructive interference.

A standing wave pattern is created by constructive and destructive interference of the incoming and reflected waves, as shown in Figure 14-22. When the incoming and reflected waves match (Figure 14-22(a)), they interfere constructively. As the incoming wave continues toward the wall and the reflected wave continues back, the crests of one eventually match the troughs of the other, and vice versa (Figure 14-22(b)). They then interfere destructively, and the entire spring is flat. Later the two waves again match (Figure 14-21(c)) and constructive interference occurs. This continual interference between incoming and reflected waves creates a wave pattern in the spring that stands still. Certain regions of the spring, called **nodes,** do not move at all. The incoming and reflected waves always interfere destructively at these points. Other regions of the spring, called **antinodes,** move up and down constantly. Here incoming and reflected waves alternately interfere constructively, destructively, constructively, and so forth.

Vibrations at one frequency create standing waves, while those at another do not. If you shake the end of a spring you can actually feel the difference. A lot of energy is needed to keep a wave moving at most frequencies. But when you move the spring at a standing wave frequency—one at

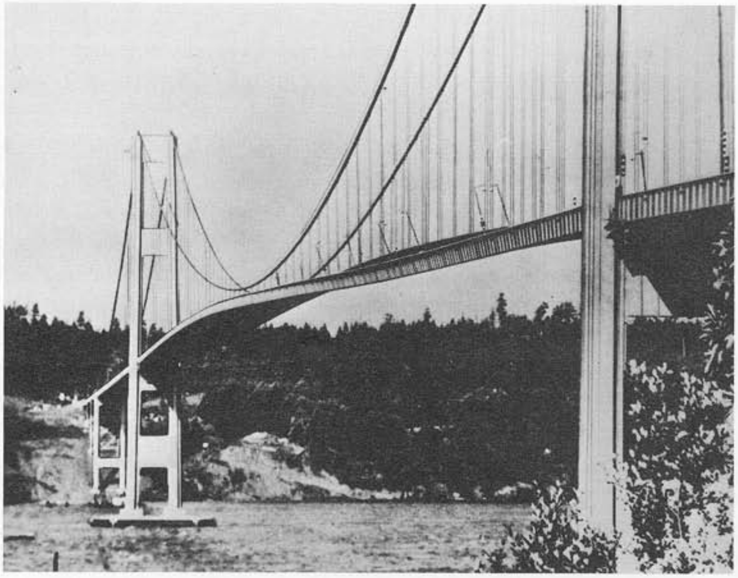


Figure 14-23
The Tacoma Narrows Bridge provided a spectacular example of resonance shortly before its collapse on November 7, 1940.

which outgoing and returning waves match—the pattern is maintained with very little energy. Since the reflected waves constantly reinforce the outgoing waves, the system loses very little energy to the surrounding air or to the thermal energy of the spring itself. The small pushes you provide at just the right times replace this lost energy; more substantial pushes can increase the amplitude of the standing wave.

Standing waves occur in many objects—springs, ropes, metal rods, drum heads, and violin strings. Even buildings and bridges vibrate in standing wave patterns. Each object has unique frequencies, called **natural frequencies,** at which standing waves occur. In musical instruments, these standing waves are a means of creation. In buildings and bridges, they can be a means of destruction.

Resonance

On November 7, 1940, the bridge spanning the narrows at Tacoma, Washington, collapsed. From the day it was built, the concrete-and-steel suspension bridge had vibrated noticeably in the wind. Drivers on the bridge sometimes saw cars in front of them vanish and reappear as the bridge oscillated. On the fateful day these oscillations grew steadily until they became violent (Figure 14-23). The bridge looked very much like our spring rather than a semirigid structure made from solid iron girders 2 m thick. Within a few hours, the bridge had collapsed. The culprit was resonance.

Resonance occurs when the frequency of the energy source matches a natural frequency of the vibrating medium. The spring in Figure 14-21(b) is resonating; so is the Tacoma Narrows Bridge in Figure 14-23. In the case of the bridge, the amplitude of the standing waves increased to the point where the structure could no longer stand the strain and collapsed. The same phenomenon can cause a building to collapse during an earthquake. When the

Figure 14-24
The standing waves produced in the string are transmitted to the body of the violin through the bridge. Standing waves in the body of the violin create the musical sounds we enjoy.

ground shakes at a certain frequency, standing waves will be set up in a building that has that particular natural frequency. The building may crack or collapse under the strain, while an adjacent building with a different natural frequency remains undamaged.

The Tacoma Narrows Bridge had solid steel beams, which played a key role in its collapse. When a flat object such as a beam blocks the wind, it creates oscillating turbulence patterns on the downwind side of the object. The oscillating gusts of wind push alternately upward and downward at a rate that depends on the dimensions of the object blocking the wind. In the case of the Tacoma Narrows Bridge, the choice of solid steel beams led to wind oscillations on the downwind side that happened to match a natural frequency of the bridge. Each oscillation of the wind caused the bridge to oscillate higher, until the bridge finally tore itself apart.

Not all applications of resonance are destructive. The resonance that architects and engineers desperately try to avoid, instrument makers eagerly try to discover. A violin is designed so that the standing waves produced in the string can be transmitted to the wooden body of the violin (Figure 14-24). For centuries violin makers have refined the art of selecting the best woods and sculpting them to resonate in ways we find pleasurable.

Harmonic Series

Most vibrating objects produce standing waves at several different natural frequencies. The spring shown in Figure 14-25 vibrates in a standing wave pattern at frequencies of 2 Hz, 4 Hz, 6 Hz, 8 Hz, and so on. The lowest natural frequency of an object, in this example 2 Hz, is called the object's **fundamental frequency.** Other natural frequencies of the spring are integer multiples of its fundamental frequency. Collectively, all the resonant frequencies of an object form a **harmonic series.**

To understand how the frequencies in a harmonic series are established, consider the ways in which waves can fit along the spring. Once the standing wave has been established, your hand and the wall provide fixed points of contact for the spring. (While you do move your hand slightly to replace energy lost to the surrounding air, ideally the wave energy would just bounce back and forth between the wall and your hand.) Any standing wave established in the spring must have nodes located at these two end points. The standing wave produced at the fundamental frequency has only these two nodes. Consequently, one-half of a wavelength fits along the length of the spring. The next resonant frequency, 4 Hz, produces a wave with three nodes—one at each end and one in the middle. One full wavelength now fits along the spring. The next resonant frequency, 6 Hz, has four nodes—one and one-half wavelengths—and so forth. A series of resonant frequencies, such as that shown in Figure 14-25, consists of those frequencies for which one-half, one, one and one-half, two (and so on) wavelengths fit along the spring.

Since standing waves are produced when outgoing waves match the arrival of reflected waves, the fundamental frequency of a medium depends on

One goal in science is to simplify—to draw together the diverse phenomena we observe into as few categories as possible. The wave concepts that have emerged from observations of water waves, springs, and vibrating strings prove equally powerful in describing sound and light. Chapter 15 offers you a closer look at the wave model and its effectiveness in drawing together remarkably diverse phenomena.

CHAPTER SUMMARY

Wave motion is the propagation of a disturbance through a medium. It is a process by which energy is transferred from a source to a receiver without a simultaneous transfer of mass. Wave motion requires an energy source, an energy receiver, and a medium through which the energy is transferred. Comparing the direction in which the medium vibrates with the direction in which the energy travels leads to the identification of two kinds of waves. In a *transverse wave,* the medium vibrates perpendicular to the direction of energy transfer. A *longitudinal wave* is a wave in which the medium vibrates parallel to the direction of energy transfer.

A wave is described in terms of its amplitude, frequency, and wavelength. The *amplitude* of a wave describes its height, the maximum distance the parts of the medium move from their natural position. Amplitude is related to the amount of energy carried by the wave. The *frequency* of a wave is the number of complete cycles executed by a segment of the medium in 1 s. It is related to the rate at which energy is transmitted by the wave. *Wavelength* is the distance taken up along the medium by one complete cycle. The frequency and wavelength of a wave are related to one another by the concept of wave speed:

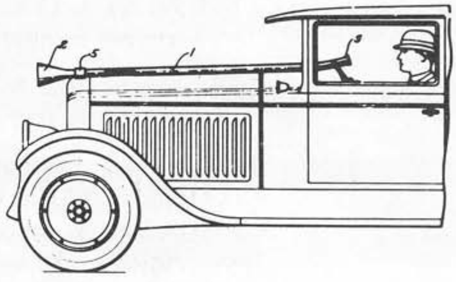
$$\text{Wave speed} = \text{frequency} \times \text{wavelength}$$

Wave speed describes how fast the disturbance moves through the medium and consequently the rate of energy transfer.

When either the wave source or receiver moves relative to the other, the frequency of the waves received is different from the frequency of the waves emitted. This difference in frequency is called the *Doppler effect.* The greater the relative speed between the source and receiver, the larger the difference in frequency reported by the receiver.

As waves move from one medium to another, they can be reflected, refracted, or absorbed. Waves that are *reflected* remain in the original medium. Reflected waves obey the *law of reflection:* The angle of incidence equals the angle of reflection. Waves that are transmitted into a new medium change speed. This change in speed leads to a change in wavelength and a change in direction called wave *refraction.* If the wave slows down, the angle of refraction is less than the angle of incidence. If the wave increases its speed, the angle of refraction is greater than the angle of incidence. Waves that are *absorbed* by the new medium convert their energy into some other form, usually thermal energy.

GETTING THE MESSAGE ACROSS



Today when we see a pedestrian in front of our car, we either stop or honk the horn. Eugene Baker apparently felt that the horn was too impersonal. He wanted a more direct communication between the driver and the pedestrian. To convey messages, Mr. Baker applied the ideas of wave reflection and resonance. If a driver saw someone standing in his way, he would speak into the tube (3). The sound would be reflected off the inside of the narrow tube (1) and thus travel to the megaphone (2) at the end. The shape of the megaphone assured that all of the sound was directed—via reflections—toward the pedestrian. The length of the tube affected the frequencies that would be transmitted. By selecting a rather long tube, Mr. Baker created a situation in which the low frequencies have standing waves in the tube. The driver's voice would seem to be lower to the pedestrian than it actually was because of these standing waves.

Waves that meet in space combine according to the *superposition principle.* The combined wave has a displacement at each point in the medium that is the sum of the displacements caused by each wave separately. Two identical waves that meet so that crest matches crest and trough matches trough combine to produce a wave with twice the amplitude of the two separate waves. This is called *constructive interference.* Two identical waves that meet so that crest matches trough annihilate one another. This is called *destructive interference.*

Under certain circumstances, an incident wave and its reflection will interfere with one another to produce a standing wave. A *standing wave* is a wave pattern that appears stationary in the medium. Points in the medium that do not move are called *nodes.* Points of maximum displacement are called *antinodes.* The motion of the medium in a standing wave pattern arises from alternating periods of constructive and destructive interference between the incoming and reflected waves. Standing waves are created when an energy source vibrates at one of the *natural frequencies* of the medium. The natural frequency of the medium depends on the wave speed and length of the medium. Vibration at a natural frequency, called *resonance,* can destroy structures like bridges or produce pleasurable sounds in musical instruments.

ANSWERS TO SELF-CHECKS

14A. Waves in A have a smaller amplitude, a greater wavelength, and a smaller frequency than those in D.

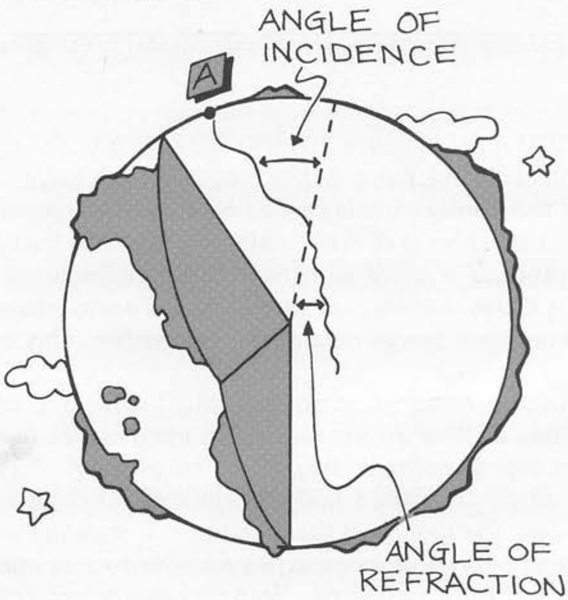
Waves in B have the same amplitude but a greater wavelength and a smaller frequency than those in D.
Waves in C have a smaller amplitude, a greater wavelength, and a smaller frequency than those in D.

14B. Wave speed = (440 Hz)(3 m) = 1320 m/s. Sound travels more rapidly in water than in air.

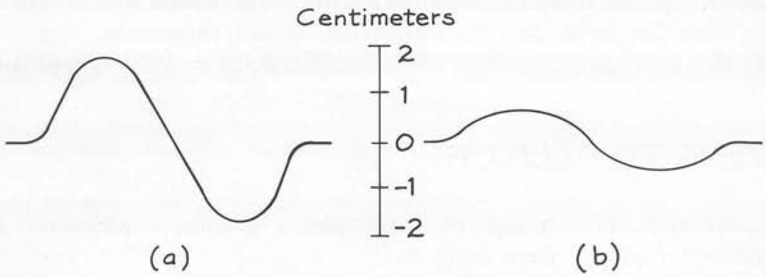
14C. It does not matter whether the wave source or the wave receiver is moving. As Y moves toward the boat, the waves will be pushed together. Y reports receiving a frequency higher than 1 Hz. X is not moving relative to the boat. X reports receiving a frequency of 1 Hz, the same frequency emitted at the boat.

14D. Seismic stations at *B* will report receiving transverse waves, but those at *C* will not.

14E. Since the waves slow down substantially when they enter the earth's core, the angle of refraction will be less than the angle of incidence, as shown below. The longitudinal waves will have a shorter wavelength in the core than in the mantle.



14F. The waves add as shown below.



14G. Since the spring is now longer, the wavelength of the fundamental frequency will be longer. A longer wavelength corresponds to a lower fundamental frequency than that shown in Figure 14-25.

PROBLEMS AND QUESTIONS

A. Review of Chapter Material

A1. Define each of the terms listed below:
Wave motion
Transverse wave
Longitudinal wave
Amplitude
Frequency
Wavelength
Wave speed
Reflection
Refraction
Doppler effect
Absorption
Superposition principle
Constructive interference
Destructive interference
Standing wave
Nodes
Antinodes
Resonance
Fundamental frequency

A2. How is wave motion different from the other processes by which energy is transferred?

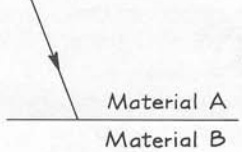
A3. How are longitudinal waves different from transverse waves?

A4. What affects the speed at which waves travel?

A5. How do geologists use earthquake waves to build a model of the interior of the earth?

A6. Why does a moving source or receiver cause a change in the frequency of waves reported by the receiver?

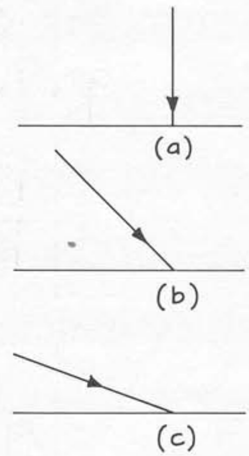
A7. Sketch the path of the refracted waves for each case.



a. The wave speed in A is greater than in B.

b. The wave speed in B is greater than in A.

A8. Sketch the path of the reflected wave in each situation shown below.



A9. When waves are transmitted into a new medium, they change speed. How does this change in speed lead to a change in wavelength? A change in direction?

A10. What happens to the energy transmitted by a wave when the wave is absorbed by the new medium?

A11. Under what circumstances will constructive and destructive interference occur?

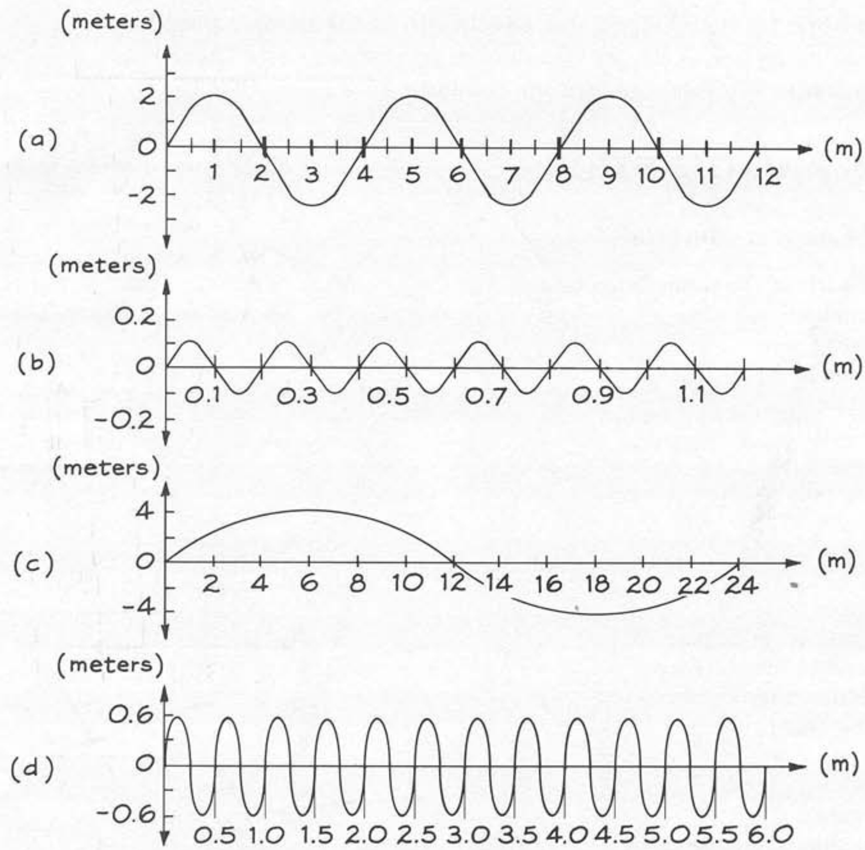
A12. Describe how constructive and destructive interference explain the production of standing waves.

A13. Why are standing waves produced only at selected frequencies?

A14. What two variables determine the fundamental frequency of a medium?

B. Using the Chapter Material

B1. A spring is attached to the end of a swinging pendulum. Draw a diagram showing how the pendulum must move to produce longitudinal waves in the spring. How must it be attached to produce transverse waves?



B2. What are the amplitudes and wavelengths of the waves shown above?

B3. In one of its vibrations, the Tacoma Narrows Bridge vibrated 6 times in 60 s. What was the bridge's frequency?

B4. Complete the following table.

Frequency	*Wavelength*	*Speed*
400 Hz	0.75 m	?
?	1.25 m	300 m/s
150 Hz	?	300 m/s
500 Hz	?	500 m/s
?	2.00 m	500 m/s
1000 Hz	0.50 m	?
100 Hz	0.40 m	?
100 Hz	?	80 m/s
?	1.60 m	160 m/s

B5. Use the results of the table completed in Question B4 to determine:

a. what happens to the frequency if the wavelength doubles and the speed does not change

b. what happens to the wavelength if the speed decreases by one-half and the frequency does not change

c. what happens to the speed if the frequency decreases by one-half and the wavelength doubles

B6. The wave shown below is heading toward a point where the rope changes to thicker rope. The wave will travel more slowly in the new rope. Sketch the wave as it is transmitted into the new medium.

B7. The drawing that follows shows a wave at one instant in time. Draw waves that, if they interfered with this wave, would:

a. completely cancel it

b. reduce its amplitude to one-half its present value e its pres-

d. increase its amplitude to four times its present value

B8. Standing waves in an oboe have the same type of harmonic series as those in a spring. If the oboe has a fundamental frequency of 440 Hz, what will be some of the other resonant frequencies?

B9. The water strider is an insect that walks on water. As each of its feet strikes the water, a wave is sent out. Suppose the frequency at which its feet strike the water is 1 Hz; water waves travel at 0.1 m/s and the water strider moves east at 0.004 m/s. What frequencies of water waves are reported by a motionless receiver directly east of the insect? Directly west of the insect?

B10. If the Tacoma Narrows Bridge vibrated at 0.1 Hz, what must have been the frequency of the force applied by the wind?

C. Extensions to New Situations

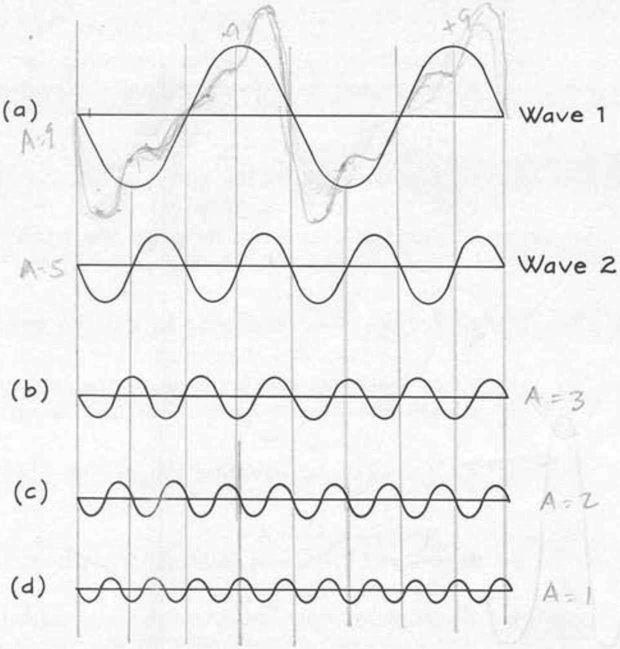
C1. A transverse wave traveling on a spring strikes a wall. The reflected wave's amplitude is in a direction opposite to the incident wave. This result can be explained by applying Newton's laws to the situation.
  a. Draw a wave that is striking a wall.
  b. In which direction does the force applied by the rope act on the wall?
  c. What is the direction of the force applied on the rope by the wall?
  d. Which object will move more easily? Why?
  e. What will be the direction of the motion of the object mentioned in part (d)?
  f. Use the answers to parts (a)–(e) to explain why the amplitude reverses upon reflection from a wall.

C2. The concept of resonance can be used to create very large waves in a swimming pool.
  a. Suppose you and several friends stand at one end of a pool and jump into it simultaneously. Describe the wave that is created and describe how it travels through the pool.
  b. What happens when the wave reaches the other end of the pool?
  c. If the water waves travel at 0.5 m/s and the pool is 50 m long, how much time will pass before the wave returns to the end where you jumped in?
  d. Suppose you and your friends get out of the pool and then jump back in just as the wave returns to your end. How will the amplitude of the next wave compare with the first?
  e. If you keep repeating the process described in (d), what will happen to the amplitude of the wave?
  f. Do you think you could empty a swimming pool this way?

C3. Some evil people have been known to use the concept of resonance to destroy a waterbed. Use the ideas presented in Question C2 to explain how you could produce large-amplitude waves in a waterbed. (*Warning:* These waves can become large enough to split the plastic in a waterbed.)

C4. The Tacoma Narrows Bridge was not the first bridge to collapse because it resonated with the wind. A British bridge designer, Sir Samuel Brown, built three bridges during the nineteenth century, all of which collapsed after oscillating in the wind. He also built a footbridge that collapsed when soldiers marched across it in step.
  a. Explain why marching in step could set up large oscillations in a bridge.
  b. Today, soldiers break step and walk across suspended footbridges. Why does this procedure eliminate the creation of standing waves?

C5. By adding selected waves together, we can obtain waves that look quite different from the simple waves from which they were built.
  a. Sketch the addition of the two waves (a) shown on the following page.
  b. To the wave you sketched in (a), add the wave shown in (b) and sketch the result.
  c. To the wave you sketched in (b), add the wave shown in (c) and sketch the result.



d. Do one more. To the wave you sketched in (c), add the wave shown in (d) and sketch the result.

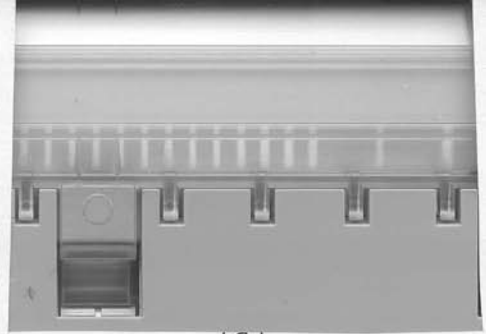
e. Does your result in (d) look similar to any of the waves you added? (We discuss this idea more in the next chapter.)

C6. Earthquake waves travel through the earth and are received by stations on the other side. Some stations receive both longitudinal and transverse waves, while others receive only longitudinal waves. Explain why this supports the theory that the core of the earth is liquid.

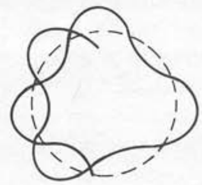
C7. When you strike a water glass, you can establish standing waves on the rim of the glass. As you see it from above, the glass forms a circle. The standing waves are similar to those shown in the next column.

a. Identify the nodes and antinodes for the wave shown in (a).

b. Suppose a wave on a circular glass looks like that in (b). Explain why standing waves cannot occur.



(a)



(b)

c. Sketch a standing wave that has fewer nodes than the one in the circle.

d. Use your results to state a general rule relating the wavelength of circular standing waves to the circumference of of a circle.

C8. The earth is believed to have three quite different layers, shown in Figure 14-8. Use the information on wave speed given in Table 14-2 to discuss changes in the direction of motion as a wave travels from a point on the earth, through the earth to a point on the opposite side.

D. Activities

D1. Try the swimming pool experiment described in Problem C2.

D2. Try to find the nodes on a guitar string. Place small pieces of paper on the string and pluck it. Move the paper around until it undergoes the least vibration. Why is that location near a node?

D3. Watch electric wires, telephone lines, and clotheslines on windy days. Sometimes you will see standing waves.