# Chapter 3
## Vibrations and Waves

**Overlapping waves.**

Many things in nature wiggle and jiggle. We call a wiggle in time a *vibration.* A vibration cannot exist in an instant, for the body that vibrates needs time to move to and fro. When we strike a bell the vibrations continue for some time before they die down. We call a wiggle in space and time a *wave.* A wave cannot exist in one place but must extend from one place to another. Light and sound are both vibrations that propagate through space as waves, but of two very different kinds. Sound is the propagation of vibrations through a material medium—a solid, liquid, or gas. If there is no medium to vibrate, then no sound is possible. On the other hand, light is a vibration not of matter, but of nonmaterial electric and magnetic fields. Light can pass through many materials, but it needs none; it can propagate through a vacuum, for example between the sun and the earth. But the source of all waves—sound, light, or whatever—is something that is vibrating. For sound it can be the vibrating prongs of a tuning fork and for light the vibrations of electrons in an atom. Waves may be periodic vibrations, as in music, or nonperiodic wave pulses, as in the cracking sound of a firecracker or the snapping of one's fingers. We shall begin our study of vibrations and waves by considering the motion of a simple pendulum.

## Vibration of a Pendulum

If we suspend a stone at the end of a piece of string, we have a simple pendulum. Pendulums swing to and fro with such regularity that for a long time they were used to control the motion of most clocks. They can still be found in grandfather clocks and cuckoo clocks. Galileo discovered that the time a pendulum takes to swing to and fro through small distances depends only on the *length of the pendulum*.* The time of a to-and-fro swing, called the **period**, does not depend on the mass of the pendulum or on the size of the arc through which it swings.

In addition to length, the period of a pendulum depends on the acceleration of gravity. Oil and mineral prospectors use very sensitive pendulums to detect slight differences in this acceleration, which is affected by the densities of underlying formations.

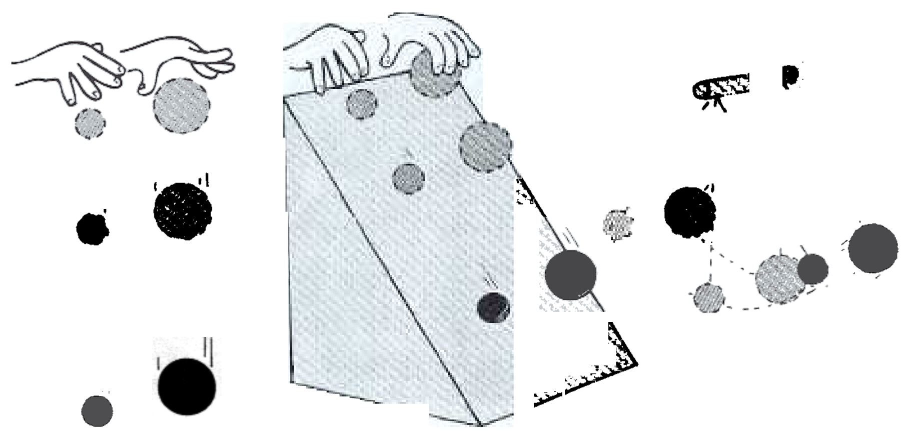


**FIGURE 18.1** Drop two balls of different mass and they accelerate at *g*. Let them slide without friction down the same incline and they slide together at the same fraction of *g*. Tie them to strings of the same length so they are pendulums, and they swing to and fro in unison. In all cases, the motions are independent of mass.

A long pendulum has a longer period than a shorter pendulum; that is, it swings to and fro less frequently than a short pendulum. When walking, we allow our legs to swing with the help of gravity, like a pendulum. In the same way that a long pendulum has a greater period, a person with long legs tends to walk with a slower stride than a person with short legs. This is most noticeable in long-legged animals such as giraffes, horses, and ostriches, which run with a slower gait than do short-legged animals such as dachshunds, hamsters, and mice.

## Wave Description

The to-and-fro vibratory motion (often called *oscillatory* motion) of a swinging pendulum in a small arc is called **simple harmonic motion**.[†] The pendulum bob filled with sand in Figure 18.2 exhibits simple harmonic motion above a conveyor belt. When the

* The exact equation for the period of a simple pendulum is $T = 2\pi\sqrt{l/g}$, where $T$ is the period, $l$ is the length of the pendulum, and $g$ is the acceleration of gravity.

[†] The condition for simple harmonic motion is that the restoring force is proportional to the displacement from equilibrium. This condition is nearly always met, at least approximately, for most vibrations. The component of weight that restores a displaced pendulum to its equilibrium position is directly proportional to the pendulum's displacement (for small angles)—likewise for a bob attached to a spring. Recall from page 202 in Chapter 11, Hooke's law for a spring: $F = k\Delta x$, where the force to stretch (or compress) a spring is directly proportional to the distance stretched (or compressed).

a

b

FIGURE 18.2 Frank Oppenheimer at the San Francisco Exploratorium demonstrates (a) a straight line traced by a swinging pendulum bob that leaks sand on the stationary conveyor belt. (b) When the conveyor belt is uniformly moving, a sine curve is traced.

conveyor belt is not moving (left), the sand traces out a straight line. More interestingly, when the conveyor belt is moving at constant speed (right), the sand traces out a special curve known as a **sine curve**.

A sine curve can also be traced by a bob attached to a spring undergoing vertical simple harmonic motion (Figure 18.3). A marking pen attached to the bob traces a sine curve on a sheet of paper that is moved horizontally at constant speed. A sine curve is a pictorial representation of a wave. Like a water wave, the high points of a sine wave are called *crests*, and the low points are called *troughs*. The straight dashed line represents the "home" position, or midpoint of the vibration. The term **amplitude** refers to the distance from the midpoint to the crest (or trough) of the wave. So the amplitude equals the maximum displacement from equilibrium.

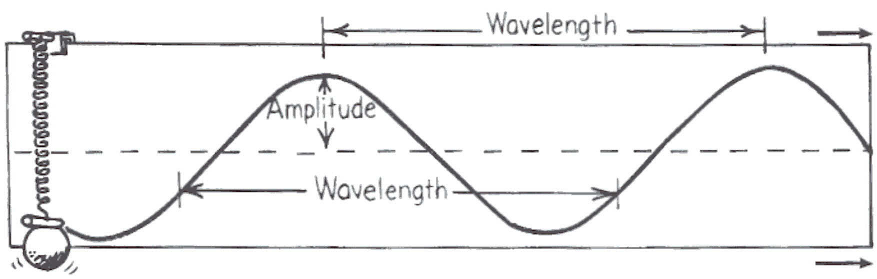



FIGURE 18.3 A sine curve.

The **wavelength** of a wave is the distance from the top of one crest to the top of the next one. Or equivalently, the wavelength is the distance between any successive identical parts of the wave. The wavelengths of waves at the beach are measured in meters, the wavelengths of ripples in a pond in centimeters, and the wavelengths of light in billionths of a meter (nanometers).

How frequently a vibration occurs is described by its **frequency**. The frequency of a vibrating pendulum, or object on a spring, specifies the number of to-and-fro vibrations it makes in a given time (usually one second). A complete to-and-fro oscillation is one vibration. If it occurs in one second, the frequency is one vibration per second. If two vibrations occur in one second, the frequency is two vibrations per second, and so forth.

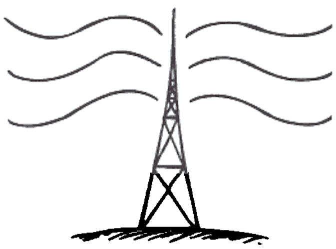


**FIGURE 18.4** Electrons in the transmitting antenna vibrate 940,000 times each second and produce 940-kHz radio waves.

The unit of frequency is called the **hertz** (Hz), after Heinrich Hertz, who demonstrated radio waves in 1886. One vibration per second is 1 hertz; two vibrations per second is 2 hertz, and so on. Higher frequencies are measured in kilohertz (kHz, thousands of hertz), and still higher frequencies in megahertz (MHz, millions of hertz) or gigahertz (GHz—billions of hertz). AM radio waves are measured in kilohertz, while FM radio waves are measured in megahertz; radar and microwave ovens operate at gigahertz frequencies. A station at 960 kHz on the AM radio dial, for example, broadcasts radio waves that have a frequency of 960,000 vibrations per second. A station at 101.7 MHz on the FM dial broadcasts radio waves with a frequency of 101,700,000 hertz. These radio-wave frequencies are the frequencies at which electrons are forced to vibrate in the antenna of a radio station's transmitting tower. The source of all waves is something that vibrates. The frequency of the vibrating source and the frequency of the wave it produces are the same.

If an object's frequency is known, its period can be calculated, and vice versa. Suppose, for example, that a pendulum makes two vibrations in one second. Its frequency is 2 Hz. The time needed to complete one vibration—that is, the period of vibration—is $\frac{1}{2}$ second. Or if the vibration frequency is 3 Hz, then the period is $\frac{1}{3}$ second. The frequency and period are the inverse of each other:

$$\text{Frequency} = \frac{1}{\text{period}}$$

or vice versa:

$$\text{Period} = \frac{1}{\text{frequency}}$$

# Questions

1. What is the frequency in vibrations per second of a 60-Hz wave? What is its period?
2. Gusts of wind make the Sears Building in Chicago sway back and forth at a vibration frequency of about 0.1 Hz. What is its period of vibration?

# Answers

1. A 60-Hz wave vibrates 60 times per second and has a period of $\frac{1}{60}$ second.
2. The period is 1/frequency = 1/(0.1 Hz) = 1/(0.1 vibration/s) = 10 s. Each vibration therefore takes 10 seconds.

## Wave Motion

Most information about our surroundings comes to us in some form of waves. It is through wave motion that sounds come to our ears, light to our eyes, and electromagnetic signals to our radios and television sets. Through *wave motion,* energy can be transferred from a source to a receiver without the transfer of matter between the two points.

Wave motion can be most easily understood by first considering its simplest case in a horizontally stretched rope. If one end of such a rope is shaken up and down, a rhythmic disturbance travels along the rope. Each particle of the rope moves up and down, while at the same time the disturbance moves along the length of the rope. The medium, rope or whatever, returns to its initial condition after the disturbance has passed.

Perhaps a more familiar example of wave motion is provided by a water wave. If a stone is dropped into a quiet pond, waves will travel outward in expanding circles, the centers of which are at the source of the disturbance. In this case we might think that water is being transported with the waves, since water is splashed onto previously dry ground when the waves meet the shore. We should realize, however, that barring obstacles the water will run back into the pond, and things will be much as they were in the beginning: The surface of the water will have been disturbed, but the water itself will have gone nowhere. A leaf on the surface will bob up and down as the waves pass, but will end up where it started. Again, the medium returns to its initial condition after the disturbance has passed.

Let us consider another example of a wave to illustrate that what is transported from one place to another is a disturbance in a medium, not the medium itself. If you view a field of tall grass from an elevated position on a gusty day, you will see waves travel across the grass. The individual stems of grass do not leave their places; instead, they swing to and fro. Furthermore, if you stand in a narrow footpath, the grass that blows over the edge of the path, brushing against your legs, is very much like the water that doused the shore in our earlier example. While wave motion continues, the tall grass swings back and forth, vibrating between definite limits but going nowhere. When the wave motion stops, the grass returns to its initial position.

## Wave Speed

The speed of periodic wave motion is related to the frequency and wavelength of the waves. We can understand this by considering the simple case of water waves (Figures 18.5 and 18.6). Imagine that we fix our eyes at a stationary point on the surface of water and observe the waves passing by this point. We can measure how much time passes between the arrival of one crest and the arrival of the next one (the period), and also observe the distance between crests (the wavelength). We know that speed is defined as distance divided by time. In this case, the distance is one wavelength and the time is one period, so wave speed = wavelength/period.

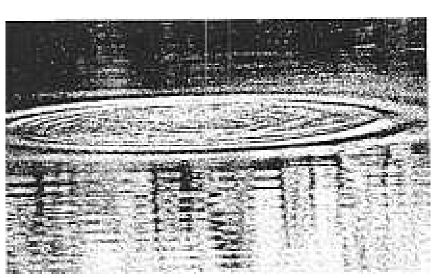


**FIGURE 18.5** Water waves.

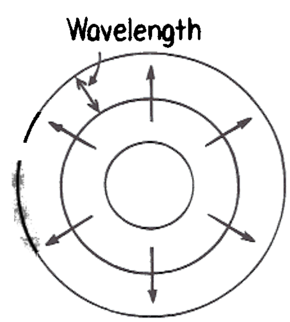



**FIGURE 18.6** A top view of water waves.

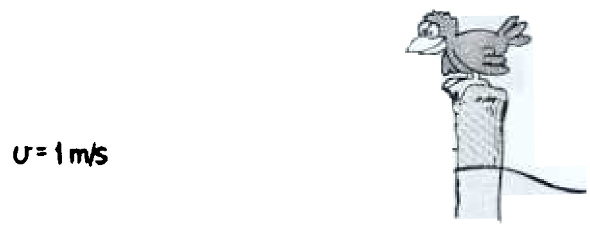



**FIGURE 18.7** If the wavelength is 1 m, and one wavelength per second passes the pole, then the speed of the wave is 1 m/s.

For example, if the wavelength is 10 meters and the time between crests at a point on the surface is 0.5 second, the wave moves 10 meters in 0.5 seconds and its speed is 10 meters divided by 0.5 seconds, or 20 meters per second.

Since period is equal to the inverse of frequency, the formula wave speed = wavelength/period can also be written

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

This relationship holds true for all kinds of waves, whether they are water waves, sound waves, or light waves.

## Questions

1. If a train of freight cars, each 10 m long, rolls by you at the rate of three cars each second, what is the speed of the train?
2. If a water wave oscillates up and down three times each second and the distance between wave crests is 2 m, what is its frequency? Its wavelength? Its wave speed?

## Transverse Waves

Fasten one end of a rope to a wall and hold the free end in your hand. If you suddenly twitch the free end up and then down, a pulse will travel along the rope and back (Figure 18.8). In this case the motion of the rope (up and down arrows) is at right angles to the direction of wave speed. The right-angled, or sideways, motion is called *transverse motion*. Now shake the rope with a regular, continuing up-and-down motion, and the series

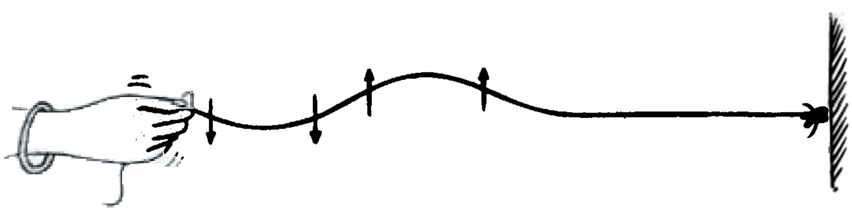


**FIGURE 18.8** A transverse wave.

## Answers

1. 30 m/s. We can see this in two ways. (a) According to the speed definition from Chapter 2, $v = d/t = 3 \times 10\ \text{m}/1\ \text{s} = 30$ m/s, since 30 m of train passes you in 1 s. (b) If we compare our train to wave motion, where wavelength corresponds to 10 m and frequency is 3 Hz, then Speed = wavelength × frequency = 10 m × 3 Hz = 10 m × 3/s = 30 m/s.
2. The frequency of the wave is 3 Hz, its wavelength is 2 m, and its wave speed = wavelength × frequency = 2 m × 3/s = 6 m/s. It is customary to express this as the equation $v = \lambda f$ where $v$ is wave speed, $\lambda$ (the Greek letter lambda) is wavelength, and $f$ is wave frequency.

of pulses will produce a wave. Since the motion of the medium (the rope in this case) is transverse to the direction the wave travels, this type of wave is called a **transverse wave**.

Waves in the stretched strings of musical instruments and upon the surfaces of liquids are transverse. We will see later that electromagnetic waves, which make up radio waves and light, are also transverse.

## Longitudinal Waves

Not all waves are transverse. Sometimes parts that make up a medium move to and fro in the same direction in which the wave travels. Motion is *along* the direction of the wave rather than at right angles to it. This produces a **longitudinal wave**.

Both a transverse and a longitudinal wave can be demonstrated with a spring or a Slinky stretched out on the floor, as shown in Figure 18.9. A transverse wave is demonstrated by shaking the end of a Slinky up and down. A longitudinal wave is demonstrated by rapidly pulling and pushing the end of the Slinky toward and away from you. In this case we see that the medium vibrates parallel to the direction of energy transfer. Part of the Slinky is compressed, and a wave of *compression* travels along the spring. Between successive compressions is a stretched region, called a *rarefaction*. Both compressions and rarefactions travel in the same direction along the Slinky. Sound waves are longitudinal waves.

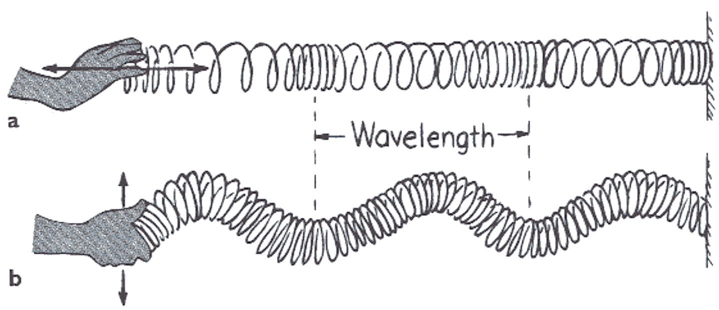



**FIGURE 18.9** Both waves transfer energy from left to right. (a) When the end of the Slinky is pushed and pulled forward and back, a longitudinal wave is produced. (b) When it's shaken up and down, a transverse wave is produced.

Waves that travel in the ground generated by earthquakes are of two main types: longitudinal P waves, and transverse S waves. (Geology students often remember P waves as "push-pull" waves, and S waves as "side-to-side" waves.) S waves cannot travel through liquid matter, while P waves can travel through both molten and solid parts of the earth's interior. Study of these waves reveals much about the earth's interior.

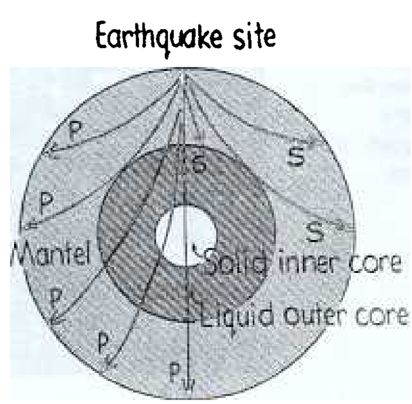



**FIGURE 18.10** Waves generated by an earthquake. P waves are longitudinal and travel through both molten and solid materials. S waves are transverse and travel only through solid materials. Reflections and refractions of the waves provide information about the earth's interior.

The wavelength of a longitudinal wave is the distance between successive compressions or equivalently, the distance between successive rarefactions. The most common example of longitudinal waves is sound in air. Elements of air vibrate to and fro about some equilibrium position as the waves move by. We will treat sound waves in detail in the next chapter.

## Interference

Whereas a material object like a rock will not share its space with another rock, more than one vibration or wave can exist at the same time in the same space. If we drop two rocks in water, the waves produced by each can overlap and form an **interference pattern**. Within the pattern, wave effects may be increased, decreased, or neutralized.

When more than one wave occupies the same space at the same time, the displacements add at every point. This is the *superposition principle*. So when the crest of one wave overlaps the crest of another, their individual effects add together to produce a wave of increased amplitude. This is called *constructive interference* (Figure 18.11). When the crest of one wave overlaps the trough of another, their individual effects are reduced. The high part of one wave simply fills in the low part of another. This is called *destructive interference*.

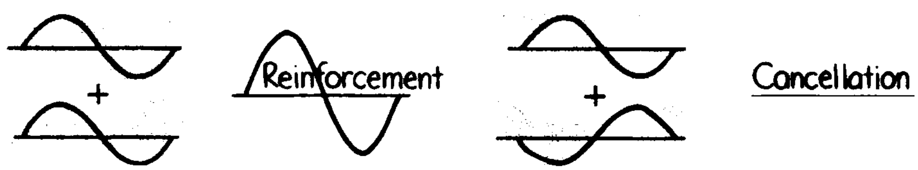



**FIGURE 18.11** Constructive and destructive interference in a transverse wave.

Wave interference is easiest to see in water. In Figure 18.12 we see the interference pattern made when two vibrating objects touch the surface of water. We can see the regions where the crest of one wave overlaps the trough of another to produce regions of zero amplitude. At points along these regions, the waves arrive out of step. We say they are *out of phase* with each other.

Interference is characteristic of all wave motion, whether the waves are water waves, sound waves, or light waves. We will treat the interference of sound in the next chapter and the interference of light in Chapter 28.

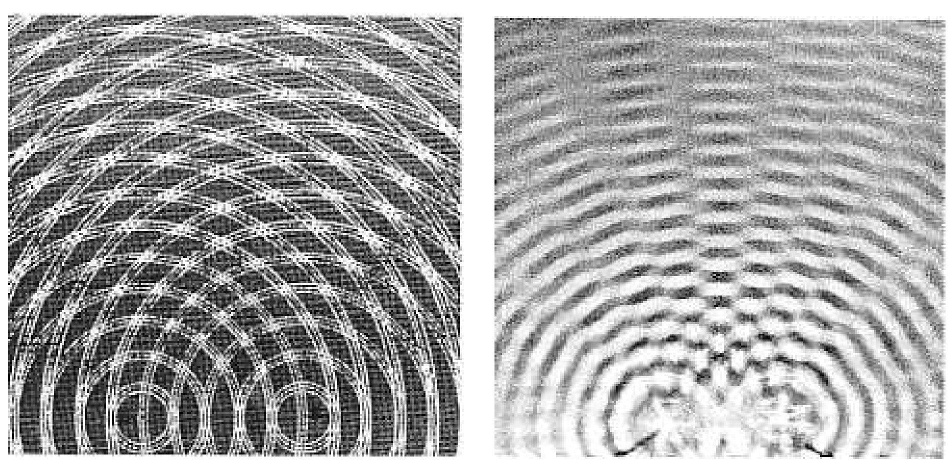


**FIGURE 18.12** Two sets of overlapping water waves produce an interference pattern. The left diagram is an idealized drawing of the expanding waves from the two sources. The right diagram is a photograph of an actual interference pattern.

## Standing Waves

If we tie a rope to a wall and shake the free end up and down, we produce a train of waves in the rope. The wall is too rigid to shake, so the waves are reflected back along the rope. By shaking the rope just right, we can cause the incident and reflected waves to form a **standing wave**, where parts of the rope, called the *nodes*, are stationary. Nodes are the regions of minimal or zero energy, whereas *antinodes* (not labeled in Figure 18.13) are the regions of maximum displacement and maximum energy. You can hold your fingers on either side of the nodes and the rope doesn't touch them. Other parts of the rope, especially the antinodes, would make contact with your fingers. Antinodes occur halfway between nodes.

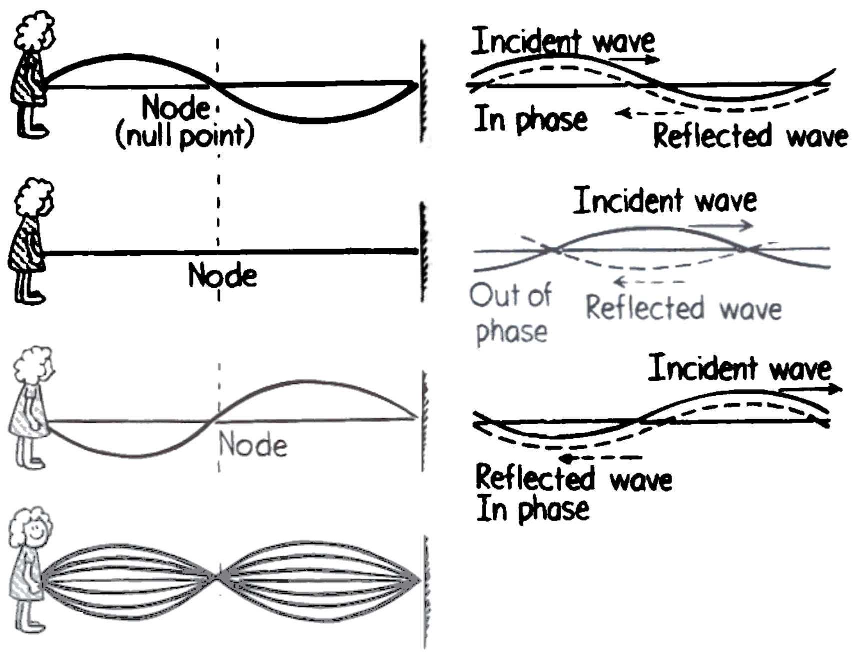



**FIGURE 18.13** The incident and reflected waves interfere to produce a standing wave.

Standing waves are the result of interference (and as we will see in the next chapter, *resonance*). When two sets of waves of equal amplitude and wavelength pass through each other in opposite directions, the waves are steadily in and out of phase with each other. They produce stable regions of constructive and destructive interference.

It is easy to make standing waves yourself. Tie a rope, or better, a rubber tube between two firm supports. Shake the tube up and down with your hand near one of the supports. If you shake the tube with the right frequency, you will set up a standing wave as shown in Figure 18.14a. Shake the tube with twice the frequency, and a standing wave of half the previous wavelength, having two loops, will result. (The distance between successive nodes is a half wavelength; two loops make up a full wavelength.) Triple the frequency, and a standing wave with one-third the original wavelength, having three loops, results, and so forth.


**FIGURE 18.14** (a) Shake the rope until you set up a standing wave of one segment ($\frac{1}{2}$ wavelength). (b) Shake with twice the frequency and produce a wave with two segments (1 wavelength). (c) Shake with three times the frequency and produce three segments ($1\frac{1}{2}$ wavelengths).

Standing waves are set up in the strings of musical instruments when plucked, bowed, or struck. They are set up in the air in an organ pipe, a trumpet, or a clarinet, and the air of a soda-pop bottle when air is blown over the top. Standing waves can be set up in a tub of water or a cup of coffee by sloshing it back and forth with the right frequency. Standing waves can be produced with either transverse or longitudinal vibrations.

## Questions

1. Is it possible for one wave to cancel another wave so that no amplitude remains?
2. Suppose you set up a standing wave of three segments, as shown in Figure 18.14c. If you shake with twice as much frequency, how many wave segments will occur in your new standing wave? How many wavelengths?

# Doppler Effect

A pattern of water waves produced by a bug jiggling its legs and bobbing up and down in the middle of a quiet puddle is shown in Figure 18.15. The bug is not going anywhere but is merely treading water in a fixed position. The waves it makes spread over the surface of the water. The waves form concentric circles, because wave speed is the same in all directions. If the bug bobs in the water at a constant frequency, the distance between wave crests (the wavelength) is the same in all directions. Waves encounter point A as frequently as they encounter point B. This means that the frequency of wave motion is

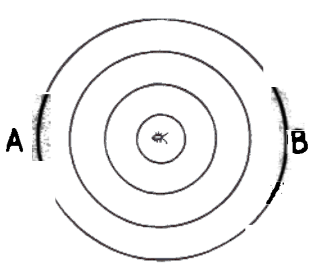



**FIGURE 18.15** Top view of water waves made by a stationary bug jiggling in still water.

## Answers

1. Yes. This is called destructive interference. In a standing wave in a rope, for example, parts of the rope have no amplitude—the nodes.
2. If you impart twice the frequency to the rope, you'll produce a standing wave with twice as many segments. You'll have six segments. Since a full wavelength has two segments, you'll have three complete wavelengths in your standing wave.

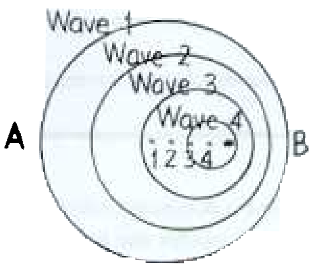



**FIGURE 18.16** Water waves made by a bug swimming in still water.

the same at points A and B, or anywhere in the vicinity of the bug. This wave frequency is the same as the bobbing frequency of the bug.

Suppose the jiggling bug moves across the water at a speed less than the wave speed. In effect, the bug chases part of the waves it has produced. The wave pattern is distorted and is no longer made of concentric circles (Figure 18.16). The center of the outer wave was made when the bug was at the center of that circle. The center of the next smaller wave was made when the bug was at the center of that circle, and so forth. The centers of the circular waves move in the direction of the swimming bug. Although the bug maintains the same bobbing frequency as before, an observer at B would see the waves coming more often. The observer would measure a higher frequency. This is because each successive wave has a shorter distance to travel and therefore arrives at B more frequently than if the bug weren't moving toward B. An observer at A, on the other hand, measures a *lower* frequency because of the longer time between wave-crest arrivals. This is because, to reach A, each crest has to travel farther than the one ahead of it due to the bug's motion. This change in frequency due to the motion of the source (or receiver) is called the **Doppler effect** (after the Austrian scientist Christian Doppler, 1803–1853).

Water waves spread over the flat surface of the water. Sound and light waves, on the other hand, travel in three-dimensional space in all directions like an expanding balloon. Just as circular waves are closer together in front of the swimming bug, spherical sound or light waves ahead of a moving source are closer together and reach a receiver more frequently.

The Doppler effect is evident when you hear the changing pitch of a car horn as the car passes you. When the car approaches, the pitch is higher than normal (higher like a higher note on a musical scale). This is because the crests of the sound waves are hitting your ear more frequently. And when the car passes and moves away, you hear a drop in pitch because the crests of the waves are hitting your ear less frequently.

**FIGURE 18.17** The pitch of sound gets higher as the source moves toward you; the pitch gets lower as the source moves away.

The Doppler effect also occurs for light. When a light source approaches, there is an increase in its measured frequency; and when it recedes, there is a decrease in its frequency. An increase in frequency is called a *blue shift*, because the increase is toward the high frequency, or blue, end of the color spectrum. A decrease in frequency is called a *red shift*, referring to a shift toward the lower-frequency, or red, end of the color spectrum. Distant galaxies, for example, show a red shift in the light they emit. A measurement of this shift permits a calculation of their speeds of recession. A rapidly spinning star shows a red shift on the side turning away from us and a blue shift on the side turning toward us. This enables a calculation of the star's spin rate.

**Question** When a sound source moves toward you, do you measure an increase or decrease in wave speed?

## Bow Waves

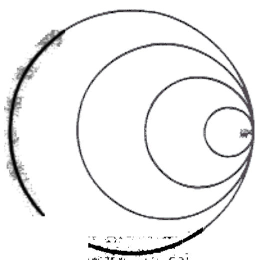


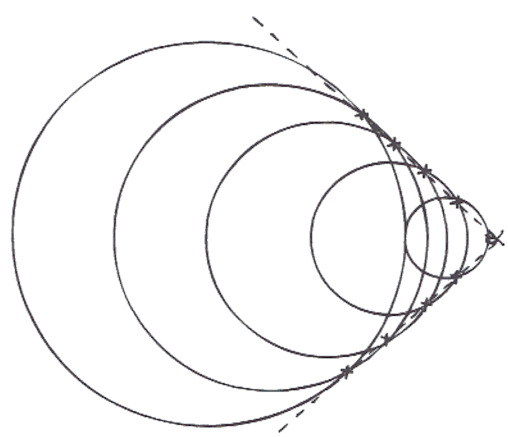
**FIGURE 18.18** Wave pattern made by a bug swimming at wave speed.

When the speed of a source is as great as the speed of the waves it produces, something interesting happens. The waves pile up in front of the source. Consider the bug in our previous example when it swims as fast as the wave speed. Can you see that the bug will keep up with the waves it produces? Instead of the waves moving ahead of the bug, they superimpose and hump up on one another directly in front of the bug (Figure 18.18). The bug moves right along with the leading edge of the waves it is producing.

A similar thing happens when an aircraft travels at the speed of sound. In the early days of jet aircraft, it was believed that this pile-up of sound waves in front of the airplane imposed a "sound barrier" and that to go faster than the speed of sound, the plane would have to "break the sound barrier." What actually happens is that the overlapping wave crests disrupt the flow of air over the wings, making it more difficult to control the craft. But the barrier is not real. Just as a boat can easily travel faster than the waves it produces, with sufficient power an aircraft easily travels faster than the speed of sound. Then we say that it is *supersonic*. A supersonic airplane flies into smooth, undisturbed air because no sound wave can propagate out in front of it. Similarly, a bug swimming faster than the speed of water waves finds itself always entering into water with a smooth, unrippled surface.

When the bug swims faster than wave speed, ideally it produces a wave pattern as shown in Figure 18.19. It outruns the waves it produces. The waves overlap at the edges, and the pattern made by these overlapping waves is a V shape, called a **bow wave**, which appears to be dragging behind the bug. The familiar bow wave generated by a speedboat knifing through the water is a non-periodic wave produced by the overlapping of many periodic circular waves.

**FIGURE 18.19** Wave pattern made by a bug swimming faster than wave speed.



**Answer** Neither! It is the *frequency* of a wave that undergoes a change where there is motion of the source, not the *wave speed*. Be clear about the distinction between frequency and speed. How frequently a wave vibrates is altogether different from how fast the disturbance moves from one place to another.

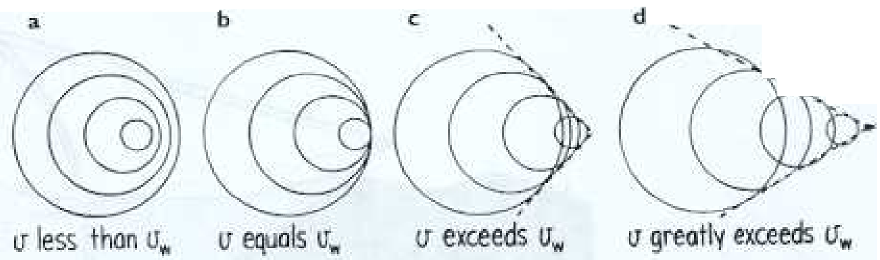



**FIGURE 18.20** Patterns made by a bug swimming at successively greater speeds. Overlapping at the edges occurs only when the bug swims faster than wave speed.

Some wave patterns made by sources moving at various speeds are shown in Figure 18.20. Note that after the speed of the source exceeds wave speed, increased speed of the source produces a narrower V shape.*

## Shock Waves

A speedboat knifing through the water generates a two-dimensional bow wave. A supersonic aircraft similarly generates a three-dimensional **shock wave**. Just as a bow wave is produced by overlapping circles that form a V, a shock wave is produced by overlapping spheres that form a cone. And just as the bow wave of a speedboat spreads until it reaches the shore of a lake, the conical wake generated by a supersonic craft spreads until it reaches the ground.

The bow wave of a speedboat that passes by can splash and douse you if you are at the water's edge. In a sense, you can say that you are hit by a "water boom." In the same way, when the conical shell of compressed air that sweeps behind a supersonic aircraft reaches listeners on the ground below, the sharp crack they hear is described as a **sonic boom**.

We don't hear a sonic boom from slower-than-sound, or subsonic, aircraft because the sound waves reach our ears one at a time and are perceived as one continuous tone. Only when the craft moves faster than sound do the waves overlap to reach the listener in a single burst. The sudden increase in pressure is much the same in effect as the sudden expansion of air produced by an explosion. Both processes direct a burst of high-pressure air to the listener. The ear is hard pressed to distinguish between the high pressure from an explosion and the high pressure from many overlapping waves.

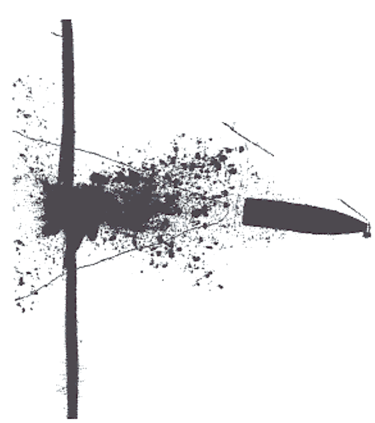


**FIGURE 18.21** Shock wave of a bullet piercing a sheet of Plexiglas. Light is deflected as it passes through the compressed air that makes up the shock wave, which makes it visible. Note the slight bending of the wave (not shown in following figures) due to air temperature and density changes.

* Bow waves generated by boats in water are more complex than is indicated here. Our idealized treatment serves as an analogy for the production of the less complex shock waves in air.

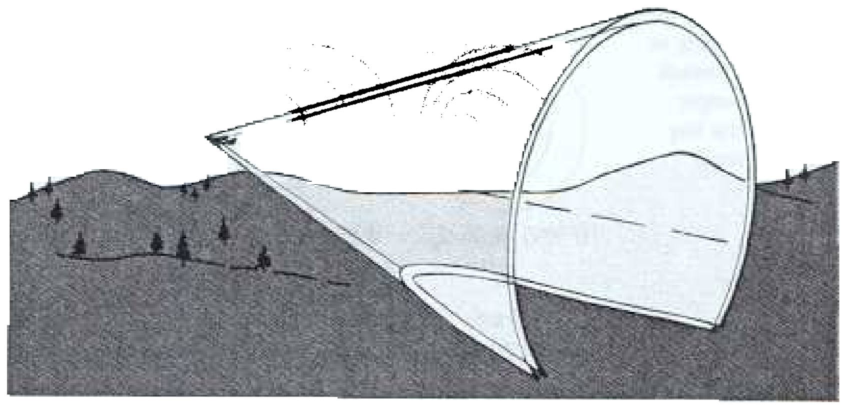


FIGURE 18.22 A shock wave.

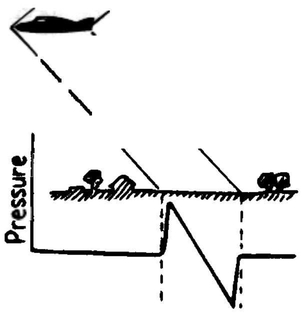



**FIGURE 18.23 The shock wave is actually made up of two cones—a high-pressure cone with the apex at the bow and a low-pressure cone with the apex at the tail. A graph of the air pressure at ground level between the cones takes the shape of the letter N.**

A water skier is familiar with the fact that next to the high hump of the V-shaped bow wave is a V-shaped depression. The same is true of a shock wave, which usually consists of two cones: a high-pressure cone generated at the bow of the supersonic aircraft and a low-pressure cone that follows at the tail of the craft.* The edges of these cones are visible in the photograph of the supersonic bullet in Figure 18.21. Between these two cones the air pressure rises sharply to above atmospheric pressure, then falls below atmospheric pressure before sharply returning to normal beyond the inner tail cone (Figure 18.23). This overpressure suddenly followed by underpressure intensifies the sonic boom.

A common misconception is that sonic booms are produced when an aircraft flies through the "sound barrier"—that is, just as the aircraft surpasses the speed of sound. This is the same as saying that a boat produces a bow wave when it first overtakes its own waves. This is not so. The fact is that a shock wave and its resulting sonic boom are swept continuously behind an aircraft traveling faster than sound, just as a bow wave is swept continuously behind a speedboat. In Figure 18.24, listener B is in the process of hearing a sonic boom. Listener C has already heard it, and listener A will hear it shortly. The aircraft that generated this shock wave may have broken through the sound barrier hours ago!

It is not necessary that the moving source be "noisy" to produce a shock wave. Once an object is moving faster than the speed of sound, it will *make* sound. A supersonic bullet passing overhead produces a crack, which is a small sonic boom. If the bullet were larger and disturbed more air in its path, the crack would be more boomlike. When the a lion tamer cracks a circus whip, the cracking sound is actually a sonic boom produced by the tip of the whip when it travels faster than the speed of sound. Both the bullet and the whip are not in themselves sound sources, but when traveling at supersonic speeds they produce their own sound as they generate shock waves.


**FIGURE 18.24 The shock wave has not yet reached listener A, but is now reaching listener B and has already reached listener C.**

*** Shock waves are often more complex and involve multiple**

## Summary of Terms

**Sine curve** A wave form traced by simple harmonic motion, which can be made visible on a moving conveyor belt by a pendulum swinging at right angles above the moving belt.

**Amplitude** For a wave or vibration, the maximum displacement on either side of the equilibrium (midpoint) position.

**Wavelength** The distance between successive crests, troughs, or identical parts of a wave.

**Frequency** For a vibrating body or medium, the number of vibrations per unit time. For a wave, the number of crests that pass a particular point per unit time.

**Hertz** The SI unit of frequency. One hertz (symbol Hz) equals one vibration per second.

**Period** The time in which a vibration is completed. The period of a wave equals the period of the source, and is equal to 1/frequency.

**Wave speed** The speed with which waves pass a particular point:

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

**Transverse wave** A wave in which the vibration is in a direction perpendicular (transverse) to the direction in which the wave travels. Light consists of transverse waves.

**Longitudinal wave** A wave in which the medium vibrates in a direction parallel (longitudinal) to the direction in which the wave travels. Sound consists of longitudinal waves.

**Interference pattern** The pattern formed by superposition of different sets of waves that produces mutual reinforcement in some places and cancellation in others.

**Standing wave** A stationary wave pattern formed in a medium when two sets of identical waves pass through the medium in opposite directions.

**Doppler effect** The shift in received frequency due to motion of a vibrating source toward or away from a receiver.

**Bow wave** The V-shaped wave made by an object moving across a liquid surface at a speed greater than the wave speed.

**Shock wave** The cone-shaped wave made by an object moving at supersonic speed through a fluid.

**Sonic boom** The loud sound resulting from the incidence of a shock wave.

## Review Questions

1. What is a *wiggle in time* called? A *wiggle in space and time?*
2. What is the source of all waves?
3. Distinguish between sound waves and light waves.

### Vibration of a Pendulum

4. What feature about a pendulum makes it useful in a grandfather clock?
5. What is the period of a pendulum?
6. If a pendulum takes one second to make a complete to and fro swing, how great is its period?
7. The period of a certain pendulum is 2 s, and the period of another is 1 s. Which pendulum is longer?

### Wave Description

8. How is a sine curve related to a wave?
9. Distinguish between these different parts of a wave: amplitude, wavelength, frequency, and period.
10. How many vibrations per second are represented in a radio wave of 101.7 MHz?
11. How do *frequency* and *period* relate to each other?

### Wave Motion

12. Exactly what is it that moves from source to receiver in wave motion?
13. Does the medium in which a wave moves travel along with the wave itself? Give examples to support your answer.

### Wave Speed

14. What is the relationship among frequency, wavelength, and wave speed?
15. As the frequency of a wave of constant speed is increased, does the wavelength increase or decrease?

### Transverse Waves

16. In a transverse wave, in which direction do the vibrations move when compared with the direction of wave travel?

### Longitudinal Waves

17. In a longitudinal wave, in which direction do the vibrations move when compared with the direction of wave travel?
18. How do compressions and rarefactions of longitudinal waves compare to crests and troughs of transverse waves?

### Interference

19. Distinguish between *constructive interference* and *destructive* interference.
20. What does it mean to say one wave is out of phase with another?
21. What kinds of waves can show interference?

### Standing Waves

22. What causes a standing wave?

23. What is a *node?* What is an *antinode?*

### Doppler Effect

24. In the Doppler effect, does frequency change when the source moves? Does wavelength change? Does wave speed change?
25. Can the Doppler effect be observed with longitudinal waves, transverse waves, or both?
26. What is meant by a blue shift and a red shift for light?

### Bow Waves

27. How fast must a bug swim to keep up with the waves it is producing? How fast must a boat move to produce a bow wave?
28. How do the speed of a source of waves and the speed of the waves themselves compare for the production of a bow wave?
29. How does the V shape of a bow wave depend on the speed of the source?

### Shock Waves

30. How is a bow wave similar to a shock wave? How are they different?
31. How does the V shape of a shock wave depend on the speed of the source?
32. True or false: A sonic boom occurs only when an aircraft is breaking through the sound barrier.
33. True or false: In order for an object to produce a sonic boom, it must be "noisy."

## Projects

1. Tie a rubber tube, a spring, or a rope to a fixed support and produce standing waves. See how many nodes you can produce.
2. Wet your finger and rub it slowly around the rim of a thin-rimmed, stemmed glass while you hold the base of the glass firmly to a tabletop with your other hand. The friction of your finger will excite standing waves in the glass, much like the wave made on the strings of a violin by the friction from a violin bow. Try it with a metal bowl.

## Exercises

1. A grandfather pendulum clock keeps perfect time. Then it is brought to a summer home high in the mountains. Does it run faster, slower, or the same? Explain.
2. If a pendulum is shortened, does its frequency increase or decrease? What about its period?
3. You let an empty suitcase swing to and fro at its natural frequency. If the case were filled with books, would the natural frequency be lower, greater, or the same as before?
4. Is the time required to swing to and fro (the period) on a playground swing longer or shorter when you stand rather than sit on the swing? Explain.
5. Why doesn't the frequency of a simple pendulum depend on its mass?
6. You clamp one end of a hacksaw blade in a vise and twang the free end. It vibrates. Now repeat, but first put a wad of clay on the free end. How, if at all, will the frequency of vibration differ? Would it make a difference if the wad of clay were stuck to the middle? Explain. (Why could this question have been asked back in Chapter 7?)
7. The needle of a sewing machine moves up and down in simple harmonic motion. Its driving force comes from a rotating wheel that is powered by an electric motor. How do you suppose the period of the up-and-down needle compares to the period of the rotating wheel?
8. What kind of motion should you impart to the nozzle of a garden hose so that the resulting stream of water approximates a sine curve?
9. What kind of motion should you impart to a stretched coiled spring (or Slinky) to provide a transverse wave? A longitudinal wave?
10. What kind of wave is each of the following: (a) An ocean wave rolling toward Waikiki beach? (b) The sound of one whale calling another whale under water? (c) A pulse sent down a stretched rope by snapping one end of it?
11. If a gas tap is turned on for a few seconds, someone a couple of meters away will hear the gas escaping long before she smells it. What does this indicate about the speed of sound and the motion of molecules in the sound-carrying medium?
12. If we double the frequency of a vibrating object, what happens to its period?
13. Red light has a longer wavelength than violet light. Which has the greater frequency?
14. What is the frequency of the second hand of a clock? The minute hand? The hour hand?
15. What is the source of wave motion?
16. You dip your finger repeatedly into a puddle of water and make waves. What happens to the wavelength if you dip your finger more frequently?
17. How does the frequency of vibration of a small object floating in water compare to the number of waves passing it each second?

18. How far, in terms of wavelength, does a wave travel in one period?
19. A rock is dropped in water, and waves spread over the flat surface of the water. What becomes of the energy in these waves when they die out?
20. The wave patterns seen in Figure 18.5 are composed of circles. What does this tell you about the speed of waves moving in different directions?
21. Why is lightning seen before thunder is heard?
22. A pair of loudspeakers on two sides of a stage are emitting identical pure tones (tones of a fixed frequency and fixed wavelength in air). When you stand in the center aisle, equally distant from the two speakers, you hear the sound loud and clear. Why does the intensity of the sound diminish considerably when you step to one side? Suggestion: Use a diagram to make your point.
23. A banjo player plucks the middle of an open string. Where are the nodes of the standing wave in the string? What is the wavelength of the vibrating string?
24. Violinists sometimes bow a string to produce maximum vibration (antinodes) at one-quarter and three-quarters of the string length rather than at the middle of the string. Then the string vibrates with a wavelength equal to the string length rather than twice the string length. (See Figures 18.14 a and b.) What is the effect on frequency when this occurs?
25. Why is there a Doppler effect when the source of sound is stationary and the listener is in motion? In which direction should the listener move to hear a higher frequency? A lower frequency?
26. A railroad locomotive is at rest with its whistle shrieking, then starts moving toward you. (a) Does the frequency that you hear increase, decrease, or stay the same? (b) How about the wavelength reaching your ear? (c) How about the speed of sound in the air between you and the locomotive?
27. When you blow your horn while driving toward a stationary listener, an increased frequency of the horn is heard by the listener. Would the listener hear an increase in horn frequency if he were also in a car traveling at the same speed in the same direction as you are? Explain.
28. Is there an appreciable Doppler effect when the motion of the source is at right angles to a listener? Explain.
29. How does the Doppler effect aid police in detecting speeding motorists?
30. Astronomers find that light coming from one edge of the sun has a slightly higher frequency than light from the opposite edge. What do these measurements tell us about the sun's motion?
31. Would it be correct to say that the Doppler effect is the apparent change in the speed of a wave due to motion of the source? (Why is this question a test of reading comprehension as well as a test of physics knowledge?)
32. How does the phenomenon of interference play a role in the production of bow or shock waves?
33. What can you say about the speed of a boat that makes a bow wave?
34. Does the conical angle of a shock wave open wider, narrow down, or remain constant as a supersonic aircraft increases its speed?
35. If the sound of an airplane does not come from the part of the sky where the plane is seen, does this imply that the airplane is traveling faster than the speed of sound? Explain.
36. Does a sonic boom occur only at the moment when an aircraft exceeds the speed of sound? Explain.
37. Why is it that a subsonic aircraft, no matter how loud it may be, cannot produce a sonic boom?
38. Imagine a super-fast fish that is able to swim faster than the speed of sound in water. Would such a fish produce a "sonic boom"?
39. Make up a multiple-choice question that would check a classmate's understanding of the distinction between a transverse and longitudinal wave.
40. Make up two multiple-choice questions that would check a classmate's understanding of the terms that describe a wave.

## Problems

1. A skipper on a boat notices wave crests passing his anchor chain every 5 s. He estimates the distance between wave crests to be 15 m. He also correctly estimates the speed of the waves. What is this speed?
2. A weight suspended from a spring is seen to bob up and down over a distance of 20 centimeters twice each second. What is its frequency? Its period? Its amplitude?
3. Radio waves travel at the speed of light—300,000 km/s. What is the wavelength of radio waves received at 100 MHz on your radio dial?
4. A mosquito flaps its wings 600 vibrations per second, which produces the annoying 600-Hz buzz. The speed of sound is 340 m/s. How far does the sound travel between wing beats? In other words, find the wavelength of the mosquito's sound.

5. On a keyboard, you strike middle C, which has a frequency of 256 Hz. (a) What is the period of one vibration of this tone? (b) As the sound leaves the instrument at a speed of 340 m/s, what is its wavelength in air?
6. (a) If you were so foolish as to play your keyboard instrument under water, where the speed of sound is 1500 m/s, what would be the wavelength of the middle-C tone in water? (b) Explain *why* middle C (or any other tone) has a longer wavelength in water than in air.
7. The wavelength of the signal from TV Channel 6 is 3.42 m. Does Channel 6 broadcast on a frequency above or below the FM radio band, which is 88 to 108 MHz?
8. As shown in the drawing at the right, the half-angle of the shock wave cone generated by a supersonic transport is 45°. What is the speed of the plane relative to the speed of sound?