25 Vibrations and Waves

Vibrations carry energy.

All around us we see things that wiggle and jiggle. Even things too small to see, such as atoms, are constantly wiggling and jiggling. A wiggle in time is a **vibration.** A vibration cannot exist in one instant, but needs time to move back and forth. Strike a bell and the vibrations will continue for some time before they die down.

A wiggle in space and time is a **wave.** A wave cannot exist in one place but must extend from one place to another. Light and sound are both forms of energy that move through space as waves. This chapter is about vibrations and waves, and the following chapters continue with the study of sound and light.

25.1 Vibration of a Pendulum

Suspend a stone at the end of a string and you have a simple pendulum. Pendulums swing back and forth with such regularity that they have long been used to control the motion of clocks. Galileo discovered that the time a pendulum takes to swing back and forth through small angles does not depend on the mass of the pendulum or on the distance through which it swings. The time of a back-and-forth swing—called the **period**—depends only on *the length of the pendulum* and *the acceleration of gravity.**

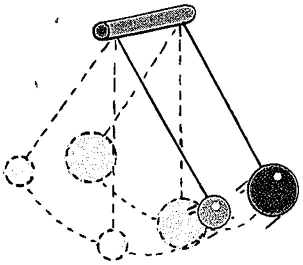

Figure 25.1 ▲
Two pendulums of the same length have the same period regardless of mass.

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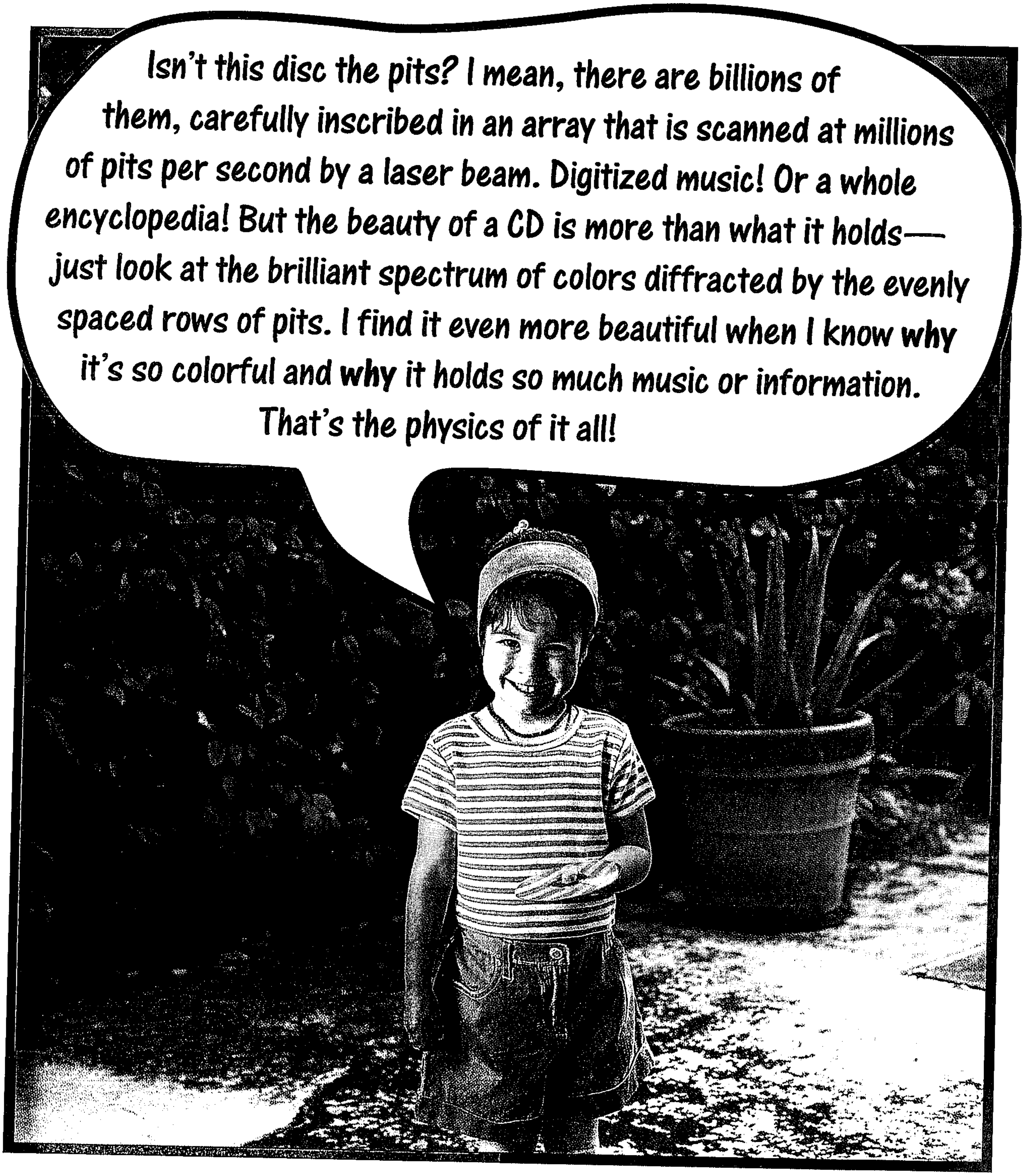
* The exact relationship for the period T of a simple pendulum is

$$T = 2\pi\sqrt{\frac{L}{g}}$$

where L is the length of the pendulum, and g is the acceleration of gravity.

IV

Sound and Light



A long pendulum has a longer period than a shorter pendulum; that is, it swings back and forth more slowly—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.

25.2 Wave Description

The back-and-forth vibratory motion (often called oscillatory motion) of a swinging pendulum is called **simple harmonic motion.*** The pendulum bob filled with sand in Figure 25.2 exhibits simple harmonic motion above a conveyor belt. When the conveyor belt is stationary (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.**

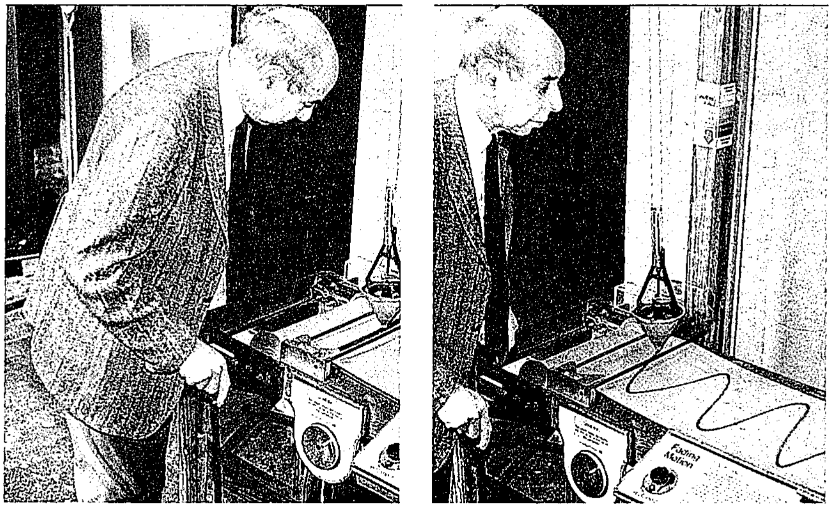


Figure 25.2 ▲
Frank Oppenheimer, founder of the Exploratorium® science museum in San Francisco, demonstrates that a pendulum swinging back and forth traces out a straight line over a stationary surface, and a sine curve when the surface moves at constant speed.

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* The condition for simple harmonic motion, nearly always met for most vibrations, is that the restoring force is proportional to the displacement from equilibrium. 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 weight attached to a spring. Recall from Section 18.3, Hooke's law for a spring: $F = k\Delta x$, where the force that stretches (or compresses) a spring is directly proportional to the distance the spring is stretched (or compressed).

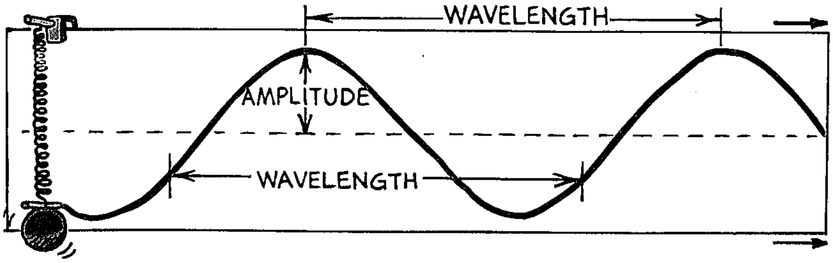


Figure 25.3 ▲
A sine curve.

The same can be done with a weight attached to a spring undergoing vertical simple harmonic motion, shown in Figure 25.3. A marking pen attached to the bob traces a sine curve on a sheet of paper that is moving horizontally at constant speed. A sine curve is a pictorial representation of a wave. Like a water wave, the high points 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.

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 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).

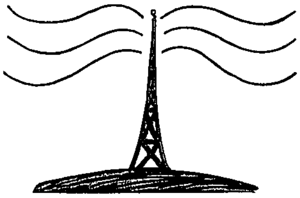


Figure 25.4 ▲
Electrons in the transmitting antenna of a radio station at 960 kHz on the AM dial vibrate 960 000 times each second and produce 960-kHz radio waves.

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 back-and-forth vibrations it makes in a given time (usually one second). A complete back-and-forth vibration is one cycle. If it occurs in one second, the frequency is one vibration per second or one cycle per second. If two vibrations occur in one second, the frequency is two vibrations or two cycles per second.

The unit of frequency is called the **hertz** (Hz), after Heinrich Hertz, who demonstrated radio waves in 1886. One cycle per second is 1 hertz, two cycles 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 broadcast in kilohertz, while FM radio waves are broadcast in megahertz; radar and microwave ovens operate at gigahertz. 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 MHz on the FM dial broadcasts radio waves with a frequency of 101 000 000 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 is the same.

If the frequency of a vibrating object 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 1/2 second. Or if the vibration period is 3 Hz, then the period is 1/3 second. As you can see below, frequency and period are inverses of each other:

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

and vice versa,

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

■ Questions

1. What is the frequency in vibrations per second of a 100-Hz wave?
2. The Sears® Building in Chicago sways back and forth at a frequency of about 0.1 Hz. What is its period of vibration?

25.3 Wave Motion

Most of the information around us gets to us in some form of wave. Sound is energy that travels to our ears in the form of one kind of wave. Light is energy that comes to our eyes in the form of a different kind of wave (an electromagnetic wave). The signals that reach our radio and television sets also travel in the form of electromagnetic waves.

When energy is transferred by a wave from a vibrating source to a distant receiver, there is no transfer of matter between the two points. To see this, think about the very simple wave produced when one end of a horizontally stretched string is shaken up and down (Figure 25.5). After the end of the string is shaken, a rhythmic disturbance travels along the string. Each part of the string moves up and down while the disturbance moves horizontally along the length of the string. It is the disturbance that moves along the length of the string, not parts of the string itself.

■ Answers

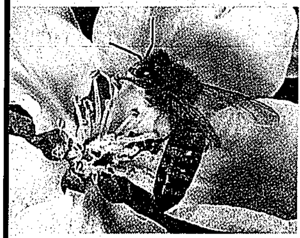
1. A 100-Hz wave vibrates 100 times per second.
2. The period is

$$\frac{1}{\text{frequency}} = \frac{1\text{ vib}}{0.1\text{ Hz}} = \frac{1\text{ vib}}{0.1\text{ vib/s}} = 10\text{ s.}$$

Thus, each vibration takes 10 seconds.

LINK TO ENTOMOLOGY

Noisy Bugs



Big bumblebees flap their wings at about 130 flaps per second, and produce sound of 130 Hz. A honeybee flaps its wings at 225 flaps per second and produces a higher-pitched sound of 225 Hz. The annoying high-pitched whine of a mosquito results from its wings flapping at 600 Hz. These sounds are produced by pressure variations in the air caused by vibrating wings.

Figure 25.5 ▲
When the string is shaken up and down, a disturbance moves along the length of the string.

DOING PHYSICS

Making Waves

Oscillate a marking pen back and forth across a piece of paper as you pull the paper in a direction perpendicular to your oscillation. You'll get a curve that may resemble a sine curve, and will have a certain wavelength. What happens to the wavelength when you pull the paper faster? Next, repeatedly dip your finger into a wide pan of water to make circular waves on the surface. Will the wavelength of the waves increase, decrease, or remain the same when you dip your finger more frequently?

Activity

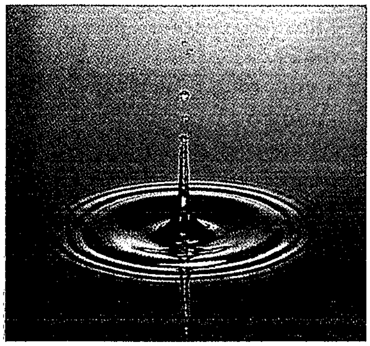


Figure 25.6 ▲
A circular water wave in a still pond.

Drop a stone in a quiet pond and you'll produce a wave that moves out from the center in an expanding circle (Figure 25.6). It is the disturbance that moves, not the water, for after the disturbance passes, the water is where it was before the wave passed.

When someone speaks to you from across the room, the sound wave is a disturbance in the air that travels across the room. The air molecules themselves do not move along, as they would in a wind. The air, like the rope and the water in the previous examples, is the medium through which wave energy travels. The energy transferred from a vibrating source to a receiver is carried by a *disturbance* in a medium, not by matter moving from one place to another within the medium.

25.4 Wave Speed

The speed of a wave depends on the medium through which the wave moves. Sound waves, for example, move at speeds of about 330 m/s to 350 m/s in air (depending on temperature), and about four times faster in water. Whatever the medium, the speed, frequency, and wavelength of the wave are related. Consider the simple case of water waves. Imagine that you fix your eyes at a stationary point on the surface of water and observe the waves passing by this point. If you count the number of crests that pass each second (the frequency) and also observe the distance between crests (the wavelength), you can then calculate the horizontal distance a particular crest moves each second.

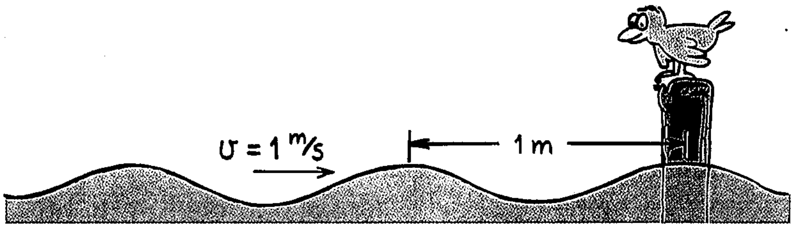


Figure 25.7 ▶
If the wavelength is 1 meter, and one wavelength per second passes the pole, then the speed of the wave is 1 m/s.

For example, if two crests pass a stationary point each second, and if the wavelength is 3 meters, then 2 × 3 meters of waves pass by in 1 second. The waves therefore move at 6 meters per second. We can say the same thing this way:

wave speed = frequency × wavelength

Or in equation form

$$v = f\lambda$$

where v is wave speed, f is wave frequency, and λ (Greek letter lambda) is wavelength. This relationship holds for all kinds of waves, whether they are water waves, sound waves, radio waves, or light waves.

Table 25.1 shows some frequencies and corresponding wavelengths of sound in air at the same temperature. Notice that the product of frequency and wavelength is the same for each example—340 m/s in this case. During a concert, you do not hear the high notes in a chord before you hear the low notes. The sounds of all instruments reach you at the same time. Notice that low frequencies have long wavelengths, and high frequencies have shorter wavelengths. Frequency and wavelength vary inversely to produce the same wave speed for all sounds.

Table 25.1 Sound Waves

Frequency (Hz)	Wavelength (m)	Wave Speed (m/s)
160	2.13	340
264	1.29	340
396	0.86	340
528	0.64	340

Computational Example

If a train of freight cars, each 10 m long, rolls by you at the rate of 2 cars each second, what is the speed of the train?

This can be seen in two ways, the Chapter 2 way and the Chapter 25 way.

From Chapter 2 recall that

$$v = \frac{d}{t} = \frac{2 \times 10\ \text{m}}{1\ \text{s}} = 20\ \text{m/s}$$

where d is the length of that part of the train that passes you in time t.

Here in Chapter 25 we compare the train to wave motion, where the wavelength corresponds to 10 m, and the frequency is 2 Hz. Then

$$\begin{aligned} \text{wave speed} &= \text{frequency} \times \text{wavelength} \\ &= (2\ \text{Hz}) \times (10\ \text{m}) = 20\ \text{m/s} \end{aligned}$$

One of the nice things about physics is that different ways of looking at things produce the same answer. When this doesn't happen, and there is no error in computation, then the validity of one (or both!) of those ways is suspect.

Questions

1. If a water wave vibrates up and down two times each second and the distance between wave crests is 1.5 m, what is the frequency of the wave? What is its wavelength? What is its speed?
2. What is the wavelength of a 340-Hz sound wave when the speed of sound in air is 340 m/s?

25.5 Transverse Waves

Suppose you create a wave along a rope by shaking the free end up and down as shown in Figure 25.8. In this case the motion of the rope (shown by the up and down arrows) is at right angles to the direction in which the wave is moving. Whenever the motion of the medium (the rope in this case) is at right angles to the direction in which a wave travels, the wave is a **transverse wave.**

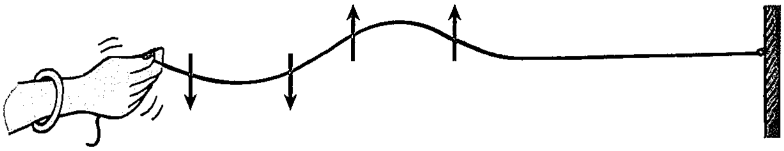


Figure 25.8 ▲
A transverse wave.

Waves in the stretched strings of musical instruments and upon the surfaces of liquids are transverse. As Chapter 27 will show, the electromagnetic waves that make up radio waves and light are also transverse.

25.6 Longitudinal Waves

Not all waves are transverse. Sometimes the particles of the medium move back and forth in the same direction in which the wave travels. The particles move *along* the direction of the wave rather than at right angles to it. This kind of wave is a **longitudinal wave.**

Both transverse and longitudinal waves can be demonstrated with a loosely-coiled spring, or Slinky®, as shown in Figure 25.9. A

Answers

1. The frequency of the wave is 2 Hz; its wavelength is 1.5 m; and its wave speed is frequency × wavelength = (2 Hz) × (1.5 m) = 3 m/s.
2. The wavelength of the 340-Hz sound wave must be 1 m. Then wave speed = (340 Hz) × (1 m) = 340 m/s.

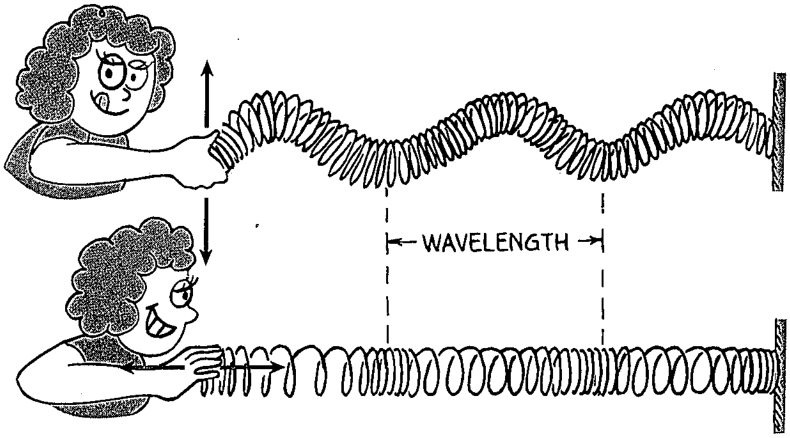


Figure 25.9
Both waves transfer energy from left to right. When the end of a coiled spring is shaken up and down (top), a transverse wave is produced. When it is shaken in and out (bottom), a longitudinal wave is produced.

transverse wave is demonstrated by shaking the end of a Slinky up and down. A longitudinal wave is demonstrated by shaking the end of the Slinky in and out. In this case we see that the medium vibrates parallel to the direction of energy transfer. Sound waves are longitudinal waves, and will be discussed in the next chapter.

25.7 Interference

A material object such as a rock will not share its space with another rock. But more than one vibration or wave can exist at the same time in the same space. If you 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 the crest of one wave overlaps the crest of another, their individual effects add together. The result is a wave of increased amplitude. This is called **constructive interference,** or reinforcement (Figure 25.10, top). 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,** or cancellation (Figure 25.10, bottom).

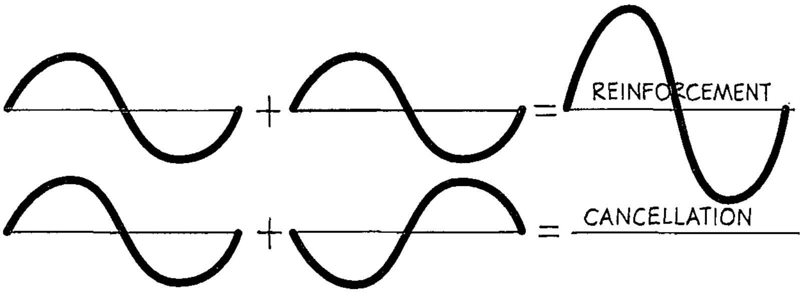


Figure 25.10 ▲
Constructive interference (top) and destructive interference (bottom) in a transverse wave.

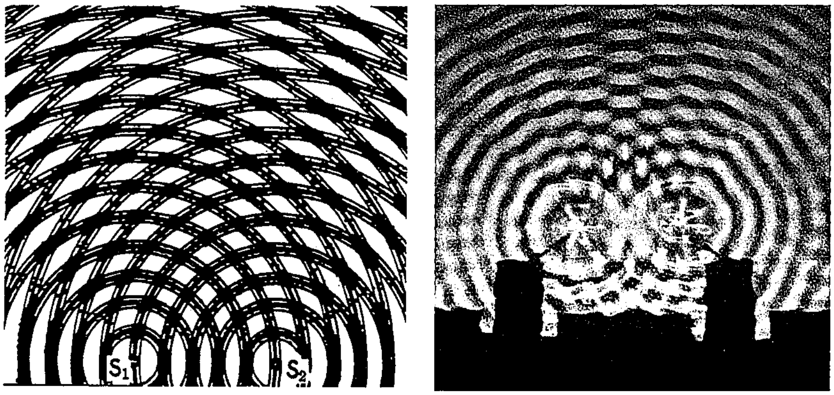


Figure 25.11 ▶
Two overlapping water waves produce an interference pattern.

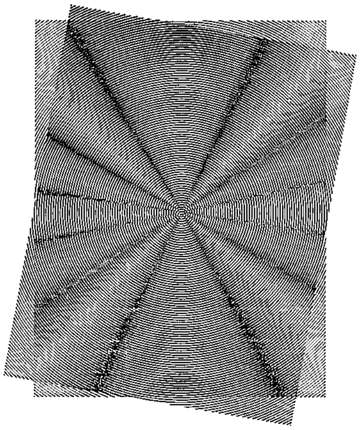


Figure 25.12 ▲
Moiré pattern.

Wave interference is easiest to see in water. Figure 25.11 (right) shows the interference pattern made when two vibrating objects touch the surface of water. The gray "spokes" are regions where a crest of one wave overlaps the trough of another to produce regions of zero amplitude. At points along these regions, the waves from the two objects arrive "out of step." We say that they are **out of phase** with one another. The dark- and light-striped regions are where the crests of one wave overlap the crests of the other, and the troughs overlap as well. In these regions, the two waves arrive "in step." They are **in phase** with each other.

Interference patterns are nicely illustrated by the overlapping of concentric circles printed on a pair of clear sheets, as shown in Figure 25.12. When the sheets overlap with their centers slightly apart, a so-called *moiré pattern* is formed that is very similar to the interference pattern of water waves (or any kind of waves). A slight shift in either of the sheets produces noticeably different patterns. If a pair of such sheets is available, be sure to try this and see the variety of patterns for yourself.

Interference is characteristic of all wave motion, whether the waves are water waves, sound waves, or light waves. The interference of sound is treated in the next chapter, and the interference of light in Chapter 31.

25.8 Standing Waves

If you tie a rope to a wall and shake the free end up and down, you will produce a wave in the rope. The wall is too rigid to shake, so the wave is reflected back along the rope to you. By shaking the rope just right, you can cause the incident (original) and reflected waves to form a **standing wave.** In a standing wave certain parts of the rope, called the **nodes,** remain stationary.

Interestingly enough, you could hold your fingers on either side of the rope at a node, and the rope would not touch them. Other parts of the rope would make contact with your fingers. The positions on a standing wave with the largest amplitudes are known as **antinodes**. Antinodes occur halfway between nodes.

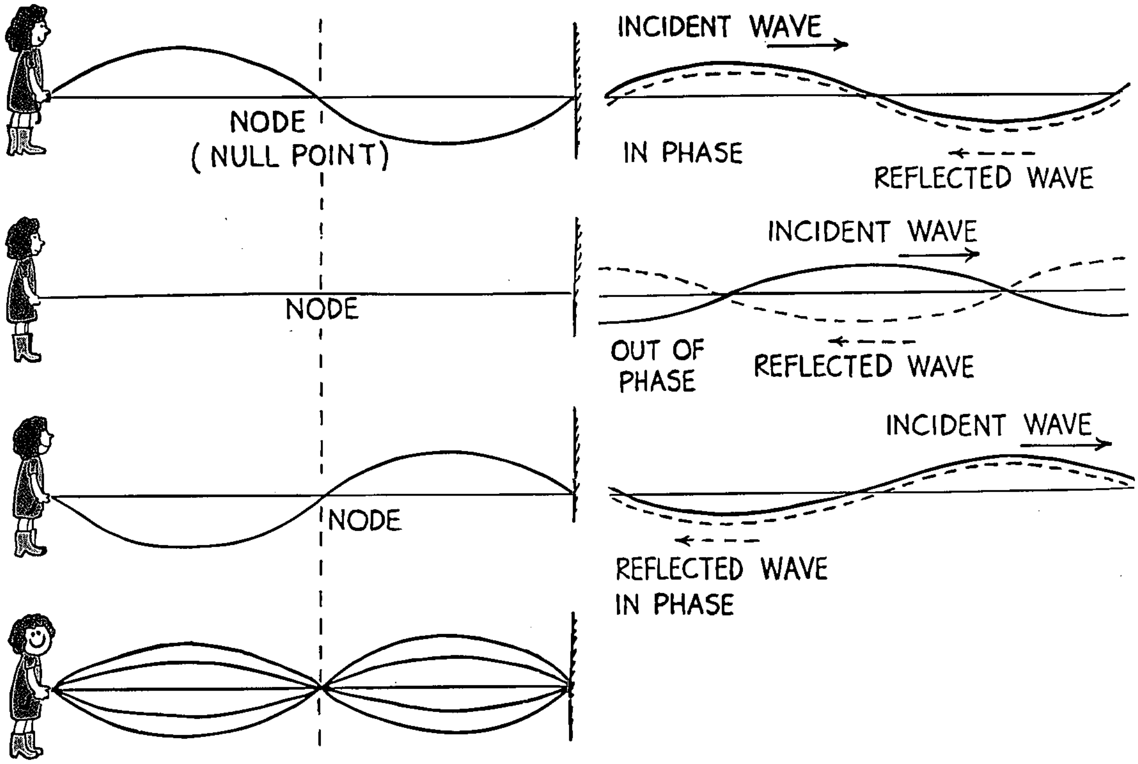
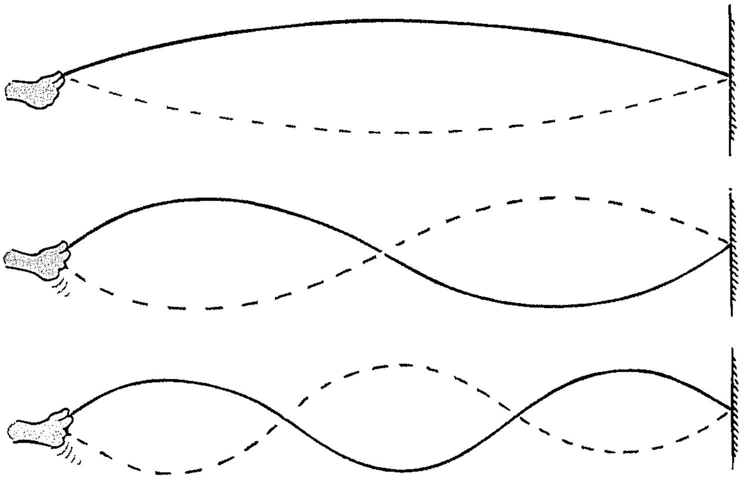


Figure 25.13 ▲
The incident and reflected waves interfere to produce a standing wave. The nodes are places that remain stationary.

Standing waves are the result of interference. When two waves of equal amplitude and wavelength pass through each other in opposite directions, the waves are always out of phase at the nodes. The nodes are stable regions of destructive interference (Figure 25.13).

You can produce a variety of standing waves by shaking the rope at different frequencies. The easiest standing wave to produce has one segment (Figure 25.14, top). If you keep doubling the frequency, you'll produce more interesting waves.



◀ **Figure 25.14**
(Top) Shake the rope until you set up a standing wave of one segment (rope length equals $\frac{1}{2}$ wavelength). (Center) Shake with twice the frequency and produce a standing wave with two segments (rope length equals 1 wavelength). (Bottom) Shake with three times the frequency and produce a standing wave with three segments (rope length equals $1\frac{1}{2}$ wavelengths).

Standing waves are set up in the strings of musical instruments that are plucked, bowed, or struck. They are set up in the air in an organ pipe and the air of a soda-pop bottle when air is blown over the top. Standing waves can be produced in either transverse or longitudinal waves.

■ Questions

1. Is it possible for one wave to cancel another wave so that the combined amplitude is zero?
2. Suppose you set up a standing wave of three segments, as shown in Figure 25.14 (bottom). If you shake with twice the frequency, how many wave segments will occur in your new standing wave? How many wavelengths will there be?

25.9 The Doppler Effect

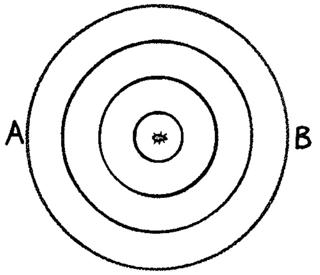


Figure 25.15 ▲
Top view of circular water wave made by a stationary bug jiggling in still water.

Imagine a bug jiggling its legs and bobbing up and down in the middle of a quiet puddle, as shown in Figure 25.15. Suppose the bug is not going anywhere but is merely treading water in a fixed position. The crests of the wave it makes are concentric circles, because the 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) will be the same for all successive waves. Waves encounter point A as frequently as they encounter point B. This means that the frequency of wave motion is 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.

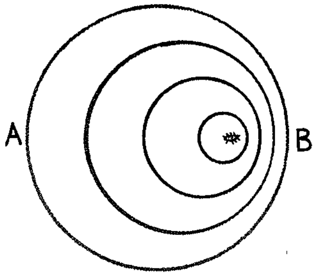


Figure 25.16 ▲
The wave pattern made by a bug swimming in still water.

Suppose the jiggling bug moves across the water at a speed less than the wave speed. In effect, the bug chases part of the crests it has produced. The wave pattern is distorted and is no longer concentric, as shown in Figure 25.16. The center of the outer crest was made when the bug was at the center of that circle. The center of the next smaller crest was made when the bug was at the center of that circle, and so forth. The centers of the circular crests move in the direction of the swimming bug. Although the bug maintains the same bobbing frequency as before, an observer at B would encounter the crests more often. The observer would encounter a *higher* frequency. This is because each successive crest has a shorter distance to travel so they arrive at B more frequently than if the bug were not moving toward B.

■ 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.

An observer at A, on the other hand, encounters a *lower* frequency because of the longer time between wave-crest arrivals. 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). The greater the speed of the source, the greater will be the Doppler effect.

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 wave crests are closer together in front of the swimming bug, spherical sound or light wave crests ahead of a moving source are closer together than those behind the source and encounter 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 (that is, higher on the musical scale). This occurs because the sound wave crests are encountering you more frequently. And when the car passes and moves away, you hear a drop in pitch because the wave crests are encountering you less frequently.

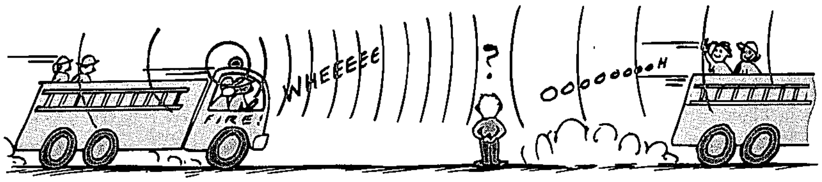


Figure 25.17
The pitch of sound is greater when the source moves toward you, and less when the source moves away.

Police make use of the Doppler effect of radar waves in measuring the speeds of cars on the highway. Radar waves are electromagnetic waves, lower in frequency than light and higher in frequency than radio waves. Police bounce them off moving cars, and a computer built into the radar system calculates the speed of the car relative to the radar unit by comparing the frequency of the radar emitted by the antenna with the frequency of the reflected waves (Figure 25.18).

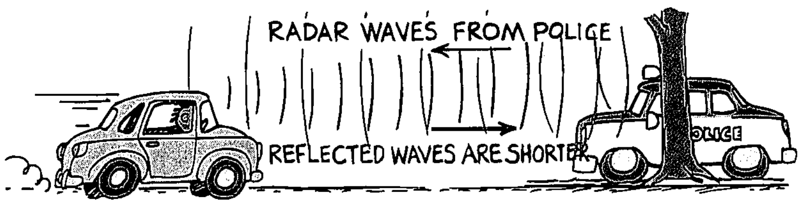


Figure 25.18
The police calculate a car's speed by measuring the Doppler effect of radar waves.

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 the low-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 enables astronomers to calculate 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 source moves toward you, do you measure an increase or decrease in wave speed?

25.10 Bow Waves

When the speed of the source in a medium is as great as the speed of the waves it produces, something interesting happens. The waves pile up. Consider the bug in the previous example when it swims as fast as the wave speed. Can you see that the bug will "keep up" with the wave crests it produces? Instead of the crests getting ahead of the bug, they pile up or superimpose on one another directly in front of the bug, as suggested in Figure 25.19. The bug moves right along with the leading edge of the waves it is producing.

The same thing happens when an aircraft travels at the speed of sound. In the early days of jet aircraft, it was believed that this pileup 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, so that it is harder to control the plane when it is flying close to the speed of sound. But the barrier is not real. Just as a boat can easily travel faster than the speed of water waves, an airplane with sufficient power can easily travel faster than the speed of sound. Then we say that it is *supersonic*—faster than sound. 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.

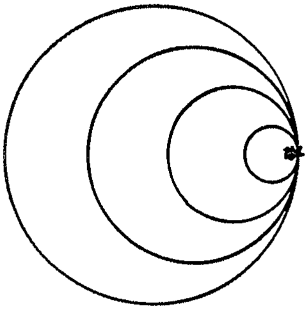


Figure 25.19 ▲
The wave pattern made by a bug swimming at the wave speed.

When the bug swims faster than wave speed, ideally it produces a wave pattern as shown in Figure 25.20. It outruns the wave crests it produces. The crests overlap at the edges, and the pattern made by these overlapping crests 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 produced by the overlapping of many circular wave crests.

■ 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 it moves from one place to another.

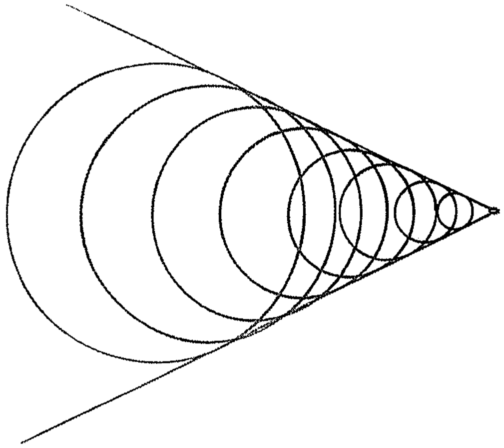


Figure 25.20
The wave pattern made by a bug swimming faster than the wave speed.

Figure 25.21 shows some wave patterns made by sources moving at various speeds. Note that after the speed of the source exceeds the wave speed, increased speed produces a narrower V shape.

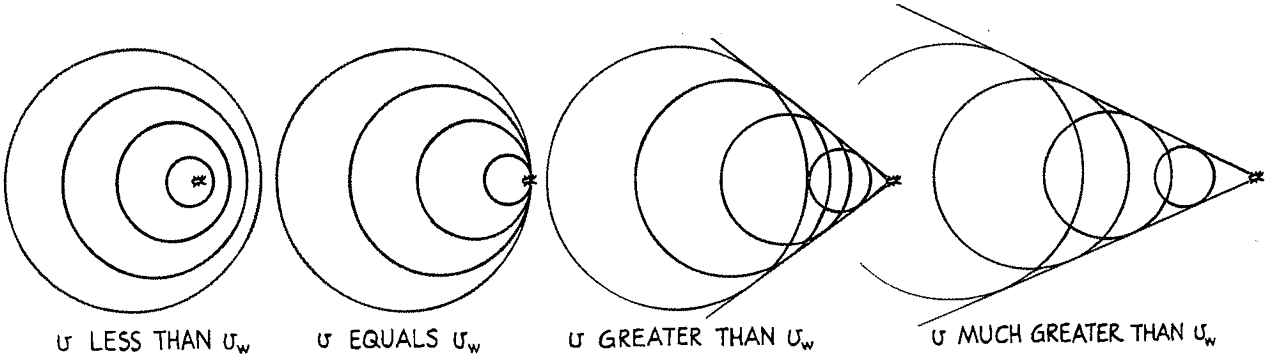


Figure 25.21 ▲
Patterns made by a bug swimming at successively greater speeds. Overlapping at the edges occurs only when the source travels faster than wave speed.

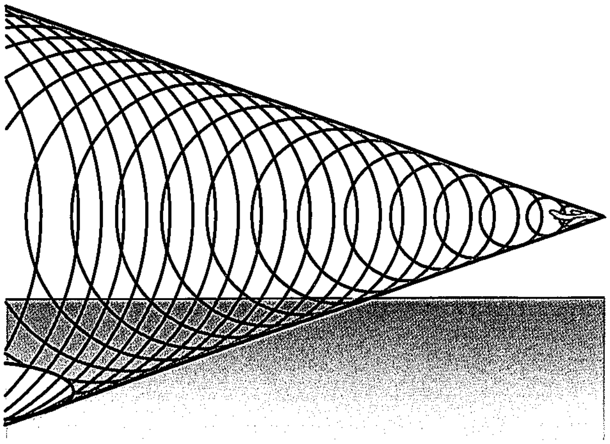
25.11 Shock Waves

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 shock wave 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 a slower-than-sound, or subsonic, aircraft, because the sound wave crests reach our ears one at a time and are perceived as a continuous tone. Only when the craft

Figure 25.22 ▶
A shock wave from a supersonic aircraft.



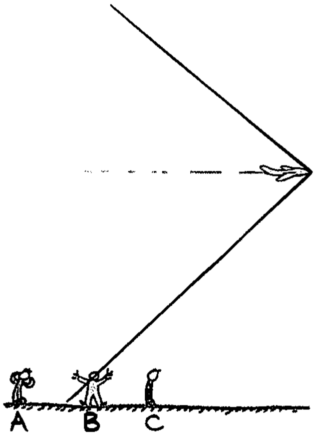


Figure 25.23 ▲
The shock wave has not yet encountered listener C, but is now encountering listener B, and has already passed listener A.

moves faster than sound do the crests overlap and encounter the listener in a single burst. The sudden increase in pressure has much the same 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 cannot distinguish between the high pressure from an explosion and the high pressure from many overlapping wave crests.

A common misconception is that sonic booms are produced at the moment that an aircraft flies through the "sound barrier"—that is, just as the aircraft surpasses the speed of sound. This is equivalent to saying that a boat produces a bow wave only 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 25.23, listener B is in the process of hearing a sonic boom. Listener A has already heard it, and listener C 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 emit sound for it 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 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. Snap a towel and the end can exceed the speed of sound and produce a mini sonic boom. The bullet, whip, and towel are not in themselves sound sources, but when traveling at supersonic speeds they produce their own sound as waves of air are generated to the sides of the moving objects.

On the matter of sound in general: You know that you'll damage your eyes if you stare at the sun. What many people don't know is that you'll similarly damage your ears if you overexpose them to loud sounds. Do as your author does when in a room with very loud music—leave. If for any reason you don't want to leave—really enjoyable music or good camaraderie with friends—stay, but use ear plugs of some kind! You're not being a wimp when you give the same care to your ears that you give to your eyes.

25 Chapter Review

Concept Summary

A vibration is a wiggle in time, and a wave is a wiggle in time and space.

- The period of a wave is the time it takes for one complete back-and-forth vibration.
- The wavelength is the distance between successive identical parts of the wave.
- A wave carries energy from a vibrating source to a receiver without transferring matter from one to the other.
- The frequency, or the number of vibrations in a given time, multiplied by the wavelength equals the speed of the wave.

In a transverse wave, the medium moves at right angles to the direction in which the wave travels.

- Electromagnetic waves, such as light and radio waves, are transverse.

In a longitudinal wave, the medium moves back and forth parallel to the direction in which the wave travels.

- Sound waves are longitudinal.

Interference patterns occur when waves from different sources arrive at the same point at the same time.

- In constructive interference, crest overlaps crest, or trough overlaps trough.
- In destructive interference, a crest overlaps a trough.
- In a standing wave, points of complete destructive interference (at which the medium does not move) remain at the same location.

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

When an object moves through a medium faster than the speed of waves in the medium, a bow wave or shock wave spreads out behind it.

Important Terms

amplitude (25.2)
antinodes (25.8)
blue shift (25.9)
bow wave (25.10)
constructive interference (25.7)
crest (25.2)
destructive interference (25.7)
Doppler effect (25.9)
frequency (25.2)
hertz (25.2)
in phase (25.7)
interference pattern (25.7)
longitudinal wave (25.6)
node (25.8)
out of phase (25.7)
period (25.1)
red shift (25.9)
shock wave (25.11)
simple harmonic motion (25.2)
sine curve (25.2)
sonic boom (25.11)
standing wave (25.8)
transverse wave (25.5)
trough (25.2)
vibration (25.0)
wave (25.0)
wavelength (25.2)

Review Questions

1. **a.** What is a wiggle in time called?

   b. What is a wiggle in space and time called? (25.0)

2. What is the period of a pendulum? (25.1)

3. What is the period of a pendulum that takes one second to make a complete back-and-forth vibration? (25.1)

4. Suppose that a pendulum has a period of 1.5 seconds. How long does it take to make a complete back-and-forth vibration? Is this 1.5-second period pendulum longer or shorter in length than a 1-second period pendulum?

5. How is a sine curve related to a wave? (25.2)

6. Distinguish among these different parts of a wave: amplitude, crest, trough, and wavelength. (25.2)

7. Distinguish between the *period* and the *frequency* of a vibration or a wave. How do they relate to one another? (25.2)

8. Does the medium in which a wave travels move along with the wave itself? Defend your answer. (25.3)

9. How does the speed of a wave relate to its frequency and wavelength? (25.4)

10. As the frequency of sound is increased, does the wavelength increase or decrease? Give an example. (25.4)

11. Distinguish between a *transverse* wave and a *longitudinal* wave. (25.5–25.6)

12. Distinguish between *constructive* interference and *destructive* interference. (25.7)

13. Is interference a property of only some types of waves or of all types of waves? (25.7)

14. What causes a standing wave? (25.8)

15. When a wave source moves toward a receiver, does the receiver encounter an increase in wave frequency, wave speed, or both? (25.9)

16. Does the Doppler effect occur for only some types of waves or all types of waves? (25.9)

17. 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? (25.10)

18. Distinguish between a *bow* wave and a *shock* wave. (25.10–25.11)

19. **a.** What is a sonic boom?

    b. How fast must an aircraft fly in order to produce a sonic boom? (25.11)

20. If you encounter a sonic boom, is that evidence that an aircraft of some sort exceeded the speed of sound moments ago to become supersonic? Defend your answer. (25.11)

Activity

1. Tie a rubber tube, a spring, or a rope to a fixed support and produce standing waves, as Figure 25.14 suggests. See how many nodes you can produce.

Plug and Chug

1. A nurse counts 76 heartbeats in one minute. What are the period and frequency of the heart's oscillations?

2. New York's 300-m high Citicorp® Tower oscillates in the wind with a period of 6.80 s. Calculate its frequency of vibration.

3. Calculate the speed of waves in a puddle that are 0.15 m apart and made by tapping the water surface twice each second.

4. Calculate the speed of waves in water that are 0.4 m apart and have a frequency of 2 Hz.

5. The lowest frequency we can hear is 20 Hz. Calculate the wavelength associated with this frequency for sound that travels at 340 m/s. How long is this in feet?

Think and Explain

1. Red light has a longer wavelength than violet light. Which has the greater frequency?

2. If you triple the frequency of a vibrating object, what will happen to its period?

3. How far, in terms of wavelength, does a wave travel in one period?

4. The wave patterns seen in Figure 25.6 are composed of circles. What does this tell you about the speed of the waves in different directions?

5. If a wave vibrates up and down twice each second and travels a distance of 20 m each second, what is its frequency? Its wave speed? (Why is this question best answered by careful reading of the question rather than searching for a formula?)

6. Astronomers find that light coming from point A at the edge of the sun has a slightly higher frequency than light from point B at the opposite side. What do these measurements tell us about the sun's motion?

7. 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?)

8. Whenever you watch a high-flying aircraft overhead, it seems that its sound comes from behind the craft rather than from where you see it. Why is this?

9. As a supersonic aircraft gains speed, does the conical angle of its shock wave become wider, narrower, or remain constant?

10. Why is it that a subsonic aircraft, no matter how loud it may be, cannot produce a sonic boom?

Think and Solve

1. While watching ocean waves at the dock of the bay, Otis notices that 10 waves pass beneath him in 30 seconds. He also notices that the crests of successive waves exactly coincide with the posts that are 5 meters apart. What are the period, frequency, wavelength, and speed of the ocean waves?

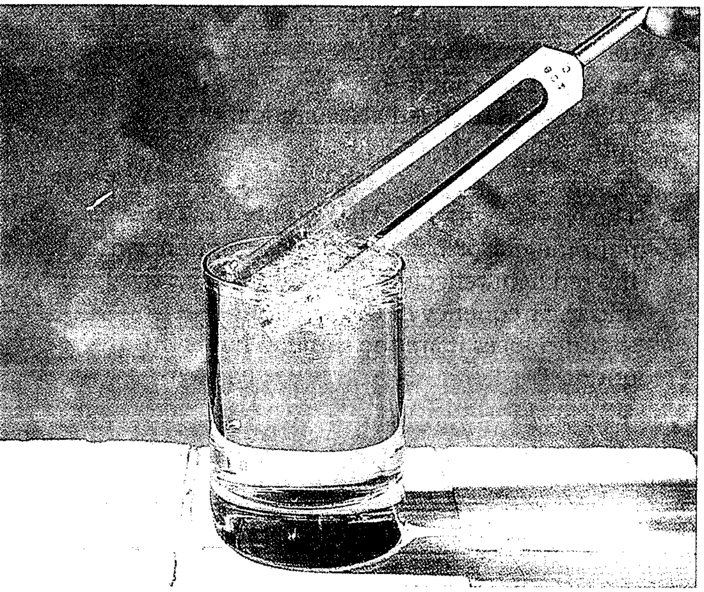
2. If a wave vibrates back-and-forth three times each second, and its wavelength is 2 meters, what is its frequency? Its period? Its speed?

3. Radio waves are electromagnetic waves that travel at the speed of light, 300 000 kilometers per second. What is the wavelength of FM radio waves received at 100 megahertz on your radio dial?

4. The wavelength of red light is about 700 nanometers, or 7×10^{-7} m. The frequency of the red light reflected from a metal surface and the frequency of the vibrating electron that produces it are the same. What is this frequency?

26

Sound



Vibrations carry energy.

Pretend an entire room is filled with Ping-Pong table tennis balls, and in the middle of the room is a big paddle. You shake the paddle back and forth. What happens? When you move the paddle to the right, it hits some Ping-Pong balls and moves them to the right. They in turn hit others, moving them to the right, and so on. You set up a "Ping-Pong ripple" that moves across the room. The process is repeated the next time you move the paddle to the right, and another Ping-Pong ripple follows the first one. As you keep shaking the paddle back and forth, you keep creating Ping-Pong ripples that flow across the room. Can you see that what you are doing is making a longitudinal wave? At the far side of the room, Ping-Pong impulses arrive at the same frequency as the vibration of your paddle.

Molecules of air behave like tiny Ping-Pong balls. Place a tuning fork in the middle of a room and strike it with a rubber hammer. What happens? The surrounding air molecules are set into motion just like balls being hit by a paddle. Longitudinal waves flow through the air with a frequency equal to that of the vibrating prongs of the tuning fork. We hear these vibrations as sound. There is very little difference between the idea of a shaking paddle bumping into Ping-Pong balls and a vibrating tuning fork bumping into air molecules. In both cases vibrations are carried throughout the surrounding medium—the balls or the air.

Figure 26.1 ▲
Vibrate a Ping-Pong paddle in the midst of a lot of Ping-Pong balls, and they will transmit rhythmic pulses.

26.1 The Origin of Sound

All sounds are produced by the vibrations of material objects. In a piano, violin, or guitar, a sound wave is produced by vibrating strings; in a saxophone, by a vibrating reed; in a flute, by a fluttering