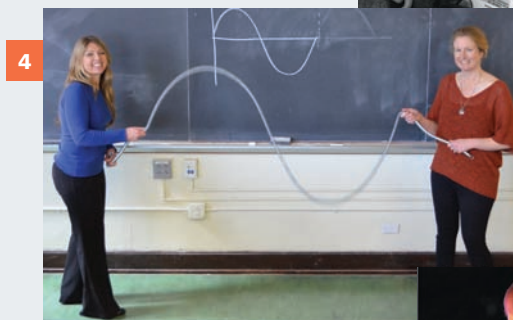
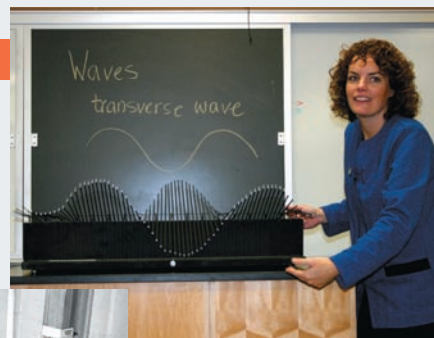


19

CHAPTER 19

Vibrations and Waves

- 19.1 Good Vibrations
- 19.2 Wave Description
- 19.3 Wave Motion
- 19.4 Wave Speed
- 19.5 Wave Interference
- 19.6 Doppler Effect
- 19.7 Bow Waves
- 19.8 Shock Waves



1 Diane Reindeau shows her class how waves are generated by vibrations in a classroom wave demonstrator. **2** Frank Oppenheimer at the San Francisco Exploratorium shows a straight-line trace when a swinging pendulum bob leaks sand onto a stationary conveyor belt. **3** When the conveyor belt moves in uniform motion, a sine curve is traced. **4** Jill Johnsen and Diane Lininger Markham produce transverse waves. **5** Singer, composer, and chemistry professor John Suchocki produces good vibrations.

The Exploratorium in San Francisco is not only a world-class museum of science and technology; it is also perhaps the best place on planet Earth to teach a physics class. I was honored to do so in the years 1982–2000. The Exploratorium is special because of its founder, Frank Oppenheimer, the younger brother of more famous J. Robert Oppenheimer, the director of the Los Alamos lab during World War II. Frank’s passion for doing physics was surpassed only by his passion for teaching it. I was enormously privileged to share my classroom with him when vibrations, waves, and musical sounds were the topic. I remember after one of his brilliant presentations he quietly asked me how he did. Almost tearfully, I responded, “You were great.” For it was true. In addition to his great explanations of physics, he himself exuded a personal greatness—with his insistence on excellence, lack of pretentiousness, and respect for invention and play and for his students. Frank was the most-loved teacher in my experience.



Frank Oppenheimer suffered in the political witch hunts of the 1950s when he admitted to being a member of the American Communist Party back in the depths of the Great Depression, along with many other idealistic citizens who were sensitive to the nation’s high unemployment rate at the time. Frank told me that after he refused to give the names of other members to the House Un-American Activities Committee, he was hounded by the FBI. Despite his impressive accomplishments in physics,

and despite international awards in physics, Frank was barred from practicing physics. He was, however, allowed to be a cattle farmer and teach general science at Pagosa Springs High School in Colorado. Frank went on to say that, adding insult to injury, his neighbors were warned by government agents to keep a wary eye on his potential “un-American activities.”

Frank devoted the rest of his life to exposing the general public to the wonders of science, which culminated in the Exploratorium in San Francisco. I dedicated the 5th edition of my *Conceptual Physics* to him. Before Frank died in 1985, he contributed this paragraph, which I used as the book’s opening paragraph:

By trying to understand the natural world around us, we gain confidence in our ability to determine whom to trust and what to believe about other matters as well. Without this confidence, our decisions about social, political, and economic matters are inevitably based entirely on the most appealing lie that someone else dishes out to us. Our appreciation of the noticings and discoveries of both scientists and artists therefore serves, not only to delight us, but also to help us make more satisfactory and valid decisions and to find better solutions for our individual and societal problems.

Frank’s main motive for founding the Exploratorium was to lift people by encouraging them to do for themselves and to think for themselves—a way of teaching that is now widespread. In 2013 the Exploratorium moved from the Palace of Fine Arts in San Francisco to nearby Pier 15. I’m happy to report that the new and larger Exploratorium has all the charm and good energy that Frank gave to the original Exploratorium.

19.1 Good Vibrations

In a general sense, anything that moves back and forth, to and fro, side to side, in and out, or up and down is vibrating. A *vibration* is a periodic wiggle in time. A periodic wiggle in both space and time is a *wave*. A wave extends from one place to another. Light and sound are both vibrations that propagate through space as waves—but two very different kinds of waves. Sound is a mechanical wave, the propagation of vibrations through a material medium—a solid, liquid, or gas. If there is no material medium to vibrate, then no sound is possible. Sound cannot travel in a vacuum. But light can because, as we shall learn in later chapters, light is a vibration of electric and magnetic fields—an electromagnetic wave of pure energy. Although light can pass through many materials, it needs none. This is evident when it propagates through the vacuum between the Sun and Earth. The source of all waves—mechanical or electromagnetic—is something that is vibrating. We shall begin our study of vibrations and waves by considering the motion of a simple pendulum.



- For more on Oppenheimer, read *Something Incredibly Wonderful Happens: Frank Oppenheimer and the World He Made Up* by K. C. Cole (Boston: Houghton Mifflin Harcourt, 2009).

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TUTORIAL:
Waves and Vibrations

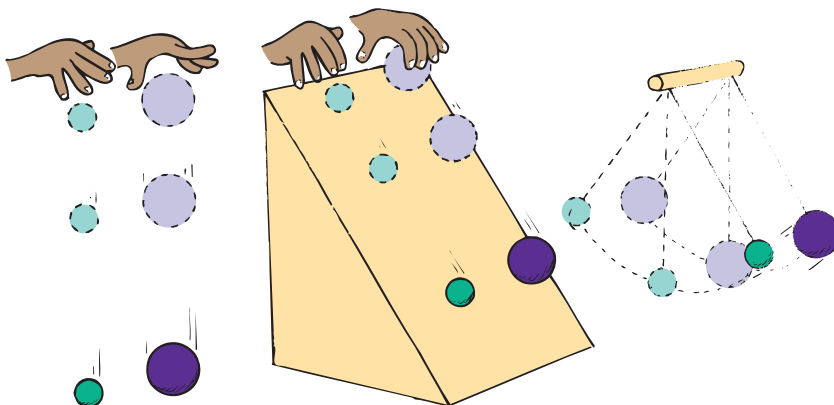
Vibration of a Pendulum

If we suspend a stone at the end of a piece of string, we have a simple pendulum. Likewise for a sand-filled container suspended at the end of a vertical pole that swings to and fro. In the chapter-opening photos, Frank Oppenheimer shows how sand leaking from such a pendulum traces a straight line on a stationary conveyor belt and then, when the belt moves at constant speed, produces a special curve known as a *sine curve*. A **sine curve** is a pictorial representation of a wave produced by simple harmonic motion.¹

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 on only the *length of the pendulum*.² The time of a to-and-fro swing, called the *period*, does not depend on either the mass of the pendulum or the size of the arc through which it swings.

FIGURE 19.1

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



In 1848, Jean Foucault devised a very long pendulum that, when swinging, appears to be changing directions during the day. Actually, Earth revolves underneath the pendulum.

A long pendulum has a longer period than a short pendulum; that is, it swings to and fro less frequently than a short pendulum. A grandfather clock's pendulum with a length of about 1 meter, for example, swings with a leisurely period of 2 seconds, while the much shorter pendulum of a cuckoo clock swings with a period that is less than a second. In addition to length, the period of a pendulum depends on the acceleration due to 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.

19.2 Wave Description

A sine curve can also be traced by a bob attached to a spring undergoing vertical simple harmonic motion (Figure 19.2). As mentioned, a sine curve is a pictorial representation of a wave. As for a water wave, the high points of a sine wave are called *crests* and the low points are called *troughs*. The straight dashed line in



SCREENCAST: Good Vibrations and Waves

¹The condition for simple harmonic motion is that the restoring force is proportional to the displacement from equilibrium. This condition is 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 Chapter 12, that Hooke's law for a spring is $F = k\Delta x$, where the force to stretch (or compress) a spring is directly proportional to the distance stretched (or compressed).

²The equation for the period of a simple pendulum for small arcs is $T = 2\pi\sqrt{\frac{L}{g}}$, where T is the period, L is the length of the pendulum, and g is the acceleration due to gravity.

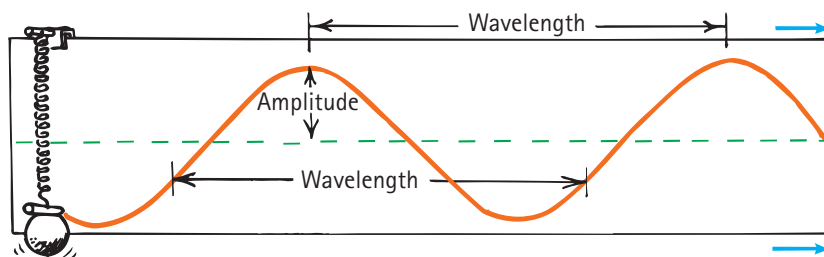


FIGURE 19.2

INTERACTIVE FIGURE



When the bob vibrates up and down, a marking pen traces a sine curve on paper that is moved horizontally at constant speed.

the figure represents the midpoint of the vibration, the equilibrium position. 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 crest. 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 are measured in centimeters, and the wavelengths of light are measured in billionths of a meter (nanometers).

How frequently a vibration occurs is described by its **frequency**. The frequency of a vibrating pendulum, or of an object on a spring, is the number of to-and-fro vibrations it makes in a given time (usually 1 second). A complete to-and-fro oscillation is one vibration. If a vibration occurs in 1 second, the frequency is one vibration per second. If two vibrations occur in 1 second, the frequency is two vibrations per second.

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, and 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. So we see that 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.

The **period** of a vibration or wave is the time for one complete vibration. If an object's frequency is known, then its period can be calculated, and vice versa. Suppose, for example, that a pendulum makes two vibrations in 1 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 frequency is 3 Hz, then the period is 1/3 second. Frequency (vibrations per second) and period (seconds per vibration) are reciprocals:

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

or, vice versa,

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



The frequency of a “classical” wave—such as a sound wave, water wave, or radio wave—matches the frequency of its vibrating source. (In the quantum world of atoms and photons, the rules are different.)

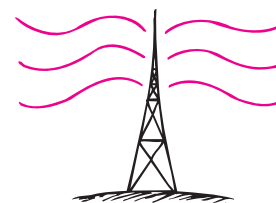


FIGURE 19.3

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

CHECK POINT

1. An electric toothbrush completes 90 cycles every second. What are (a) its frequency and (b) its period?
2. Gusts of wind make the Willis Tower in Chicago sway back and forth, completing a cycle in 10 s. What are (a) its frequency and (b) its period?

CHECK YOUR ANSWERS

1. (a) 90 cycles per second is 90 Hz; (b) 1/90 s.
2. (a) 1/10 Hz; (b) 10 s.

19.3 Wave Motion

Most information about our surroundings arrives in some form of waves. It is through wave motion that sounds are transported to our ears, light to our eyes, and electromagnetic signals to our radios and wireless phones. 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 the simple case of 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. What is propagated is the disturbance, the *energy* of wave motion, not the medium itself.

Perhaps a more familiar example of wave motion is a water wave. If a stone is dropped into a quiet pond, waves 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 flow 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, and drift to and fro, as the waves pass, but the leaf will end up where it started. Again, the medium returns to its initial condition after the disturbance has passed—even in the extreme case of a tsunami.

Let us consider another example of a wave to illustrate that what is transported from one location 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.



Numerous fans at a concert or stadium “do the wave” by rising from their seats, swinging their arms high, and then sitting back down in their seats—all in an appropriate sequence.



FIGURE 19.4
Water waves.



Mechanical waves require a medium. A Slinky needs its coils; ocean waves need water; sound from a bugle needs air; “doing the wave” in a stadium needs exuberant fans.

PRACTICING PHYSICS

Here we have a sine curve that represents a transverse wave. With a ruler, measure the wavelength and amplitude of the wave.

Wavelength _____

Amplitude _____



Transverse Waves

Fasten one end of a rope to a wall and hold the free end in your hand. If you suddenly shake the free end up and then down, a pulse will travel along the rope and back (Figure 19.5). In this case, the motion of the rope (up and down arrows) is at right angles to the direction of the 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 of pulses will produce a wave. Because 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**.

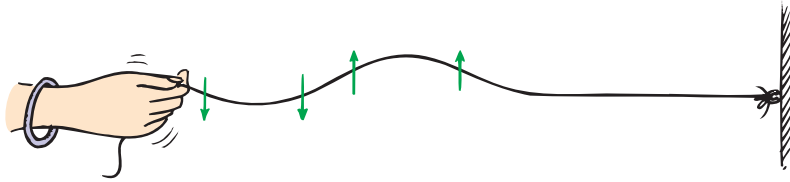


FIGURE 19.5
A transverse wave.

Waves in the stretched strings of musical instruments 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 the 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 wave and a longitudinal wave can be demonstrated with a spring or a Slinky stretched out, as shown in Figure 19.6. A transverse wave

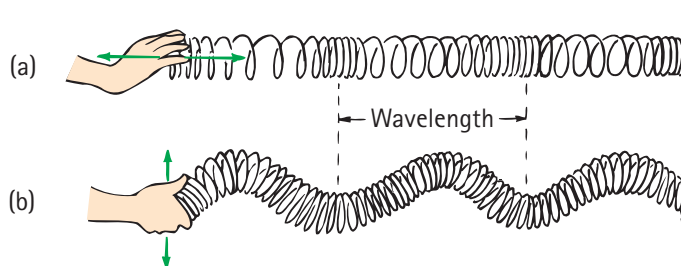


FIGURE 19.6
INTERACTIVE FIGURE 

Both waves transfer energy from left to right. (a) When the end of a Slinky is pushed and pulled rapidly along its length, a longitudinal wave is produced. (b) When it's shaken sideways, a transverse wave is produced.



SCREENCAST: Types of Waves



VIDEO: Longitudinal vs. Transverse Waves



Sound requires a medium. It can't travel in a vacuum because there's nothing to compress and stretch.

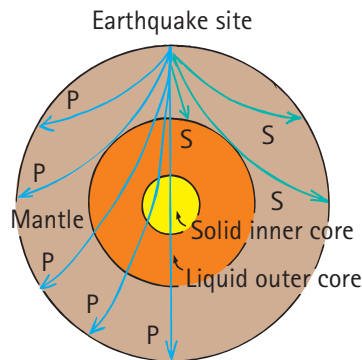


FIGURE 19.7
P and S waves generated by an earthquake.

fyi

- Waves on the surface of water are a transverse longitudinal hybrid: Water moves in loops, up and down as well as to and fro. And as with other waves, the medium makes no net progress in the direction of wave propagation.

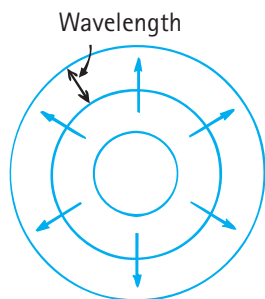


FIGURE 19.8
A top view of water waves. Each blue circle represents a crest of the expanding ripple pattern. We call these crest lines *wavefronts*.

is produced by shaking the end of a Slinky from side to side in a direction perpendicular to the Slinky. A longitudinal wave is created by rapidly pulling and pushing the end of the Slinky toward and away from you in a direction parallel to the Slinky. 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. In 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.

Waves that have been generated by earthquakes and that travel in the ground are of two main types: longitudinal P waves and transverse S waves. (Geology students often remember P waves as faster “push–pull” waves, and S waves as slower “side-to-side” waves.) S waves cannot travel through liquid matter, but P waves can travel through both molten and solid parts of Earth’s interior. Study of these waves reveals much about 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 Chapter 20.

19.4 Wave Speed

The speed of periodic wave motion is related to the frequency and wavelength of the waves. We can understand this by considering a top view of the simple case of water waves (Figure 19.8). Imagine that we fix our eyes on 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.

For example, if the wavelength is 1.5 m and the time between crests at a point on the surface is 0.5 s, then the wave moves 1.5 m in 0.5 s and its speed is 1.5 m divided by 0.5 s, or 3 m/s.

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

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

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

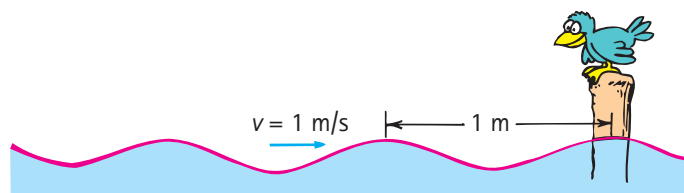


FIGURE 19.9
INTERACTIVE FIGURE 

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

CHECK POINT

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? What is its wavelength? What is its wave speed?

CHECK YOUR ANSWERS

1. 30 m/s. We can see this in two ways: (a) According to the definition of speed from Chapter 2, $v = d/t = (3 \times 10 \text{ m})/1 \text{ s} = 30 \text{ m/s}$, 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 = frequency \times wavelength = $3 \text{ Hz} \times 10 \text{ m} = 3/s \times 10 \text{ m} = 30 \text{ m/s}$. (Note that 3 Hz is 3 cycles in 1 s, or simply 3/s, because cycles, just a count, needn't be written in the unit for frequency.)
2. The frequency of the wave is 3 Hz, its wavelength is 2 m, and its wave speed = frequency \times wavelength = $3/s \times 2 \text{ m} = 6 \text{ m/s}$.



The speed v of a wave can be expressed by the equation $v = f\lambda$, where f is the wave frequency and λ (the Greek letter lambda) is the wavelength of the wave.

19.5 Wave Interference

Whereas a material object such as 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 meet and produce **wave interference**. The overlapping of waves can 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 19.10). 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*.

Wave interference is easiest to see in water. In Figure 19.11 we see the interference pattern made when two vibrating objects touch the surface of water. We can

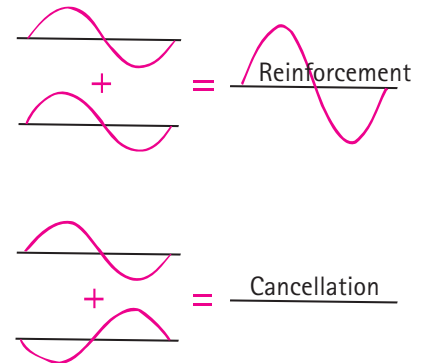


FIGURE 19.10 Constructive and destructive interference in a transverse wave.

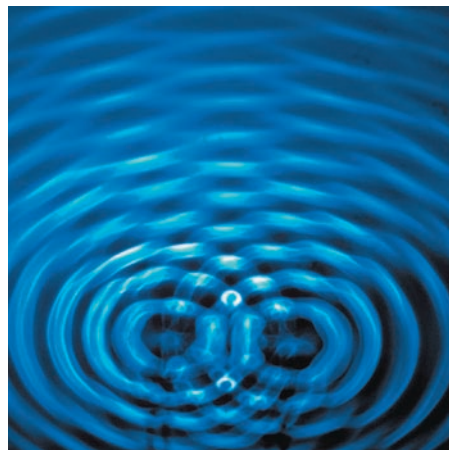
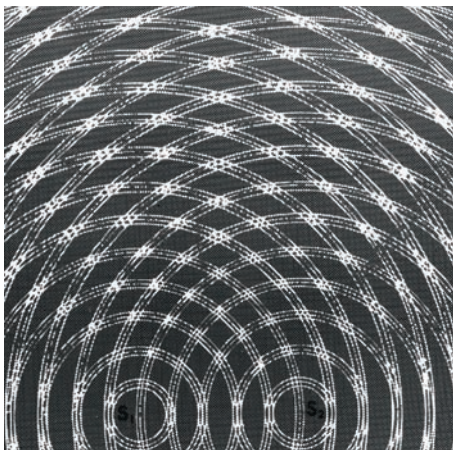


FIGURE 19.11 Two sets of overlapping water waves produce an interference pattern. The left image is an idealized drawing of the expanding waves from the two sources. The right image is a photograph of an actual interference pattern.

see the 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 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 Chapter 20 and the interference of light in Chapter 29.

Standing Waves

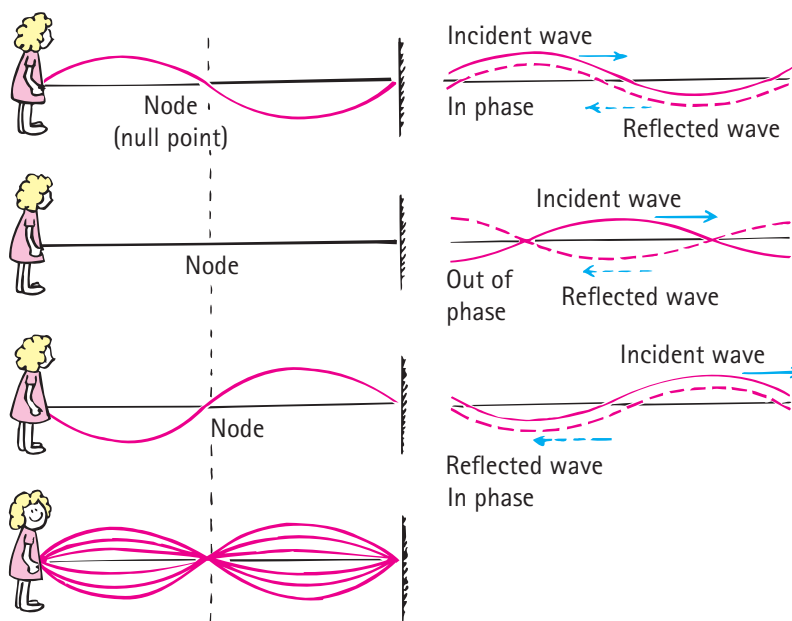
If we tie a rope to a wall and shake the free end up and down, we produce a train of waves in the rope. The wall is too rigid to shake, so the waves are reflected back along the rope. By shaking the rope just right, we can cause the incident and reflected waves to form a **standing wave**, where parts of the rope, called the *nodes*, appear to be standing still. Nodes are the regions of minimal or zero displacement, with minimal or zero energy. *Antinodes* (not labeled in Figure 19.12), in contrast, are the regions of maximum displacement and maximum energy. You can hold your fingers just over and under 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 19.12

INTERACTIVE FIGURE



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



Standing waves are the result of interference (and, as we will see in Chapter 20, *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. This occurs for a wave that reflects upon itself. Stable regions of constructive and destructive interference are produced.

It is easy to make standing waves yourself. Tie a rope—or, better, a rubber tube—to a firm support. Shake the tube up and down with your hand. If you shake the tube with the right frequency, you will set up a standing wave, as shown in Figure 19.13a. Shake the tube with twice the frequency, and a standing wave of half the previous wavelength, having two loops, will result (Figure 19.13b). (The distance between successive nodes is a half wavelength; two loops constitute a full wavelength.) If you triple the frequency, a standing wave with one-third the original wavelength, having three loops, will result (Figure 19.13c); and so forth.

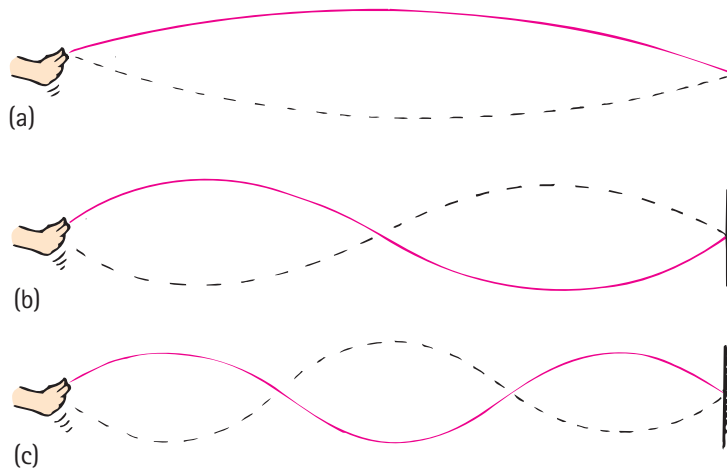


FIGURE 19.13
INTERACTIVE FIGURE 

- (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 they are 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 in a cup of coffee by sloshing the tub or cup back and forth with the right frequency. Standing waves can be produced with either transverse or longitudinal vibrations.



An organ pipe or flute makes sound with standing waves in a column of air.

CHECK POINT

1. Is it possible for one wave to cancel another wave so that no amplitude remains at certain points?
2. Suppose you set up a standing wave of three segments, as shown in Figure 19.13c. If you shake with twice as much frequency, how many wave segments will occur in your new standing wave? How many wavelengths?

CHECK YOUR 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, so you'll have six segments. Since a full wavelength has two segments, you'll have three complete wavelengths in your standing wave.



FIGURE 19.14
Satchmo produces standing waves of sound in his trumpet.

19.6 Doppler Effect

A pattern of water waves produced by a bug jigglng its legs and bobbing up and down in the middle of a quiet puddle is shown in Figure 19.15. The bug is not going anywhere but is merely treading water in a fixed position. The waves 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) 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 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.

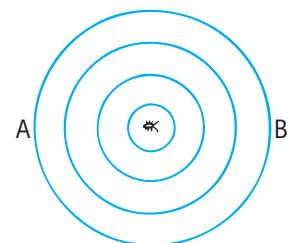
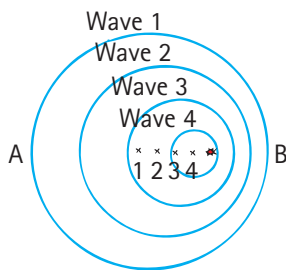


FIGURE 19.15
Top view of water waves formed by a stationary bug jigglng in still water. The blue circles represent wavefronts in the expanding pattern.

MasteringPhysics®

TUTORIAL:
Doppler Effect**FIGURE 19.16****INTERACTIVE FIGURE**

Water waves formed by a bug swimming in still water toward point B.

**VIDEO: Doppler Effect****FIGURE 19.17****INTERACTIVE FIGURE**

The pitch (frequency) of sound is higher when a source is moving toward you, and lower when the source is moving away.



Suppose the jiggling bug moves across the water at a speed lower 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 19.16). 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, would measure a *lower* frequency because of the longer time between wave-crest arrivals. This is because, in order 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 an ambulance siren as it passes you. When the vehicle approaches, the pitch is higher than normal (like a higher note on a musical scale). This is because the crests of the sound waves encounter your ear more frequently. And when the vehicle passes and moves away, you hear a drop in pitch because the crests of the waves hit your ear less frequently.

The Doppler effect also occurs for light. When a light source approaches, there is an increase in its measured frequency; 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 red-shifted light from the side turning away from us and blue-shifted light from the side turning toward us. This enables astronomers to calculate the star's spin rate.



Be clear about the distinction between *frequency* and *speed*. How frequently a wave vibrates is altogether different from how fast it moves from one location to another.

CHECK POINT

While you're at rest, a sound source moves toward you. Do you measure the speed of its sound wave to be greater or less than if the source were stationary?

CHECK YOUR ANSWER

Neither! Both the *frequency* and the *wavelength* undergo a change when the source is moving, but the *wave speed* does not. Be clear about the distinction between frequency and speed.

19.7 Bow Waves

When the speed of a source is as great as the speed of the waves it produces, something interesting occurs: The waves pile up in front of the source. Consider the bug in our earlier 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 19.18). 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 in order 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 aircraft. But the barrier is not real. Just as a boat can easily travel faster than the waves it produces, an aircraft with sufficient power 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 water that has a smooth, unrippled surface.

When the bug swims faster than the wave speed, ideally it produces a wave pattern, as shown in Figure 19.19. It outruns the waves it produces. The waves overlap at the edges and produce a V shape, called a **bow wave**, that appears to be dragging behind the bug. The familiar bow wave generated by a speedboat knifing through the water is not a typical oscillatory wave. It is a disturbance produced by the overlapping of many circular waves.

Some wave patterns made by sources moving at various speeds are shown in Figure 19.20. Note that after the speed of the source exceeds the wave speed, the increased speed of the source produces a narrower V shape.³

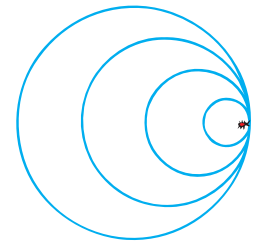
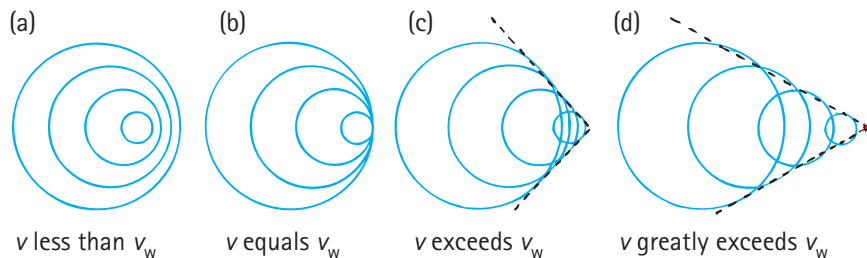


FIGURE 19.18 Wave pattern created by a bug swimming at wave speed.

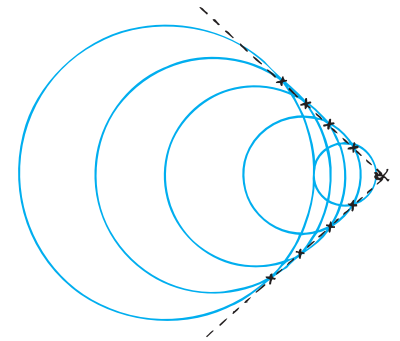


FIGURE 19.19 A bow wave, the pattern produced by a bug swimming faster than the wave speed. The points at which adjacent waves overlap (×) produce the V shape.

FIGURE 19.20 Patterns produced by a bug swimming at successively greater speeds. Overlapping at the edges occurs only when the bug swims faster than the wave speed.

19.8 Shock Waves

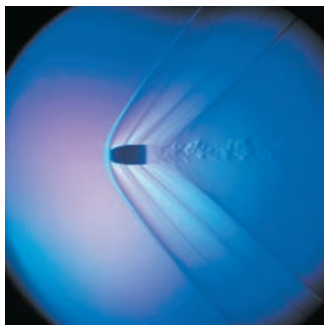
A speedboat knifing through the water generates a two-dimensional bow wave. A supersonic aircraft similarly generates a three-dimensional **shock wave**. Just as a bow wave is produced by overlapping circles that form a V, a shock wave is produced by overlapping spheres that form a cone. And, just as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

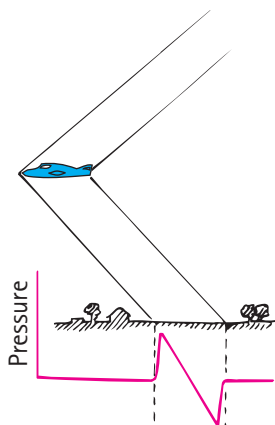
³Bow waves generated by boats in water are really more complex than is indicated here. Our idealized treatment serves as an analogy for the production of the less complex shock waves in air.



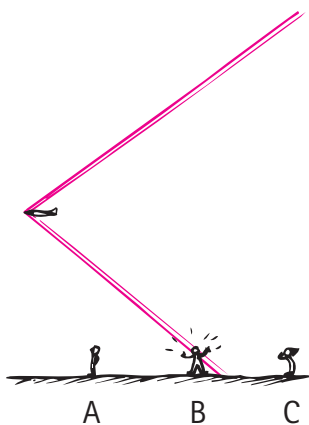
FIGURE 19.21 This aircraft is producing a cloud of water vapor that has just condensed out of the rapidly expanding air in the rarefied region behind the wall of compressed air.

**FIGURE 19.22**

The faster-than-the-speed-of-sound bullet compresses air in its path and produces visible shock-wave detail.

**FIGURE 19.23**

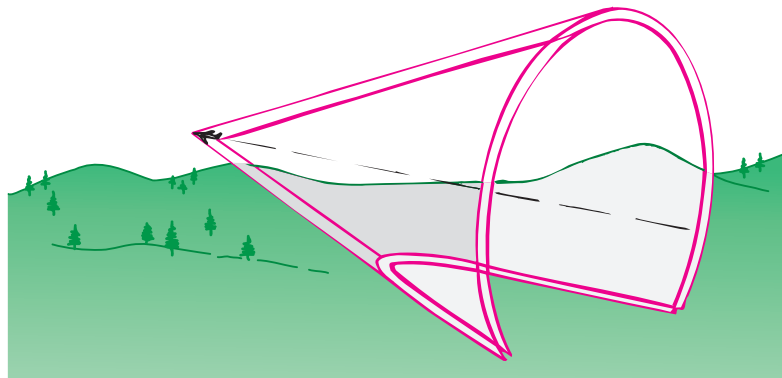
The shock wave is actually made up of two cones: a high-pressure cone with the apex at the bow of the aircraft and a low-pressure cone with the apex at the tail. A graph of the air pressure at ground level between the cones takes the shape of the letter N.

**FIGURE 19.25**

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

We don't hear a sonic boom from slower-than-sound, or subsonic, aircraft because the sound waves that reach our ears are perceived as one continuous tone. Only when the aircraft 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.

A water skier is familiar with the fact that next to the high crest 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.⁴ The edges of these cones are visible in the photograph of the supersonic bullet in Figure 19.22. 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 19.23). This overpressure suddenly followed by underpressure intensifies the sonic boom.

**FIGURE 19.24**

A shock wave.

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 and below an aircraft traveling faster than sound, just as a bow wave is swept continuously behind a speedboat. In Figure 19.25, 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 many minutes 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 boom-like. 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. 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.

⁴Shock waves are often more complex and involve multiple cones.



SUMMARY OF TERMS (KNOWLEDGE)

Sine curve The waveform 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 $1/\text{frequency}$.

Transverse wave A wave in which the medium vibrates perpendicularly (at right angles) to the direction in which the wave travels. Light waves and waves on stringed instruments are transverse.

Longitudinal wave A wave in which the medium vibrates parallel to (along) the direction in which the wave travels. Sound waves are longitudinal.

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

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

Wave interference The phenomenon that occurs when two waves meet while traveling along the same medium.

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

Standing wave A stationary interference 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 the motion of a vibrating source toward or away from a receiver.

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

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

Sonic boom The loud sound that results from the incidence of a shock wave.

READING CHECK QUESTIONS (COMPREHENSION)

19.1 Good Vibrations

1. What is a *wiggle in time* called? What do you call a *wiggle in space* and time?
2. What is the source of all waves?
3. What is meant by the *period* of a pendulum?
4. Which has the longer period: a short or a long pendulum?

19.2 Wave Description

5. How does a sine curve relate to the wave description?
6. Distinguish among these different aspects of a wave: period, amplitude, wavelength, and frequency.
7. How many vibrations per second are represented in a radio wave of 101.7 MHz?
8. How do frequency and period relate to each other?

19.3 Wave Motion

9. In one word, what is it that moves from source to receiver in wave motion?
10. Does the medium in which a wave travels move with the wave?
11. In what direction are the vibrations relative to the direction of wave travel in a transverse wave?
12. In what direction are the vibrations relative to the direction of wave travel in a longitudinal wave?

13. The wavelength of a transverse wave is the distance between successive crests (or troughs). What is the wavelength of a longitudinal wave?

19.4 Wave Speed

14. What is the relationship among frequency, wavelength, and wave speed?

19.5 Wave Interference

15. What is the superposition principle?
16. Distinguish between constructive interference and destructive interference.
17. What kinds of waves can show interference?
18. What is a node? What is an antinode?
19. Can standing waves be formed of transverse waves, longitudinal waves, or both?

19.6 Doppler Effect

20. In the Doppler effect, does frequency change? Does wave speed change?
21. Can the Doppler effect be observed with longitudinal waves, with transverse waves, or with both?
22. What is meant by a blue shift and a red shift for light?

19.7 Bow Waves

23. How fast must a bug swim to keep up with the waves it produces? How fast must it move to produce a bow wave?

24. How fast does a supersonic aircraft fly compared with the speed of sound?
25. How does the V shape of a bow wave depend on the speed of the source?

19.8 Shock Waves

26. A bow wave on the surface of water is two-dimensional. How about a shock wave in air?

27. True or false: A sonic boom occurs only when an aircraft is breaking through the sound barrier. Defend your answer.
28. True or false: In order for an object to produce a sonic boom, it must be “noisy.” Give two examples to support your answer.

THINK AND DO (HANDS-ON APPLICATION)

29. Tie a rubber tube, a spring, or a rope to a fixed support and produce standing waves. See how many nodes you can produce.
30. Wet your finger and rub it slowly around the rim of a thin-rimmed, stemmed wine 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.
31. Write a letter to Grandma and tell her how waves can cancel one another. Then describe what some of the applications of this physical phenomenon are these days.

PLUG AND CHUG (EQUATION FAMILIARIZATION)

$$\text{Frequency} = \frac{1}{\text{period}}; f = 1/T$$

32. What is the frequency, in hertz, that corresponds to each of the following periods: (a) 0.10 s, (b) 5 s, (c) 1/60 s?

$$\text{Period} = \frac{1}{\text{frequency}}; T = 1/f$$

33. What is the period, in seconds, that corresponds to each of the following frequencies: (a) 10 Hz, (b) 0.2 Hz, (c) 60 Hz?

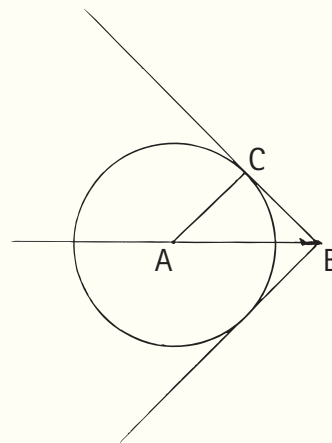
$$\text{Wave speed} = \frac{\text{wavelength}}{\text{period}} \text{ or } \text{frequency} \times \text{wavelength};$$

$$v = f\lambda$$

34. What is the speed of a water wave of frequency 2 Hz and wavelength 1.5 m?
35. How fast does a 200-Hz sound wave with a wavelength of 1.7 m travel?

THINK AND SOLVE (MATHEMATICAL APPLICATION)

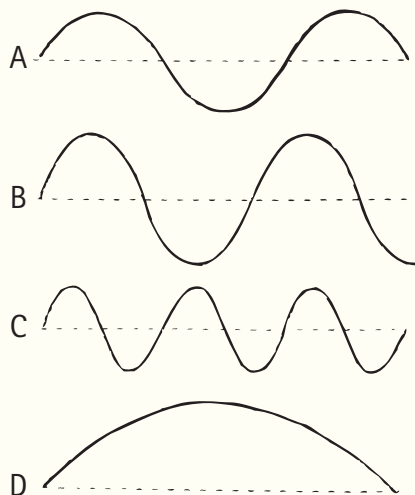
36. A skipper on a boat notices wave crests passing his anchor chain every 5 s. He estimates the distance between wave crests to be 15 m. He also correctly estimates the speed of the waves. Show that this speed is 3 m/s.
37. A weight suspended from a spring is seen to bob up and down over a distance of 20 cm twice each second. What is its frequency? Its period? Its amplitude?
38. A mosquito flaps its wings 600 vibrations per second, which produces the annoying 600-Hz buzz. Given that 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.
39. On a keyboard, you strike middle C, whose frequency is 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?
40. As shown in the drawing, the half-angle of the shock wave cone generated by a supersonic airplane is 45° . What is the speed of the plane relative to the speed of sound?



41. An astronaut on the Moon attaches a small brass ball to a 1.00-m length of string and makes a simple pendulum. She times 15 complete swings in 75 seconds. From this measurement she calculates the acceleration due to gravity on the Moon. What is her result?

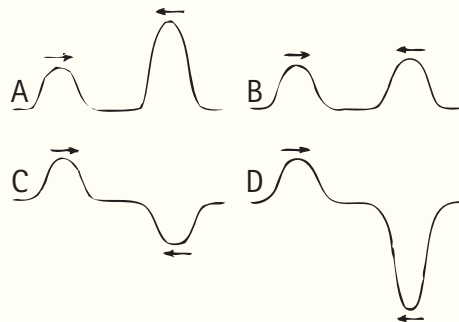
THINK AND RANK (ANALYSIS)

42. All the waves shown have the same speed in the same medium. Use a ruler and rank these waves from most to least for (a) amplitude, (b) wavelength, (c) frequency, and (d) period.

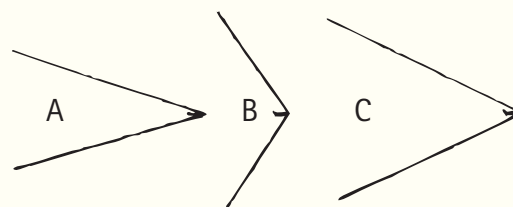


43. Shown here are four different pairs of transverse wave pulses that move toward each other. At some point in time, the pulses meet and interact (interfere) with each other. Rank the four cases, from most to least, on the

basis of the height of the peak that results when the centers of the pulses coincide.



44. Rank the pitches heard from the siren of a fire engine, from highest to lowest, when the fire engine is traveling
(a) toward the listener at 30 km/h.
(b) toward the listener at 50 km/h.
(c) away from the listener at 20 km/h.
45. The shock waves A, B, and C are produced by supersonic aircraft. Rank their speeds from highest to lowest.

**THINK AND EXPLAIN (SYNTHESIS)**

46. Does the period of a pendulum depend on the mass of the bob? On the length of the string?
47. If a pendulum is shortened, does its frequency increase or decrease? What about its period?
48. A grandfather pendulum clock keeps perfect time. Then it is relocated to a summer home high in the mountains. Does it run faster, slower, or the same? Explain.
49. You pick up an empty briefcase and let it swing to and fro at its natural frequency. If the case were filled with books, would the natural frequency be lower than, higher than, or the same as before?
50. Is the time required to swing to and fro (the period) on a playground swing longer or shorter when you stand rather than sit? Explain.
51. What happens to the period of a wave when the frequency decreases?
52. What happens to the wavelength of a wave when the frequency decreases?
53. If the speed of a wave doubles while the frequency remains the same, what happens to the wavelength?
54. If the speed of a wave doubles while the wavelength remains the same, what happens to the frequency?
55. 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 with the period of the rotating wheel? Defend your answer.

56. You use a vice to firmly clamp one end of a hacksaw blade. You twang the free end and it vibrates. If you do the same, but first place a wad of clay on the free end, how, if at all, will the frequency of the 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 8?)
57. If you shake the end of a spring to produce a wave, how does the frequency of the wave compare with the frequency of your shaking hand? Does your answer depend on whether you're producing a transverse wave or a longitudinal wave? Defend your answer.
58. 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?
59. What kind of motion should you impart to a stretched coiled spring (or Slinky) to provide a
(a) transverse wave?
(b) longitudinal wave?

60. What kind of wave is each of the following?
 - (a) The sound of one whale calling another whale under water.
 - (b) A pulse sent down a stretched rope by snapping one end of it.
 - (c) The vibrations in a guitar string.
61. Red light has a longer wavelength than violet light. Which has the higher frequency?
62. If we double the frequency of a vibrating object or the wave it produces, what happens to the period?
63. What is the frequency of the second hand of a clock? The minute hand? The hour hand?
64. If you dip your finger repeatedly into a puddle of water, it creates waves. What happens to the wavelength if you dip your finger more frequently?
65. How does the frequency of vibration of a small object floating in water compare with the number of waves passing it each second?
66. In terms of wavelength, show how far a wave travels in one period.
67. What is the source of mechanical waves? Of electromagnetic waves?
68. How many nodes, not including the endpoints, are there in a standing wave that is two wavelengths long? Three wavelengths long?
69. 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?
70. The wave patterns seen in Figures 19.4 and 19.8 are composed of circles. What does this tell you about the speed of waves moving in different directions?
71. Why is lightning seen before thunder is heard?
72. A banjo player plucks the middle of a string pinned down at both ends. Where are the nodes of the standing wave in the string? What is the wavelength of the vibrating string?
73. 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 Figure 19.13a and b.) What is the effect on the frequency when this occurs?
74. A bat chirps as it flies toward a wall. Is the frequency of the echoed chirps it receives higher than, lower than, or the same as the emitted ones?
75. A railroad locomotive is at rest with its whistle shrieking, then starts moving toward you.
 - (a) Does the frequency of sound 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?
76. Why is there a Doppler effect when the source of the sound is stationary and the listener is in motion? In which direction should the listener move to hear a higher frequency? A lower frequency?
77. When you blow your horn while driving toward a stationary listener, the listener hears an increase in the frequency of the horn. Would the listener hear an increase in the horn frequency if he or she were also in a car traveling at the same speed in the same direction as you are? Explain.
78. Is there an appreciable Doppler effect when the motion of the source is at right angles to a listener? Explain.
79. How does the Doppler effect aid police in detecting speeding motorists?
80. 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?)
81. How does the phenomenon of interference play a role in the production of bow waves or shock waves?
82. What can you say about the speed of a boat that makes a bow wave?
83. Does a sonic boom occur at the moment when an aircraft exceeds the speed of sound? Explain.
84. Why is it that a subsonic aircraft, no matter how loud it may be, cannot produce a sonic boom?
85. Imagine a superfast fish that is able to swim faster than the speed of sound in water. Would such a fish produce a “sonic boom”?
86. Make up a multiple-choice question that would check a classmate’s understanding of the distinction between a transverse wave and a longitudinal wave.
87. Make up a multiple-choice question that would check a classmate’s understanding of any of the terms that describe a wave.

THINK AND DISCUSS (EVALUATION)

88. A heavy person and a light person swing to and fro on swings of the same length. Discuss who has the longer period.
89. Does it make sense that the mass of a bob in a simple pendulum doesn't affect the frequency of the pendulum? In your discussion cite whether or not mass affects the acceleration of free fall.
90. 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 speed at which molecules diffuse through the sound-carrying medium?
91. Discuss how some learners confuse the two terms *wave speed* and *wave frequency* when they assume that the terms refer to the same thing.
92. Astronomers find that light emitted by a particular element at one edge of the Sun has a slightly higher frequency than light from that element at the opposite edge. What do these measurements tell us about the Sun's motion?
93. If the sound of an airplane does not come from the part of the sky where the plane is seen, discuss whether or not this implies that the airplane is traveling faster than the speed of sound.
94. Does the conical angle of a shock wave open wider, narrow down, or remain constant as a supersonic aircraft increases its speed? Draw a sketch to make your point.