The Big Picture

Waves—Something Else That Moves

Raymond Gendreau/Stone/Getty

Sculling on Lake Powell creates interesting wave patterns.

Imagine standing near a busy highway trying to get the attention of a friend on the other side. How could you signal your friend? You might try shouting first. You could throw something across the highway, you could make a loud noise by banging two rocks together, you could shine a flashlight at your friend, and so on.

Signals can be sent by one of two methods. One method includes ways in which material moves from you to your friend—such as throwing a pebble. The other method includes ways in which energy moves across the highway without any accompanying material. This second method represents phenomena that we usually call waves.

The study of waves has greatly expanded the physics world view. Surprisingly, however, waves do not have a strong position in our commonsense world view. It's not that wave phenomena are uncommon, but rather that many times the wave nature of the phenomena is not recognized. Plucking a guitar string, for example, doesn't usually invoke images of waves traveling up and down the string. But that is what happens. The buzzing of a bee probably does not generate thoughts of waves either. We will discover interesting examples of waves in unexpected situations.

Waves are certainly common enough—we grow up playing with water waves and listening to sound waves—but most of us do not have a good intuitive understanding of the behavior of waves. Ask yourself a few questions about waves: Do they bounce off materials? When two waves meet, do they crash like billiard balls? Is it meaningful to speak of the speed of a wave? When speaking of material objects, the answers to such questions seem obvious, but when speaking of waves, the answers require closer examination.

We study waves for two reasons. First, because they are there; studying waves adds to our understanding of how the world works. The second reason is less obvious. As we delve deeper and deeper into the workings of the world, we reach limits beyond which we cannot observe phenomena directly. Even the best imaginable magnifying instrument is too weak to allow direct observation of the subatomic worlds. Our search to understand these worlds yields evidence only by indirect methods. We must use our common experiences to model a world we cannot see. In many cases the modeling process can be reduced to asking whether the phenomenon acts like a wave or acts like a particle.

To answer the question of whether something acts like a wave or a particle, we must expand our commonsense world view to include waves. After you study such common waves as sound waves, we hope you will be ready to "hear" the harmony of the subatomic world.

It's not that wave phenomena are uncommon, but rather that many times the wave nature of the phenomena is not recognized.

15

Vibrations and Waves

▶Water drops falling onto the surface of water produce waves that move outward as expanding rings. But what is moving outward? Does the wave disturbance carry energy or momentum? What happens when two waves meet? How does wave motion differ from particle motion?

(See page 323 for the answer to this question.)

Don Bonsey/Stone/Getty

Circular waves are formed by falling water drops.

IF you stretch or compress a spring and let go, it vibrates. If you pull a pendulum off to one side and let it go, it oscillates back and forth. Such vibrations and oscillations are common motions in our everyday world. If these vibrations and oscillations affect surrounding objects or matter, a wave is often generated. Ripples on a pond, musical sounds, laser light, exploding stars, and even electrons all display some aspects of wave behavior.

Waves are responsible for many of our everyday experiences. Fortunately, nature has been kind; all waves have many of the same characteristics. Once you understand one type, you will know a great deal about the others.

We begin our study with simple vibrations and oscillations. We then examine common waves, such as waves on a rope, water waves, and sound waves, and later progress to more exotic examples, such as radio, television, light, and even "matter" waves.

▶ Extended presentation available in the *Problem Solving* supplement

Simple Vibrations

If you distort an object and release it, elastic forces restore the object to its original shape. In returning to its original shape, however, the inertia of the displaced portion of the object causes it to overshoot, creating a distortion in the opposite direction. Again, restoring forces attempt to return the object to its original shape and, again, the object overshoots. This back-and-forth motion is what we commonly call a **vibration,** or an **oscillation.** For all practical purposes, the labels are interchangeable.

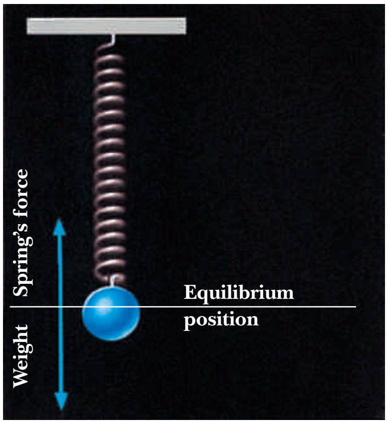


Figure 15-1 At the equilibrium position, the upward force due to the spring is equal to the weight of the mass.

A mass hanging on the end of a vertical spring exhibits a simple vibrational motion. Initially, the mass stretches the spring so that it hangs at the position where its weight is just balanced by the upward force of the spring, as shown in Figure 15-1. This position—called the **equilibrium position**—is analogous to the undistorted shape of an object. If you pull downward (or push upward) on the mass, you feel a force in the opposite direction. The size of this restoring force increases with the amount of stretch or compression you apply. If the applied force is not too large, the restoring force is proportional to the distance the mass is moved from its equilibrium position. If the force is too large, the spring will be permanently stretched and not return to its original length. In the discussion that follows, we assume that the stretch of the system is not too large. Many natural phenomena obey this condition, so little is lost by imposing this constraint.

Imagine pulling the mass down a short distance and releasing it as shown in Figure 15-2(a). Initially, a net upward force accelerates the mass upward. As the mass moves upward, the net force decreases in size (b), becoming zero when the mass reaches the equilibrium position (c). Because the mass has inertia, it overshoots the equilibrium position. The net force now acts downward (d) and slows the mass to zero speed (e). Then the mass gains speed in the downward direction (f). Again, the mass passes the equilibrium position (g). Now the net force is once again upward (h) and slows the mass until it reaches its lowest point (a). This sequence [Figure 15-2(a through a)] completes one **cycle.**

Actually, a cycle can begin at any position. It lasts until the mass returns to the original position *and* is moving in the same direction. For example, a cycle may begin when the mass passes through the equilibrium point on its way up (c) and end when it next passes through this point on the way up. Note that the cycle does not end when the mass passes through the equilibrium point on the way down (g). This motion is known as periodic motion, and the amount of time required for one cycle is known as the **period** T.

period is the time to complete one cycle ▶

If we ignore frictional effects, energy conservation (Chapter 7) tells us that the mass travels the same distance above and below the equilibrium position.

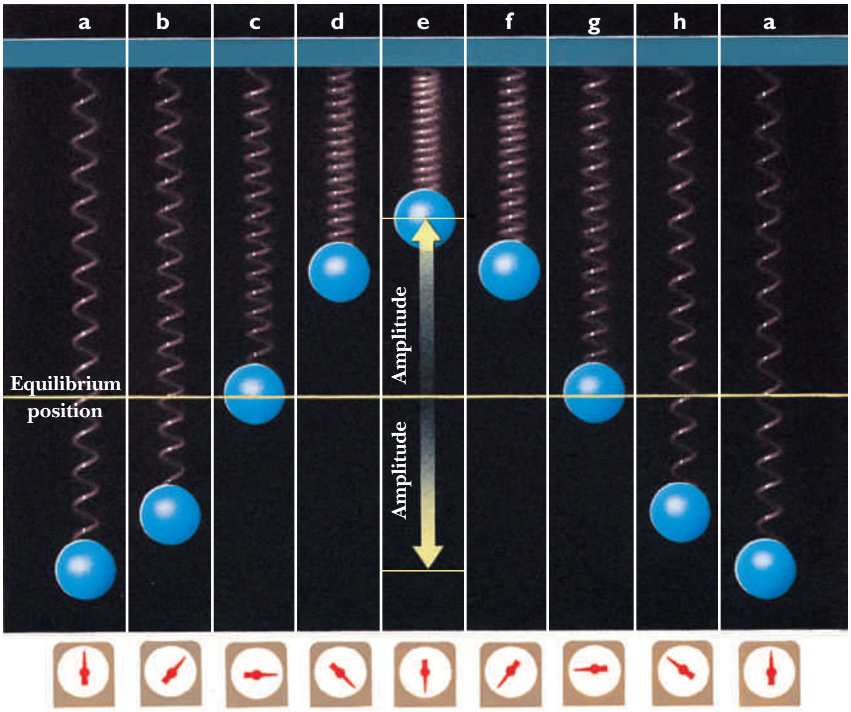


Figure 15-2 A time sequence showing one complete cycle for the vibration of a mass on a spring. The clocks show that equal time intervals separate the images.

This distance is marked in Figure 15-2 and is known as the **amplitude** of the vibration. In real situations the amplitude decreases and eventually the motion dies out because of the frictional effects that convert mechanical energy into thermal energy.

We can describe the time dependence of the vibration equally well by giving its **frequency** f, the number of cycles that occur during a unit of time. Frequency is often measured in cycles per second, or hertz (Hz). For example, concert A (the note that orchestras use for tuning) has a frequency of about 440 hertz, household electricity oscillates at 60 hertz, and your favorite FM station broadcasts radio waves near 100 million hertz.

There is a simple relationship between the frequency f and the period T—one is the reciprocal of the other:

$$f = \frac{1}{T}$$

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

$$T = \frac{1}{f}$$

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

To illustrate this relationship, let's calculate the period of a spring vibrating at a frequency of 4 hertz:

$$T = \frac{1}{f} = \frac{1}{4\text{ Hz}} = \frac{1}{4\text{ cycles/s}} = \frac{1}{4}\text{ s}$$

This calculation shows that a frequency of 4 cycles per second corresponds to a period of $\frac{1}{4}$ second. This makes sense because a spring vibrating four times per second should take $\frac{1}{4}$ of a second for each cycle. (When we state the period, we know it refers to one cycle and don't write "second per cycle.")

Are You On the Bus?

Q: What is the period of a mass that vibrates with a frequency of 10 times per second?

A: Because the period is the reciprocal of the frequency, we have

$$T = \frac{1}{f} = \frac{1}{10\ \text{Hz}} = 0.1\ \text{s}$$

We may guess that the time it takes to complete one cycle would change as the amplitude changes, but experiments show that the period remains essentially constant. It is fascinating that the amplitude of the motion does *not* affect the period and frequency. (Again, we have to be careful not to stretch the system "too much.") This means that a vibrating guitar string always plays the same frequency regardless of how hard the string is plucked.

Although the period for a mass vibrating on the end of a spring does not depend on the amplitude of the vibration, we may expect the period to change if we switch springs or masses. The stiffness of the spring and the size of the mass do change the rate of vibration.

The stiffness of a spring is characterized by how much force is needed to stretch it by a unit length. For moderate amounts of stretch or compression, this value is a constant known as the **spring constant** k. In SI units this constant is measured in newtons per meter. Larger values correspond to stiffer springs.

In trying to guess the relationship between the spring constant, mass, and period, we would expect the period to decrease as the spring constant increases because a stiffer spring means more force and therefore a quicker return to the equilibrium position. Furthermore, we would expect the period to increase as the mass increases because the inertia of a larger mass will slow the motion.

WORKING IT OUT *Period of a Mass on a Spring*

The mathematical relationship for the period of a mass on a spring can be obtained theoretically and is verified by experiment:

period of a mass on a spring ▶

$$T = 2\pi\sqrt{\frac{m}{k}}$$

where π is approximately 3.14.

As an example, consider a 0.2-kg mass hanging from a spring with a spring constant of 5 N/m:

$$T = 2\pi\sqrt{\frac{m}{k}} = 2\pi\sqrt{\frac{0.2\ \text{kg}}{5\ \text{N/m}}} = 6.28\sqrt{\frac{1}{25}\ \text{s}^2} = 1.26\ \text{s}$$

Therefore, this mass–spring combination vibrates with a period of 1.26 s, or a frequency of 0.793 Hz.

Are You On the Bus?

Q: What is the period of a 0.1-kg mass hanging from a spring with a spring constant of 0.9 N/m?

A: 2.09 s.

The Pendulum

The pendulum is another simple system that oscillates. Students are often surprised to learn (or to discover by experimenting) that the period of oscillation does not depend on the amplitude of the swing. To a very good approximation, large- and small-amplitude oscillations have the same period if we keep their amplitudes less than 30 degrees. This amazing property of pendula was first discovered by Galileo when he was a teenager sitting in church watching a swinging chandelier. (Clearly, he was not paying attention to the service.) Galileo tested his hypothesis by constructing two pendula of the same length and swinging them with different amplitudes. They swung together, verifying his hypothesis.

Let's consider the forces on a pendulum when it has been pulled to the right, as shown in Figure 15-3. The component of gravity acting along the string is balanced by the tension in the string. Therefore, the net force is the component of gravity at right angles to the string and directed toward the lower left. This restoring force causes the pendulum bob to accelerate toward the left. Although the restoring force on the bob is zero at the lowest point of the swing, the bob passes through this point (the equilibrium position) because of its inertia. The restoring force now points toward the right and slows the bob.

We found in free fall that objects with different masses fall with the same acceleration because the gravitational force is proportional to the mass. Therefore, we may expect that the motion of a pendulum would not depend on the mass of the bob. This prediction is true and can be verified easily by making two pendula of the same length with bobs of the same size made out of different materials so that they have different masses. The two pendula will swing side by side.

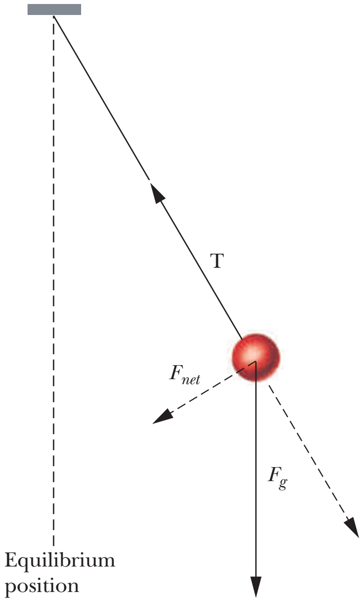


Figure 15-3 The net force on the pendulum bob accelerates it toward the equilibrium position.

Q: Why do we suggest using different materials?

A: If we use the same type of material, the size has to be different to get different masses. Different sizes may also affect the period. When doing an experiment, it is important to keep all but one factor constant.

We also know from our experiences with pendula that the period depends on the length of the pendulum; longer pendula have longer periods. Therefore, the length of the pendulum can be changed to adjust the period.

Because the restoring force for a pendulum is a component of the gravitational force, you may expect that the period depends on the strength of gravity, much as the period of the mass on the spring depends on the spring constant. This hunch is correct and can be verified by taking a pendulum to the Moon, where the acceleration due to gravity is only one-sixth as large as that on Earth.

Richarde Megna/Fundamental Photographs, NYC

A strobe photograph of a pendulum taken at 20 flashes per second. Note that the pendulum bob moves the fastest at the bottom of the swing.

Clocks

Keeping time is a process of counting the number of repetitions of a regular, recurring process, so it is reasonable that periodic motions have been important to timekeepers. Devising accurate methods for keeping time has kept many scientists, engineers, and inventors busy throughout history. The earliest methods for keeping time depended on the motions in the heavens. The day was determined by the length of time it took the Sun to make successive crossings of a north–south line and was monitored with a sundial. The month was

WORKING IT OUT | *Period of a Pendulum*

The period of a pendulum is given by

period of a pendulum ▶

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

As an example, consider a pendulum with a length of 10 m:

$$T = 2\pi\sqrt{\frac{L}{g}} = 2\pi\sqrt{\frac{10\ \text{m}}{10\ \text{m/s}^2}} = 6.28\sqrt{1\ \text{s}^2} = 6.28\ \text{s}$$

Therefore, this pendulum would oscillate with a period of 6.28 s.

Are You On the Bus?

Q: What would you expect for the period of a 1.7-m pendulum on the Moon?

A: 6.28 s.

A replica of an early mechanical clock.

determined by the length of time it took the Moon to go through its phases. The year was the length of time it took to cycle through the seasons and was monitored with a calendar, a method of counting days.

As science and commerce advanced, the need grew for increasingly accurate methods of determining time. An early method for determining medium intervals of time was to monitor the flow of a substance such as sand in an hourglass or water in a water clock. Neither of these, however, was very accurate, and because they were not periodic, they had to be restarted for each time interval. It is interesting to note that Galileo kept time with a homemade water clock in many of his early studies of falling objects.

The next generation of clocks took on a different character, employing oscillations as their basic timekeeping mechanism. Galileo's determination that the period of a pendulum does not depend on the amplitude of its swing led to Christiaan Huygens's development of the pendulum clock in 1656, 14 years after Galileo's death. One of the difficulties Huygens encountered was to develop a mechanism for supplying energy to the pendulum to maintain its swing.

Seafarers spurred the development of clocks that would keep accurate time over long periods. To determine longitude requires measuring the positions of prominent stars and comparing these positions with their positions as seen from Greenwich, England, *at the same time*. Because pendulum clocks did not work on swaying ships, several cash prizes were offered for the design and construction of suitable clocks. Beginning in 1728, John Harrison, an English instrument maker, developed a series of clocks that met the criteria, but he was not able to collect his money until 1765. One of Harrison's clocks was accurate to a few seconds after 5 months at sea.

Any periodic vibration can be used to run clocks. Grandfather clocks use pendulums to regulate the hands and are powered by hanging weights. Mechanical watches have a balance wheel fastened to a spring. Electric clocks use 60-hertz alternating electric current. Digital clocks use the vibrations of quartz crystals or resonating electric circuits.

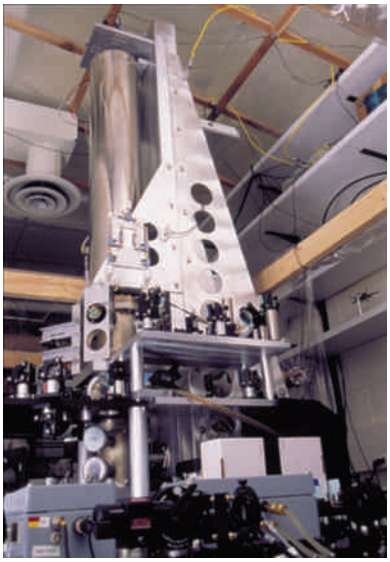
Modern time is kept with atomic clocks, which use the frequencies of atomic transitions (see Chapter 23) and are extremely insensitive to such changes in the clocks' environment as pressure and temperature. Atomic clocks are accurate to better than a second in 60 million years.

Resonance

We discovered with the mass on a spring and the pendulum that each system had a distinctive, natural frequency. The natural frequency of the pendulum is determined by its length and the acceleration due to gravity. Pulling the bob back and releasing it produces an oscillation at this particular frequency.

A child on a swing is an example of a life-size pendulum. If the child does not "pump" her legs and if no one pushes her, the amplitude of the swing continually decreases, and the child comes to rest. As every child knows, however, pumping or pushing greatly increases the amplitude. A less obvious fact is that the size of the effort—be it from pumping or pushing—is not important, but its timing is crucial. The inputs must be given at the natural frequency of the swing. If the child pumps at random times, the swinging dies out. This phenomenon of a large increase in the amplitude when a periodic force is applied to a system at its natural frequency is called **resonance.**

Resonance can also be achieved by using impulses at other special frequencies, but each of these has a definite relationship to the natural frequency. For example, if you push the child on the swing every other time, you are providing inputs at one-half of the natural frequency; every third time gives inputs at one-third of the natural frequency; and so on. Each of these frequencies causes resonance.



Modern time is kept by extremely accurate atomic clocks such as this F1 operated by the National Institute of Standards and Technology. It is accurate to 1 second in 80 million years.

Q: What happens to the amplitude of the swing if you push at twice the natural frequency?

A: In this case you would be pushing twice for each cycle. One of the pushes would negate the other, and the swing would stop.

More complex systems also have natural frequencies. If someone strikes a spoon on a table, you are not likely to mistake its sound for that of a tuning fork. The vibrations of the spoon produce sounds that are characteristic of the spoon. All objects have natural frequencies. The factors that determine these frequencies are rather complex. In general, the dominant factors are the stiffness of the material, the mass of the material, and the size of the object.

Resonance can have either good or bad effects. Although your radio receives signals from many stations simultaneously, it plays only one station at a time. The radio can be tuned so that its resonant frequency matches the broadcast frequency of your favorite station. Tuning puts the radio in resonance with one particular broadcast frequency and out of resonance with the frequencies of the competing stations. On the other hand, if the radio has an inferior speaker with one or two strong resonant frequencies, it will distort the sounds from the radio station by not giving all frequencies equal amplification.

Suppose you have a collection of pendula of different lengths, as shown in Figure 15-4. Notice that two of these pendula have the same length and thus the same natural frequency. The pendula are not independent because they are all tied to a common string. The motion of one of them is felt by all the others through pulls by the string. If you start the left-hand pendulum swinging, its back-and-forth motion creates a tug on the common string with a frequency equal to its natural, or resonant, frequency. Pendula with different frequencies jiggle a little bit but are not affected much. However, the pendulum with the same frequency resonates with the input frequency, drastically increasing its amplitude. In exactly the same way, objects resonate when input frequencies are the same as any of their natural frequencies.

If children pump at the right frequencies, they can increase the amplitudes of their motions.

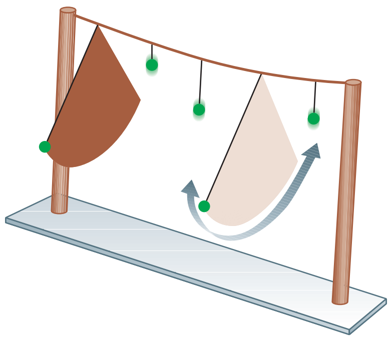


Figure 15-4 Pendula with the same natural frequency resonate with each other.

Everyday Physics | *Tacoma Narrows Bridge*

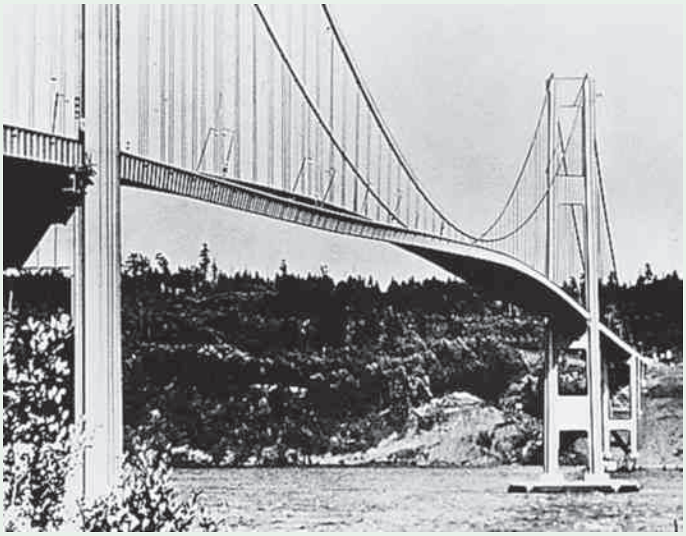
Resonant effects can sometimes have disastrous consequences. In 1940 a new bridge across one of the arms of Puget Sound in the state of Washington was opened to traffic. It was a suspension bridge with a central span of 850 meters (2800 feet). Because the bridge was designed for two lanes, it had a width of only 12 meters (40 feet). Within a few months after it opened, early-morning winds in the Sound caused the bridge to oscillate in standing-wave patterns that were so large in amplitude that the bridge failed structurally and fell into the water below, as shown in the figure.

But why did this bridge fail when other suspension bridges are still standing (including the bridge that now spans the Sound at the location of the original)? The bridge was long, narrow, and particularly flexible. Motorists often complained about the vertical oscillations and nicknamed the bridge "Galloping Gertie." However, the amplitudes of the vertical oscillations were relatively small until that fateful morning. The wind was blowing along the arm of the Sound (perpendicular to the length of the bridge) at moderate to high velocities but was not near gale force. One may speculate that fluctuations in the wind speed matched the natural frequency of the bridge, causing it to resonate. However, the wind was reasonably steady, and wind fluctuations are normally quite random. Furthermore, the forces would be horizontal, and the oscillations were vertical.

The best explanation involves the formation and shedding of vortices in the wind blowing past the bridge. *Vortices* are the eddies that you get near the ends of the oars when you row a boat. Vortices rotate in opposite directions in the wind blowing over and under the bridge. As each vortex is shed, it exerts a vertical impulse on the bridge. Therefore, if the frequency of vortex formation and shedding is near the natural frequency of the bridge for vertical oscillations, a standing wave will form just like those on a guitar string. (The frequency does not have to match exactly; it only needs to be close. How close depends on the details of the bridge construction.)

The bridge would have been fine except for another unfortunate circumstance. Besides the vertical standing wave, there were also torsional, or twisting, standing waves on the bridge. Normally, the frequencies of the two standing waves are quite different. But for the Tacoma Narrows Bridge, the two frequencies were fairly close (eight per minute for the vertical motion compared with ten per minute for the twisting motion). This allowed some of the energy from the vertical motion to be transferred to the twisting motion that eventually led to the mechanical failure of the bridge.

1. What was the periodic driving force that caused the standing wave to be formed on the bridge?
2. What uncommon characteristic of the Tacoma Narrows Bridge ultimately led to its mechanical failure?




Special Collections Div. Univ. of Washington Libraries, photo by Farquharson (both)

The Tacoma Narrows Bridge collapsed when winds set up resonant vibrations.

Waves: Vibrations That Move

Most **waves** begin with a disturbance of some material. Some disturbances, such as the clapping of hands, are onetime, abrupt events, whereas others,

Figure 15-5 A wave pulse travels along a line of dominoes.

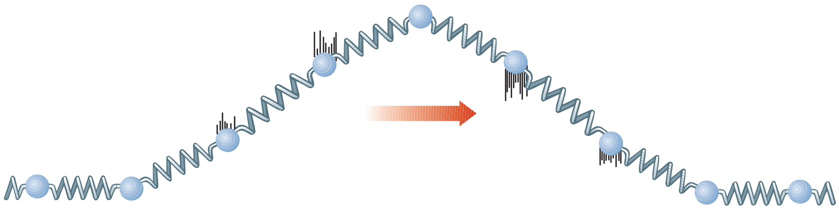


Figure 15-6 A wave disturbance can move along a chain of balls and springs.

such as the back-and-forth vibration of a guitar string, are periodic events. The simplest wave is a single pulse that moves outward as a result of a single disturbance.

Imagine a long row of dominoes lined up as shown in Figure 15-5. Once a domino is pushed over, it hits its neighbor, and its neighbor hits its neighbor, and so on, sending the disturbance along the line of dominoes. The key point is that "something" moves along the line of dominoes—from the beginning to the end—but it is not any individual domino.

Actually, the domino example is not completely analogous to what happens in most situations involving waves because there is no mechanism for restoring the dominoes in preparation for the next pulse. We can correct this omission by imagining a long chain of balls connected by identical springs, as shown in Figure 15-6. As the disturbance moves from left to right, individual balls are lifted up from their equilibrium positions and then returned to these equilibrium positions. The springs allow each ball to pull its neighbor away from equilibrium, just as the dominoes passed the disturbance from neighbor to neighbor by striking each other. After the pulse passes, the springs provide the restoring force that returns each ball to equilibrium. Notice that the pulse travels along the chain of balls without any of the balls moving in the direction of the pulse. Figure 15-6 shows the shape of the chain of balls and springs at the time the center ball reaches its maximum displacement.

In a similar manner, a pebble dropped into a pond depresses a small portion of the surface. Each vibrating portion of the surface generates disturbances in the surrounding water. As the process continues, the disturbance moves outward in circular patterns, such as those shown in Figure 15-7.

This type of disturbance, or pulse, occurs in a number of common, everyday events. A crowd transmits single pulses when a small group begins pushing. This push spreads outward through the crowd much as a ripple moves over a pond's surface. Similarly, the disturbance produced by a clap sends a single sound pulse through the air. Other examples of nonrecurrent waves include tidal bores, tidal waves, explosions, and light pulses emitted by supernovas (exploding stars).

Ian O'Leary/Stone/Getty

Figure 15-7 Water drops produce disturbances that move outward in circular patterns.

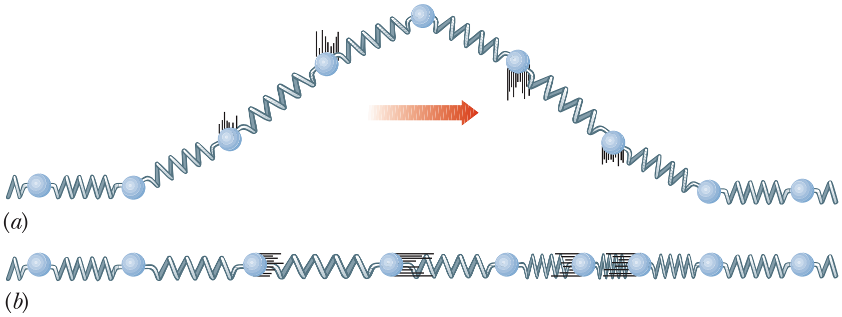


Figure 15-8 In a transverse wave (a), the medium moves perpendicular to the direction of propagation of the wave, whereas in a longitudinal wave (b), the medium's motion is parallel to the direction of propagation.

Although a wave moves outward from the original disturbance, there is no overall motion of the material. As the wave travels through the medium, the particles of the material vibrate about their equilibrium positions. Although the wave travels down the chain, the individual balls of the chain return to their original positions. The wave transports energy rather than matter from one place to another. The energy of an undisturbed particle in front of the wave is increased as the wave passes by and then returns to its original value. In a real medium, however, some of the energy of the wave is left behind as thermal energy in the medium.

There are two basic wave types. A wave in which the vibration of the medium is perpendicular to the motion of the wave is called a **transverse wave.** Waves on a rope are transverse waves. A wave in which the vibration of the medium is along the same direction as the motion of the wave is called a **longitudinal wave.** Both types can exist in the chain of balls. If a ball is moved vertically, a transverse wave is generated [Figure 15-8(a)]. If the ball is moved horizontally, the wave is longitudinal [Figure 15-8(b)].

Transverse waves can move only through a material that has some rigidity; transverse waves cannot exist within a fluid because the molecules simply slip by each other. Longitudinal waves, on the other hand, can move through most materials because the materials can be compressed and have restoring forces.

Q: Is it possible to have transverse waves on the surface of water?

A: Transverse surface waves are possible because the force of gravity tends to restore the surface to its flat equilibrium shape. Actually, the motion of the individual water molecules is a combination of transverse motion and longitudinal motion; the water molecules follow elliptical paths.

One-Dimensional Waves

Because all waves have similar properties, we can look at waves that are easy to study and then make generalizations about other waves. Imagine a clothesline tied to a post, as in Figure 15-9. A flick of the wrist generates a single wave pulse that travels away from you. On an idealized rope, the wave pulse would maintain its shape and size. On a real rope, the wave pulse slowly spreads out. We will ignore this spreading in our discussion. The wave's speed can be calculated by dividing the distance the pulse travels by the time it takes.

The speed of the wave can be changed. If you pull harder on the rope, the pulse moves faster; the speed increases as the tension in the rope increases. The speed also depends on the mass of the rope; a rope with more mass per

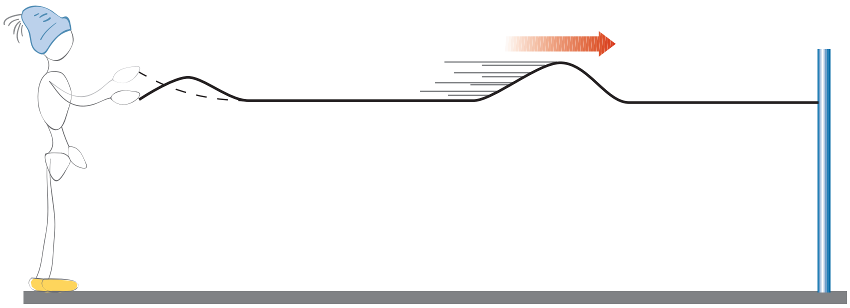


Figure 15-9 While pieces of the rope vibrate up and down, the wave moves along the rope.

unit length has a slower wave speed. Surprisingly, the amplitude of the pulse does not have much effect on the speed.

These observations make sense if we consider the vibrations of a small portion of the rope. The piece of rope is initially at rest and moves as the leading edge of the pulse arrives. How fast the rope returns to its equilibrium position determines how the pulse passes through the region (and hence, the speed of the pulse). The more massive the rope, the more sluggishly it moves. Also, if the rope is under a larger tension, the restoring forces on the piece of rope are larger and cause it to return to its equilibrium position more quickly.

FLAWED REASONING

A physics teacher has offered his class a prize if they can send a transverse pulse down a long spring and then send a second pulse down the same spring in such a manner as to catch up with the first pulse. Three students have taken up the challenge.

Trever: "I will make the first pulse with a slow movement of my hand and then make a second pulse with a very quick jerk on the spring. That should send the second pulse down the spring at a quicker speed."

Lindzee: "I think the amplitude of the pulse is what matters, not how fast you move your hand. Send the first pulse down with a big amplitude and then send the second pulse down with a small amplitude."

Courtnee: "The textbook claims that pulse speeds don't depend on how the pulse was created but only on the tension and the mass density of the spring. We can't change the mass density after we send the first pulse, but we could tighten the spring. Send the first pulse and then pull the spring tighter before we send the second pulse."

All three students are wrong. **Find the flaws in their claims.**

ANSWER Courtnee correctly points out the flaws in her classmates' reasoning. The speed of a pulse down a stretched spring does not depend on the size or shape of the pulse or the manner in which it was created. Courtnee's suggestion of stretching the spring will indeed increase the speed of transverse pulses on the spring, but this will speed up *both* pulses. The physics teacher tricked them with an impossible challenge.

When a pulse hits the end that is attached to the post, it "bounces" off and heads back. This reflected pulse has the same shape as the incident pulse but is inverted, as shown in Figure 15-10. If the incident pulse is an "up" pulse (a **crest**), the reflected pulse is a "down" pulse (a **trough**). If the end of the rope is free to move up and down, the pulse still reflects, but no inversion takes place.

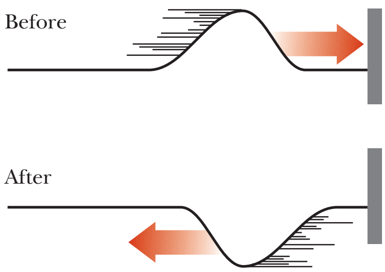


Figure 15-10 A wave pulse is inverted when it reflects from a fixed end. Note that the steep edge leads on the way in and on the way out.

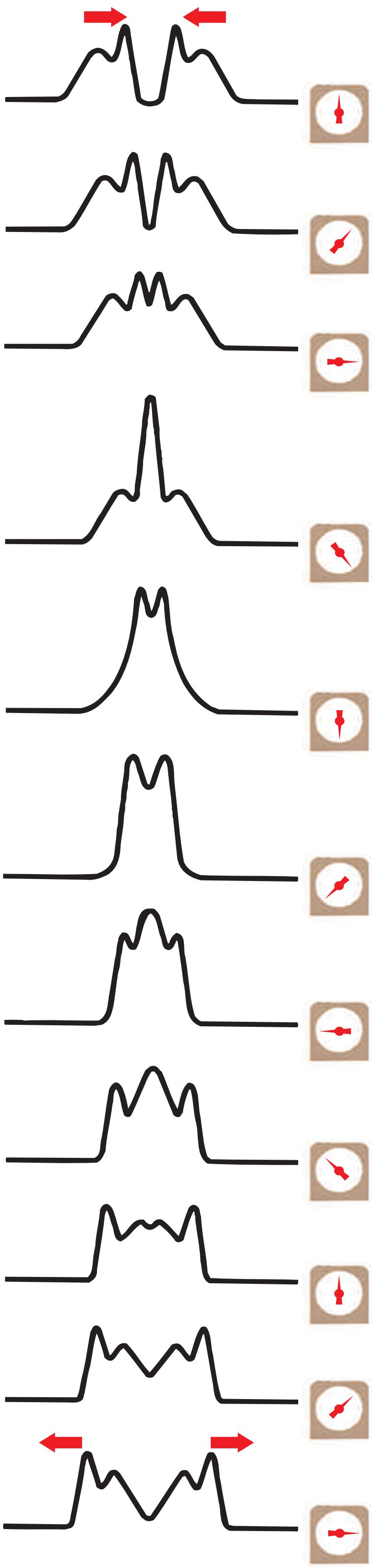


Figure 15-13 This time sequence shows that the superposition of two wave pulses yields shapes that are the sum of the individual shapes.

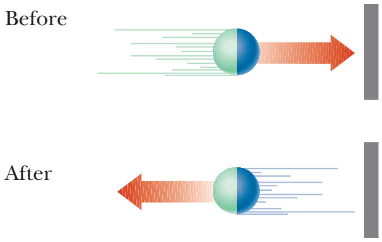


Figure 15-11 In contrast to a wave, the blue half of the ball leads on the way in and trails after reflection from the wall.

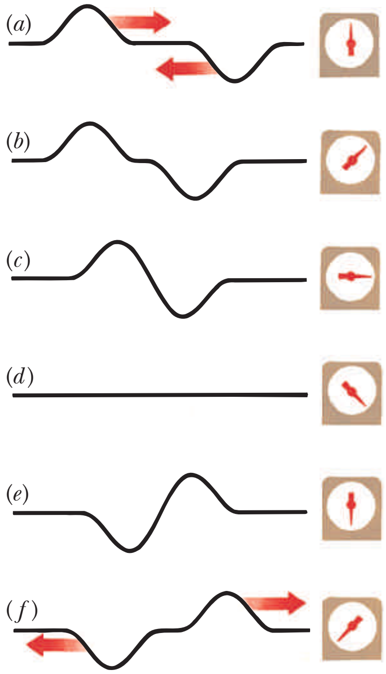


Figure 15-12 The two wave pulses on the rope pass through each other as if the other were not present.

What about the front and back of the wave pulse? To observe this you would generate a pulse that is not symmetric. The pulses shown in Figure 15-10 are steeper in front than in back. The steeper edge is away from you when the pulse moves down the rope and toward you when the reflected pulse returns. The leading edge continues to lead.

These inversions contrast with the behavior of a ball when it "reflects" from a wall. If the ball is not spinning, the top of the ball remains on top, but the leading edge is interchanged. Figure 15-11 shows that the blue half leads before the collision, whereas the green half leads afterward.

Superposition

Suppose you send a crest down the rope and, when it reflects as a trough, you send a second crest to meet it. An amazing thing happens when they meet. The waves pass through each other as if the other were not there. This is shown in Figure 15-12. Each pulse retains its own shape, clearly demonstrating that the pulses are not affected by the "collision." A similar thing happens when you throw two pebbles into a pond. Even though the wave patterns overlap, you can still see a set of circular patterns move outward from *each* splash.

In contrast, imagine what would happen if two particles—say, two Volkswagens—were to meet. Particles don't exhibit this special property of waves. It would certainly be a strange world if waves did not pass through each other. Two singers singing at the same time would garble each other's music, or the sounds from one might bounce off those from the other.

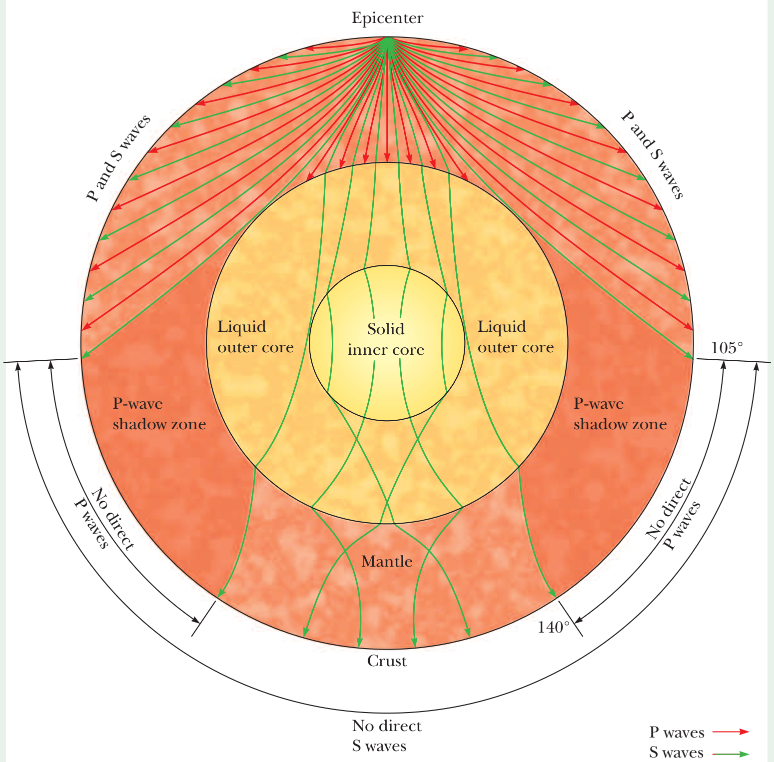
During the time the wave pulses pass through each other, the resulting disturbance is a combination of the individual ones; it is a **superposition** of the pulses. As shown in Figure 15-13, the distance of the medium from the equilibrium position, the **displacement,** is the algebraic sum of the displacements of the individual wave pulses. If we consider displacements above the equilibrium position as positive and those below as negative, we can obtain the shape of the resultant disturbance by adding these numbers at each location along the rope.

Everyday Physics | *Probing Earth*

Imagine drawing a circle to represent Earth. Further, imagine drawing a dot to show how far Earth's interior has been explored by direct drilling and sampling techniques. Where would you place the dot? The dot should be placed on the original circle. Earth is about 6400 kilometers (4000 miles) in radius, and we have drilled into its interior only about 12.2 kilometers, less than 0.2% of the distance to the center. Therefore, we must learn about Earth's interior using indirect means such as looking at signals from explosions and earthquakes.

Three kinds of wave are produced in an earthquake. One type travels along the surface, and the other two travel through Earth's interior; one of the interior waves is a longitudinal wave, and the other is a transverse wave. These waves move outward in all directions from the earthquake site and are received at numerous earthquake-monitoring sites around the world. The detection of these waves and their arrival times provides clues about Earth's interior.

Two major things happen to the waves: First, partial reflections occur at boundaries between distinctly different regions. Second, the waves change speed as the physical conditions—such as the elasticity and density—change. Changing a wave's speed usually results in the wave changing direction, a phenomenon known as refraction, which we will discuss in Chapter 18. As the waves go deeper into the interior, they speed up, causing them to change direction.



Cross section of Earth showing the paths of some waves produced by an earthquake.

The longitudinal waves are called the primary waves, or P waves, and are created by the alternating expansion and compression of the rocks near the source of the shock. This push–pull vibration can be transmitted through solids, liquids, and gases. P waves move with the highest speeds and therefore are the first to arrive at a seismograph station. P waves move at about 5 kilometers per second (11,000 miles per hour!) near the surface and speed up to about 7 kilometers per second toward the base of the upper crust.

The secondary waves, or S waves, are transverse waves. In this case the rock movement is perpendicular to the direction the wave is traveling. S waves travel through solids but cannot propagate through liquids and gases because fluids lack rigidity.

We wouldn't be able to infer much about Earth's interior if only one signal arrived at each site. There would be a number of paths that could account for the characteristics and timing of the signal. Fortunately, many sites receive multiple signals that allow large computers to piece the information together to form a model of Earth's interior. Information that is not received is also important. After an earthquake, many sites do not receive any transverse signals. This tells us that they are located in a shadow region behind a liquid core, as shown in the figure.

1. Would *transverse* or *longitudinal* waves be used to communicate with a submarine that was submerged in the ocean? Explain your choice.
2. What characteristic of all waves, transverse or longitudinal, explains the P wave shadow zone that is observed?

Source: H. Levin, *The Earth through Time* (Philadelphia: Saunders, 1992).

If two crests overlap, the disturbance is bigger than either one alone. A crest and a trough produce a smaller disturbance. If the crest and the trough are the same size and have symmetric shapes, they completely cancel at the instant of total overlap. A high-speed photograph taken at this instant yields a picture of a straight rope. This phenomenon is illustrated in Figure 15-12(d). This is not as strange as it may seem. If we take a high-speed photograph of a pendulum just as it swings through the equilibrium position, it would appear that the pendulum was not moving but simply hanging straight down. In either case, longer exposures would blur, showing the motion.

Periodic Waves

A rope moved up and down with a steady frequency and amplitude generates a train of wave pulses. All the pulses have the same size and shape as they travel down the rope. The drawing in Figure 15-14 shows a **periodic wave** moving to the right. New effects emerge when we examine periodic waves. For one thing, unlike the single pulse, periodic waves have a frequency. The frequency of the wave is the oscillation frequency of any piece of the medium.

An important property of a periodic wave is the distance between identical positions on adjacent wave pulses, called the **wavelength** of the periodic wave. This is the smallest distance for which the wave pattern repeats. It may be measured between two adjacent crests, or two adjacent troughs, or any two identical spots on adjacent pulses, as shown in Figure 15-15. The symbol used for wavelength is the Greek letter lambda λ.

The speed of the wave can be determined by measuring how far a particular crest travels in a certain time. In many situations, however, the speed is too fast, the wavelength too short, or the amplitude too small to allow us to follow the motion of a single crest. We then use an alternative procedure.

Suppose you take a number of photographs at the same frequency as the vertical vibration of any portion of the rope. You would find that all the pictures look the same. During the time the shutter of the camera was closed, each portion of the rope went through a complete cycle, ending in the position it had during the previous photograph. But this means that each crest moved from its original position to the position of the crest in front of it. That

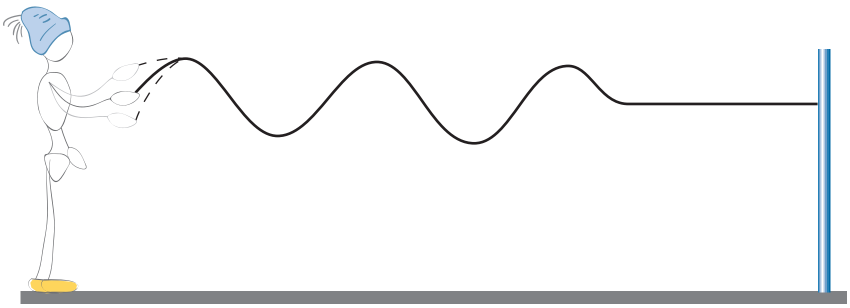


Figure 15-14 A periodic wave on a rope can be generated by moving the end up and down with a constant frequency.

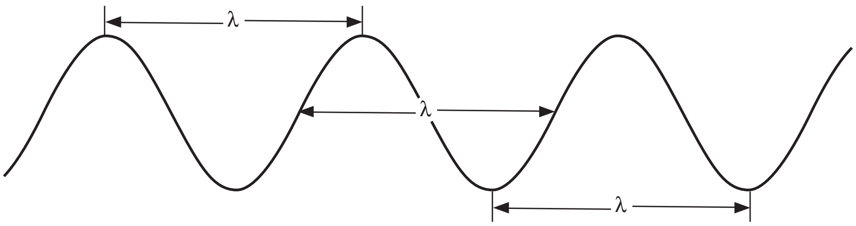


Figure 15-15 The wavelength of a periodic wave is the distance between any two identical spots on the wave.

is, the crest moved a distance equal to the wavelength λ. Because the time between exposures is equal to the period T, the wave's speed v is

$$v = \frac{\lambda}{T}$$

Because the frequency is just the reciprocal of the period, we can change the equation to read

$$v = \lambda f$$

◀ speed = wavelength × frequency

Although we developed this relationship for waves on a rope, there is nothing special about these waves. This relationship holds for all periodic waves, such as radio waves, sound waves, and water waves.

WORKING IT OUT *Speed of a Wave*

If you know any two of the three quantities in the wave equation, you can use this relationship to calculate the third. As an example, let's calculate the speed of a wave that has a frequency of 40 Hz and a wavelength of $\frac{3}{4}$ m. Multiplying the wavelength and the frequency gives us the speed:

$$v = \lambda f = (\tfrac{3}{4}\text{ m})(40\text{ Hz}) = 30\text{ m/s}$$

Q: If water waves have a frequency of 5 Hz and a wavelength of 8 cm, what is the wave speed?

A: $v = \lambda f =$ (8 cm)(5 Hz) = 40 cm/s.

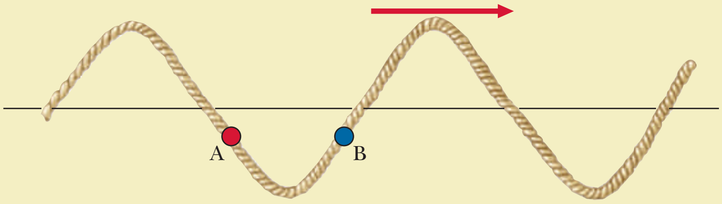
Standing Waves

When a periodic wave is confined, new effects emerge because of the superposition of the reflected waves with the original ones. Let's return to the example of a periodic wave moving down a rope toward a rigid post. When the periodic wave reflects from the post, it superimposes with the wave heading toward the post. The complete pattern results from the superposition of the original wave and reflections from both ends. In general, we get a complicated pattern with a small amplitude, but certain frequencies cause the rope to vibrate with a large amplitude. Figure 15-16 shows multiple images of a resonating rope. Although the superimposing waves move along the rope, they produce a resonant pattern that does not move along the rope. Because the pattern appears to stand still (in the horizontal direction), it is known as a **standing wave.**

It may seem strange that two identical waves traveling in opposite directions combine to produce a vibrational pattern that doesn't travel along the rope. We can see how this happens by using the superposition principle to find the results of combining the two traveling waves. Let's start at a time when the crests of the traveling wave moving to the right (the blue line in Figure 15-17) line up with the crests of the wave moving to the left (yellow line). (The blue and yellow lines lie on top of each other and are shown as a single green line.) Adding the displacements of the two traveling waves yields a wave that has the same basic shape, but twice the amplitude. This is shown by the black line in Figure 15-17(a).

FLAWED REASONING

The following question appears on the midterm exam: "A periodic wave is traveling to the right on a long, stretched rope. Two small pieces of yarn are tied to the rope, one at point A and the other at point B, as shown in the figure:



Draw an arrow for each piece of yarn, indicating the direction of its velocity when the picture was taken."

Brielle gives the following answer to this question: "Because the wave is moving to the right, the pieces of yarn must also be moving to the right. The wave is carried by the rope."

What is wrong with Brielle's reasoning, and what is the correct answer to the exam question?

ANSWER The wave is a transverse wave, meaning that the medium moves perpendicular to the direction of the wave. Therefore, the pieces of yarn can only move up or down. If we look at the wave at a slightly later time (when it has moved a little to the right), we see that the yarn at point A has moved upward and the yarn at point B has moved downward:

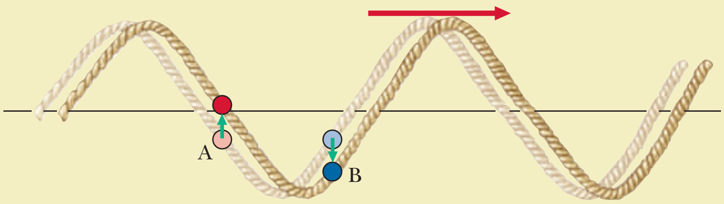


Figure 15-17(b) shows the situation a short time later. The blue wave has moved to the right, and the yellow wave has moved the same distance to the left. The superposition at this time produces a shape that still looks like one of the traveling waves but does not have as large an amplitude as before. A short time later, the crests of one wave line up with the troughs of the other. At this time the two waves cancel each other, and the rope is straight. Although the rope is straight at this instant, some parts of the rope are moving up while others are moving down. The remaining drawings in Figure 15-17 show how this pattern changes through the rest of the cycle as time progresses.

Notice that some portions of the rope do not move. Even though each traveling wave by itself would cause all pieces of the rope to move, the waves interfere to produce no motion at these points. Such locations are known as **nodes** and are located on the vertical lines indicated by N in Figure 15-17. The positions on the rope that have the largest amplitude are known as **antinodes** and are on the lines marked by A. Notice that the nodes and antinodes alternate and are equally spaced.

There is a relationship between the shape of the resonant pattern, or standing wave, and the moving periodic waves that superimpose to create it. The

Figure 15-16 A strobe drawing of a standing wave on a rope shows how the shape of the rope changes with time. The shape does not move to the left or right.

“wavelength” of the standing wave is equal to the wavelength of the underlying periodic wave. This can be seen in Figure 15-17.

Unlike the pendulum or the mass on a spring where there was only one resonant frequency, periodic waves that are confined have many different resonant frequencies. Strobe photographs of the standing wave with the lowest frequency, or **fundamental frequency,** show that the rope has shapes like those drawn in Figure 15-18. The images show how the shape of the rope changes during one-half cycle. At position 1 the rope has the largest possible crest. The displacement continually decreases until it becomes zero and the rope is straight (between positions 3 and 4). The rope’s inertia causes it to overshoot and form a trough that grows in size. At the end of the half cycle, the rope is in position 6 and beginning its upward journey. The process then repeats.

This pattern has the lowest frequency and thus the longest wavelength of the resonant modes. Notice that one-half wavelength is equal to the length of the rope, or the wavelength is twice the length of the rope. Because this is also the wavelength of the traveling waves, the longest resonant wavelength on a rope with nodes at each end is twice the length of the rope.

If we slowly increase the frequency of the traveling wave, the amplitude quickly decreases. The vibrational patterns are rather indistinct until the next resonant frequency is reached. This new resonant frequency has twice the frequency of the fundamental and is known as the second **harmonic.** Six shapes of the rope for this standing-wave pattern are shown in Figure 15-19. When the rope is low on the left side, it is high on the right, and vice versa. Because the rope has the shape of a full wavelength, the wavelength of the traveling waves is equal to the length of the rope. Note that this pattern has one more node and one more antinode than the fundamental standing wave.

We can continue this line of reasoning. A third resonant frequency can be reached by again raising the frequency of the traveling wave. This third harmonic frequency is equal to three times the fundamental frequency. This standing wave has three antinodes and four nodes, including the two at the ends of the rope. Other resonant frequencies occur at whole-number multiples of the fundamental frequency.

Remember that the product of the frequency and the wavelength is a constant. This is a consequence of the fact that the speeds of all waves on this rope are the same. Therefore, if we increase the frequency by some multiple while keeping the speed the same, the wavelength must decrease by the same multiple. The fundamental wavelength is the largest, and its associated frequency is the smallest. As we march through higher and higher frequencies, we get shorter and shorter wavelengths. The wavelengths of the higher harmonics are obtained by dividing the fundamental wavelength by successive whole

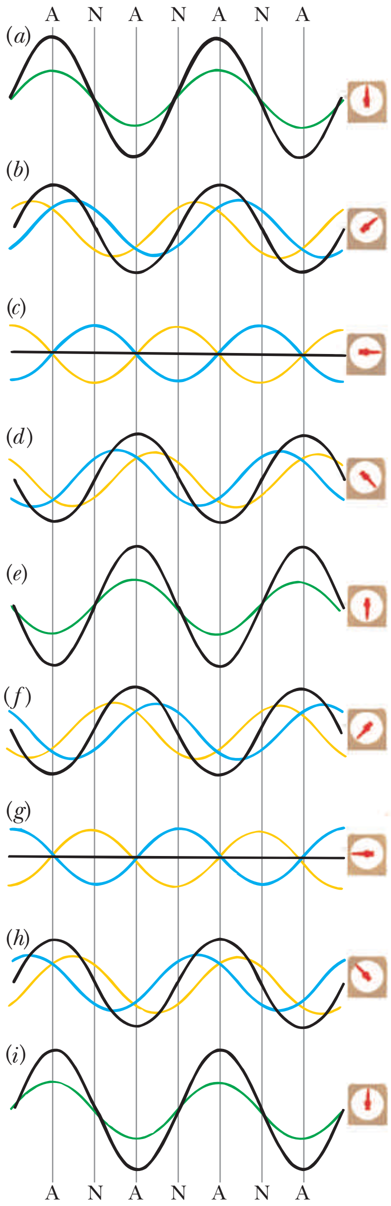


Figure 15-17 This set of strobe drawings shows how two traveling waves (the blue and yellow lines) combine to form a standing wave (the black line). Only the black line would be visible in a photograph.

Q: How does the distance between adjacent nodes or antinodes compare with the wavelength?

A: Because one antinode is up when the adjacent ones are down, each antinodal region corresponds to a crest or a trough. Therefore, the distance between adjacent antinodes or adjacent nodes is one-half wavelength. The distance between adjacent nodes and antinodes is one-quarter wavelength.

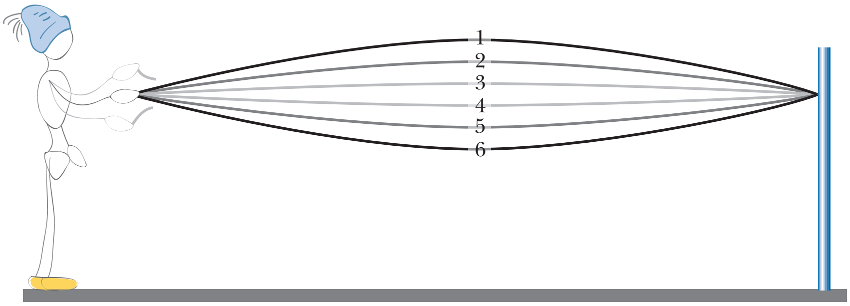


Figure 15-18 The shapes of a rope oscillating as a standing wave of the lowest frequency.

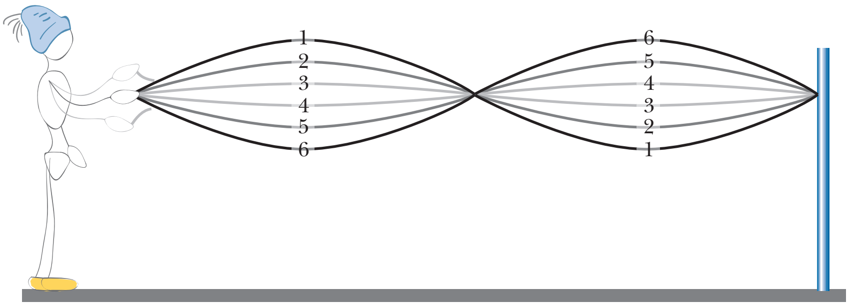


Figure 15-19 The shapes of a rope for a standing wave with the second resonant frequency.

numbers; the wavelength of the second harmonic is one-half the wavelength of the fundamental wavelength.

Q: How does the wavelength of the third harmonic compare with the length of the rope?

A: The wavelength of the third harmonic is one-third the length of the fundamental wavelength. Because the fundamental wavelength is twice the length of the rope, the wavelength of the third harmonic would be two-thirds the length of the rope.

Interference

Standing waves on a rope are an example of the superposition, or **interference,** of waves in one dimension. If we use a two-dimensional medium—say, the surface of water—we can generate some new effects.

Suppose we use two wave generators to create periodic waves on the surface of water in a ripple tank like the one in Figure 15-20(a). Because the two waves travel in the same medium, they have the same speed. We also assume that the two sources have the same frequency and that they are **in phase;** that is, both sources produce crests at the same time, troughs at the same time, and so on. The superposition of these waves creates the interference pattern shown in the photograph and drawing of Figure 15-20. The bright regions are produced by the crests, whereas the dark regions are produced by the troughs.

In some places, crest meets crest to form a supercrest, and one-half period later, trough meets trough to form a supertrough. This meeting point is a region of large amplitude; the two waves form antinodal regions. In other places, crest and trough meet. Here, if the two waves have about the same amplitude, they cancel each other, resulting in little or no amplitude; the two waves form nodal regions.

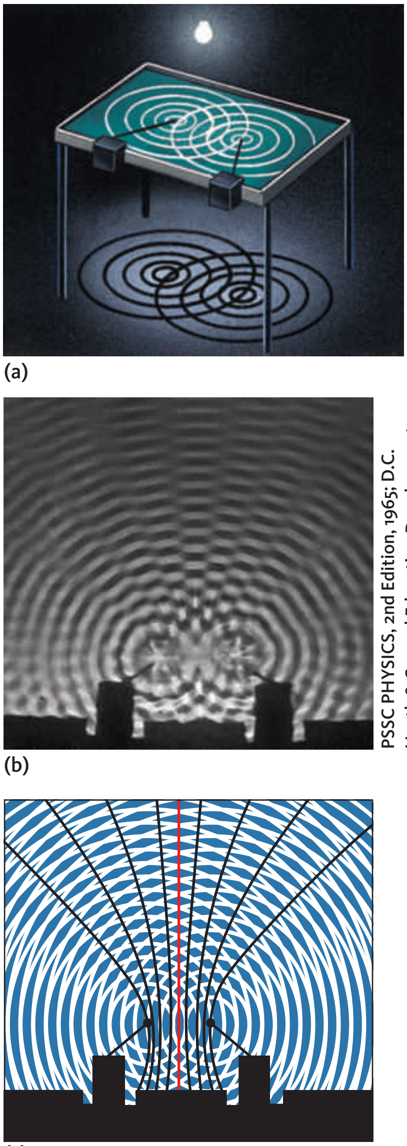
Because of the periodic nature of the waves, the nodal and antinodal regions have fixed locations. These stationary interference patterns can be observed only if the two sources emit waves of the same frequency; otherwise, one wave continually falls behind the other, and the relationships between the two waves change. The two wave sources do not have to be in phase; there can be a time delay between the generation of crests by one source and the other as long as the time delay is constant. For simplicity we usually assume that this time delay is zero; that is, the two sources are in phase.

The regions of crests and troughs lie along lines. One such antinodal line lies along the perpendicular to the midpoint of the line joining the two sources. This is the vertical red line in Figure 15-20(c). This central antinodal line is the same distance from the two sources. Therefore, crests generated at the same time at the two sources arrive at the same time at this midpoint to form supercrests. Similarly, two troughs arrive together, creating a supertrough.

Consider a point *P* off to the right side of the central line, as shown in Figure 15-21. Although nothing changes at the sources, we get a different result. Crests from the two sources no longer arrive at the same time. Crests from the left-hand source must travel a greater distance and therefore take longer to get to *P*. The amount of delay depends on the difference in the two path lengths.

If the point *P* is chosen such that the distances to the sources differ by an amount equal to one-half wavelength, crests overlap with troughs and troughs overlap with crests at point *P*. The waves cancel. There are many points that have this path difference. They form nodal lines that lie along each side of the central line, as shown by the black lines in Figure 15-20(c). An antinodal line occurs when the path lengths differ by one wavelength; the next nodal line when the paths differ by $1\frac{1}{2}$ wavelengths, and so on.

The photograph in Figure 15-22 shows the interference pattern for water waves with a longer wavelength than those in Figure 15-20. The nodal lines are now more widely spaced for the same source separation. Therefore, longer wavelengths produce wider patterns. Actually, the width of the pattern depends on the relative size of the wavelength and the source separation. As the ratio of the wavelength to the separation gets bigger, the nodal lines spread out. If the wavelength is much larger than the separation, the pattern is essentially that of a single source, whereas if it is much smaller, the nodal lines are so close together they cannot be seen.



PSSC PHYSICS, 2nd Edition, 1965; D.C. Heath & Co. and Education Development Center, Inc., Newton, MA.

Figure 15-20 (a) A light bulb above a ripple tank produces light and dark lines on the floor due to the water waves. (b) The interference pattern produced by two point sources of the same wavelength and phase. (c) The locations of the nodal lines in this pattern are shown in black; the central antinodal line is shown in red.

Diffraction

In the photographs in Figure 15-23, periodic water waves move toward a barrier. We see that the waves do not go straight through the opening in the barrier but spread out behind the barrier. This bending of a wave is called **diffraction** and is definitely not a property of particles. If a BB gun is fired repeatedly through an opening in a barrier, the pattern it produces is a precise "shadow" of the opening if we assume that no BBs bounce off the opening's edges.

Are You On the Bus?

Q: Would the central line still be an antinodal line if the two sources were completely out of phase—that is, if one source generates a crest at the same time as the other generates a trough?

A: The central line would now be a nodal line because crests and troughs would arrive at the same time.

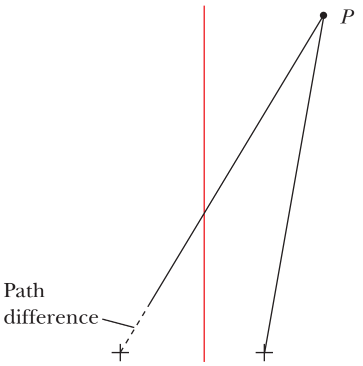
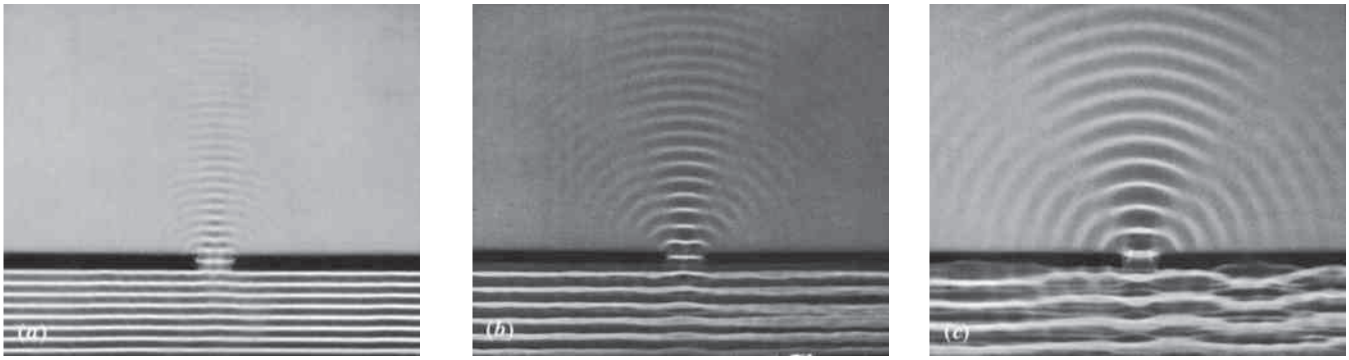


Figure 15-21 Whether the region at *P* is a nodal or antinodal region depends on the difference in the path lengths from the two sources.

Images not available due to copyright restrictions



PSSC PHYSICS, 2nd Edition, 1965; D.C. Heath & Co. and Education Development Center, Inc., Newton, MA. (all)

Figure 15-23 Ripple tank patterns of water moving upward and passing through a narrow barrier. Note that the amount of diffraction increases as the wavelength gets longer.

Courtesy of Sabina Zigman/Benjamin Cardozo High School, and by perm of PHYSICS TEACHER, vol.37, 1/99, p.55

The waves are diffracted as they pass through the openings in the seawall, producing an interesting shape at the beach.

The amount of diffraction depends on the relative sizes of the wavelength and the opening. If the wavelength is much smaller than the opening, very little diffraction is evident. As the wavelength gets closer to the size of the opening, the amount of diffraction gets bigger. In Figure 15-23(c) the opening and the wavelength are approximately the same size, and the diffraction is evident.

Notice that diffraction produces nodal and antinodal lines similar to those observed in the interference patterns from two point sources. In this case there is a broad central antinodal region with nodal lines on each side, and the diffraction pattern is created by different portions of the wave interfering with themselves. The spacing of these lines is determined by the ratio of the wavelength and the width of the opening.

Summary

Vibrations and oscillations are described by the length of time required for one cycle, the period T (or its reciprocal, the frequency f), and the amplitude of the vibration, the maximum distance the object travels from the equilibrium point. When vibrations are small, the period is independent of the amplitude. The pendulum and a mass hanging on a spring are examples of systems that vibrate.

All systems have a distinctive set of natural frequencies. A simple system such as a pendulum has only one natural frequency, whereas more complex systems have many natural frequencies. When a system is excited at a natural frequency, it resonates with a large amplitude.

Waves are vibrations moving through a medium; it is the wave (energy) that moves through the medium, not the medium itself. Transverse waves vibrate perpendicular to the direction of the wave, whereas longitudinal waves vibrate parallel to the direction of the wave. The speed of a periodic wave is equal to the product of its frequency and its wavelength, $v = \lambda f$.

Waves pass through each other as if the other were not there. When they overlap, the shape is the algebraic sum of the displacements of the individual waves. When a periodic wave is confined, resonant patterns known as standing waves can be produced. Portions of the medium that do not move are called nodes, whereas portions with the largest amplitudes are known as antinodes. The fundamental standing wave has the lowest frequency and the longest wavelength.

Two identical periodic-wave sources with a constant phase difference produce an interference pattern consisting of large-amplitude antinodal regions and zero-amplitude nodal regions. The spacing of the interference pattern depends on the relative size of the wavelength and the source separation.

Waves do not go straight through openings or around barriers but spread out. This diffraction pattern contains nodal and antinodal regions and depends on the relative sizes of the wavelength and the opening.

CHAPTER 15 *Revisited*

When waves move in a medium, the medium oscillates in place. No material is transported from one location to another; it is the disturbance that moves. Unlike with particles, when two waves pass through the same region at the same time, the individual disturbances are added together. Afterward, each wave retains its own identity.

Key Terms

amplitude The maximum distance from the equilibrium position that occurs in periodic motion.

antinode One of the positions in a standing-wave or interference pattern where there is maximum movement; that is, the amplitude is a maximum.

crest The peak of a wave disturbance.

cycle One complete repetition of a periodic motion. It may start anyplace in the motion.

diffraction The spreading of waves passing through an opening or around a barrier.

displacement In wave (or oscillatory) motion, the distance of the disturbance (or object) from its equilibrium position.

equilibrium position A position where the net force is zero.

frequency The number of times a periodic motion repeats in a unit of time. It is equal to the inverse of the period.

fundamental frequency The lowest resonant frequency for an oscillating system.

harmonic A frequency that is a whole-number multiple of the fundamental frequency.

in phase Describes two or more waves with the same wavelength and frequency that have their crests lined up.

interference The superposition of waves.

longitudinal wave A wave in which the vibrations of the medium are parallel to the direction the wave is moving.

node One of the positions in a standing-wave or interference pattern where there is no movement; that is, the amplitude is zero.

oscillation A vibration about an equilibrium position or shape.

period The shortest length of time it takes a periodic motion to repeat. It is equal to the inverse of the frequency.

periodic wave A wave in which all the pulses have the same size and shape. The wave pattern repeats itself over a distance of one wavelength and over a time of one period.

resonance A large increase in the amplitude of a vibration when a force is applied at a natural frequency of the medium or object.

spring constant The amount of force required to stretch a spring by one unit of length. The spring constant is measured in newtons per meter.

standing wave The interference pattern produced by two waves of equal amplitude and frequency traveling in opposite directions. The pattern is characterized by alternating nodal and antinodal regions.

superposition The combining of two or more waves at a location in space.

transverse wave A wave in which the vibrations of the medium are perpendicular to the direction the wave is moving.

trough A valley of a wave disturbance.

vibration An oscillation about an equilibrium position or shape.

wave The movement of energy from one place to another without any accompanying matter.

wavelength The shortest repetition length for a periodic wave. For example, it is the distance from crest to crest or trough to trough.

Questions and exercises are paired so that most odd-numbered are followed by a similar even-numbered.
Blue-numbered questions and exercises are answered in Appendix B.
indicates more challenging questions and exercises.
WebAssign **Many Conceptual Questions and Exercises for this chapter may be assigned online at WebAssign.**

Conceptual Questions

1. If the net force on a mass oscillating at the end of a vertical spring is zero at the equilibrium point, why doesn't the mass stop there?
2. If the restoring force on a pendulum is zero when it is vertical, why doesn't it quit swinging at this point?
3. A mass is oscillating up and down on a vertical spring. When the mass is above the equilibrium point and moving downward, in what direction does the net force on the mass act? When the mass is above the equilibrium point and moving upward, what is the direction of the net force on the mass? Explain.
4. A mass is oscillating up and down on a vertical spring. When the mass is below the equilibrium point and moving downward, what is the direction of its acceleration? Is the mass speeding up or slowing down? Explain.
5. A mass is oscillating up and down on a vertical spring. If the mass is increased, will the period of oscillation increase, decrease, or stay the same? Will the frequency increase, decrease, or stay the same? Explain.
6. A grandfather clock (with a pendulum) keeps perfect time on Earth. If you were to transport this clock to the Moon, would its period of oscillation increase, decrease, or stay the same? Would its frequency increase, decrease, or stay the same? Explain.
7. You hang a 1-kilogram block from a spring and find that the spring stretches 15 centimeters. What mass would you need to stretch the spring 45 centimeters?
8. Which spring would you expect to have the greater spring constant, the one in the suspension of your Chevy or the one in your watch? Why?
9. Assume that you pull the mass on a spring 1 centimeter from the equilibrium position, let go, and measure the period of the oscillation. Would you expect the period to be larger, the same, or smaller if you pulled the mass 2 centimeters from the equilibrium position? Why?
10. The amplitude of a real pendulum decreases because of frictional forces. How does the period of this real pendulum change?
11. What is the period of the hand on a clock that measures the seconds? What is its frequency?
12. What is the period of the hand on a clock that measures the minutes? What is its frequency?
13. Suppose your grandfather clock runs too fast. If the mass on the pendulum can be moved up or down, which way would you move it to adjust the clock? Explain your reasoning.
14. How does the natural frequency of a swing change when you move from sitting down to standing up?

15. You find that the exhaust system on your 1979 Chrysler Cordoba tends to rattle loudly when the tachometer, which measures the engine's frequency, reads 2000 rpm. It is relatively quiet at frequencies above or below 2000 rpm. Use the concept of resonance to explain this.

16. Why do soldiers "break step" before crossing a suspension bridge?

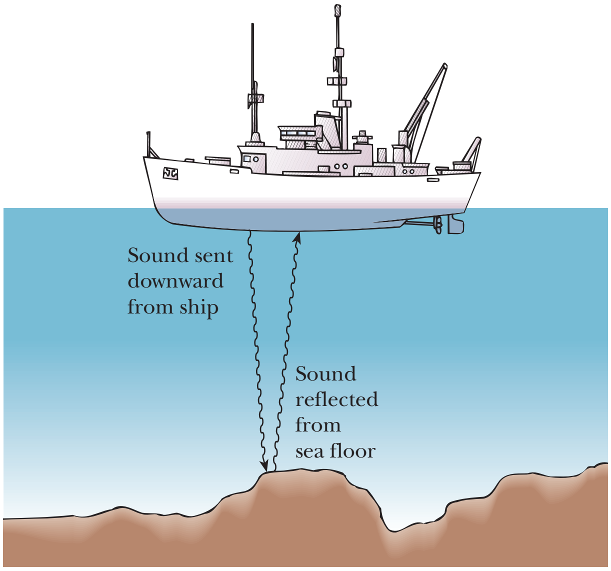
17. You hold one end of a spring in your hand and hang a block from the other end. After lifting the block up slightly and releasing it, you find that it oscillates up and down at a frequency of 2 hertz. At which of the following frequencies could you jiggle your hand up and down and produce resonance: 5 hertz, 4 hertz, 1.5 hertz, 1 hertz, or 0.5 hertz?

18. You stand to the side of the low point of a child's swing and always push the child in the same direction. Which of the following multiples of the fundamental frequency will not produce resonance: $\frac{1}{3}$, $\frac{1}{2}$, 1, or 2?

19. When you yell at your friend, are the air molecules that strike his ear the same ones that were in your lungs? Explain.

20. What is being transported along a clothesline when a wave moves from one end to the other?

21. Sonar devices use underwater sound to explore the ocean floor. Would you expect sonar to be a longitudinal or a transverse wave? Explain.



22. You fasten one end of a long spring to the base of a wall and stretch it out along the floor, holding the other end in your hand. Describe how you would generate a transverse pulse on the spring. Describe how you would generate a longitudinal pulse on the spring.

23. Is it possible for a shout to overtake a whisper? Explain.

24. You generate a small transverse pulse on a long spring stretched between a doorknob and your hand. How could you generate a second pulse that would overtake the first pulse?

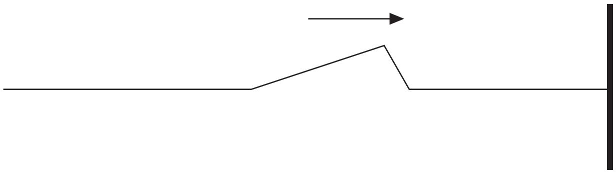
25. Which one or more of the following properties affect the speed of waves along a rope: amplitude of the pulse, shape of the pulse, tension in the rope, or the mass per unit length of the rope? Why?

26. You move your hand up and down to send a pulse along a long spring stretched between a doorknob and your hand. Which of the following would generate a slower-traveling pulse: Moving your hand the same distance as before, but more slowly; moving your hand a smaller distance at the same speed as before; or moving closer to the doorknob to decrease the tension in the spring?

27. You send a pulse of amplitude 5 centimeters down the right side of a spring. A moment later you send an identical pulse on the same side. The first pulse reflects from the fixed end and returns along the spring. When the reflected pulse meets the second pulse, will the resulting amplitude be less than, equal to, or greater than 5 centimeters? Explain your reasoning.

28. Imagine that the string in Figure 15-14 is tied to the pole with a loose loop such that the end is free to move up and down. A pulse of amplitude 10 centimeters is sent down the top of the string, and a moment later a second identical pulse is sent, also on the top. The first pulse reflects from the free boundary and returns along the string. When the reflected pulse meets the second pulse, will the resulting amplitude be less than, equal to, or greater than 10 centimeters? Explain your reasoning.

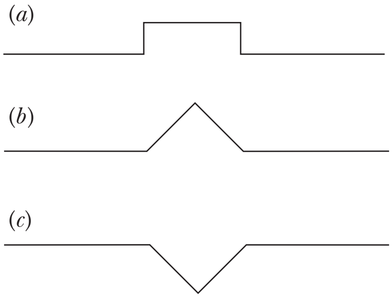
29. The pulse in the following figure is traveling on a string



to the right toward a fixed end. Draw the shape of the pulse after it reflects from the boundary.

30. A pulse in the shape of a crest is sent from left to right along a stretched rope. A trough travels in the opposite direction so that the pulses meet in the middle of the rope. Would you expect to observe a crest or a trough arrive at the right-hand end of the rope? Explain.

31. If shapes (a) and (b) in the following figure correspond to idealized wave pulses on a rope, what shape is produced when they completely overlap?



32. Repeat Question 31 for shapes (a) and (c).

33. Which of the following properties are meaningful for periodic waves but not for single pulses: frequency, wavelength, speed, amplitude?

34. In the following list of properties of periodic waves, which one is independent of the others: frequency, wavelength, speed, amplitude?

35. Two waves have the same speed but one has twice the frequency. Which wave has the longer wavelength? Explain.

36. If the frequency of a periodic wave is cut in half while the speed remains the same, what happens to the wavelength?

37. If the speed of a periodic wave doubles while the period remains the same, what happens to the wavelength?

38. What happens to the wavelength of a periodic wave if both the speed of the wave and the frequency are cut in half?

39. Travelers spaced 10 feet apart are all walking at 3 mph relative to a moving sidewalk. When the moving sidewalk ends, they continue to walk at 3 mph. An observer standing next to the moving sidewalk notes that the travelers are passing by at a frequency of 1 hertz. A second observer stands just beyond the end of the moving sidewalk and notes the frequency at which the travelers pass.

Would this frequency be greater than, equal to, or less than 1 hertz? Is the spacing between the travelers after leaving the moving sidewalk greater than, equal to, or less than 10 feet? Explain.

40. A waterproof electric buzzer has a membrane that vibrates at a constant frequency of 440 hertz. The buzzer is placed in a bucket of water. Knowing that the speed of sound is much greater in water than in air, will the frequency of the sound heard in the air be greater than, equal to, or less than 440 hertz? Will the wavelength of the sound in air be greater than, equal to, or less than what it was in the water? Explain. (*Hint:* Review Question 39 and think of the travelers as the wave crests.)

41. Draw a diagram to represent the standing-wave pattern for the third harmonic of a rope fixed at both ends. How many antinodes are there?

42. Draw a diagram to represent the standing-wave pattern for the fourth harmonic of a rope fixed at both ends. How many nodes are there?

43. How much higher is the frequency of the fifth harmonic on a rope than the fundamental frequency?

44. How much higher is the frequency of the sixth harmonic on a rope than that of the second?

45. How many antinodes are there when a rope fixed at both ends vibrates in its third harmonic?

46. How many nodes are there when a rope fixed at both ends vibrates in its fourth harmonic?

47. Standing waves can be established on a rope that is fixed on one end but free to slide up and down a pole on the other. The fixed end remains a node, while the free end must be an antinode. Draw diagrams to represent the standing-wave patterns for the two lowest frequencies.

48. How does the fundamental wavelength of standing waves on a string with one end fixed and the other free compare to the fundamental wavelength if the same string is held with both ends fixed?

49. How does the wavelength of the fourth harmonic on a rope with both ends fixed compare with the length of the rope?

50. How does the wavelength of the fourth harmonic on a rope with both ends fixed compare with that of the second harmonic?

51. A longitudinal standing wave can be established in a long aluminum rod by stroking it with rosin on your fingers. If the rod is held tightly at its midpoint, what is the wavelength of the fundamental standing wave? Assume that there are antinodes at each end of the rod and a node where the rod is held.

52. What is the wavelength of the fundamental standing wave for the rod in Question 51 if it is held midway between the center and one end? Will the resulting pitch be higher or lower than when the rod was held at its midpoint? Explain.

53. Two point sources produce waves of the same wavelength and are in phase. At a point midway between the sources, would you expect to find a node or an antinode? Explain.

54. Two point sources produce waves of the same wavelength and are completely out of phase (that is, one produces a crest at the same time as the other produces a trough). At a point midway between the sources, would you expect to find a node or an antinode? Why?

55. What happens to the spacing of the antinodal lines in an interference pattern when the two sources are moved farther apart? Explain.

56. As you increase the frequency, what happens to the spacing of the nodal lines in an interference pattern produced by two sources? Explain.

Courtesy of VWR Corporation

57. An interference pattern is produced in a ripple tank. As the two sources are brought closer together, does the separation of the locations of maximum amplitude along the far edge of the tank decrease, increase, or remain the same? Why?

58. As the frequency of the two sources forming an interference pattern in a ripple tank increases, does the separation of the locations of minimum amplitude along the far edge of the tank increase, decrease, or remain the same? Why?

59. What happens to the spacing of the antinodal lines in an interference pattern when the two slits are moved farther apart? Explain.

60. As you increase the frequency, what happens to the spacing of the nodal lines in a diffraction pattern? Explain.

Exercises

61. If a mass on a spring takes 6 s to complete two cycles, what is its period?

62. If a mass on a spring has a frequency of 4 Hz, what is its period?

63. A Foucault pendulum with a length of 9 m has a period of 6 s. What is its frequency?

64. A mass on a spring bobs up and down over a distance of 30 cm from the top to the bottom of its path twice each second. What are its period and amplitude?

65. A spring hanging from the ceiling has an unstretched length of 80 cm. A mass is then suspended at rest from the spring, causing its length to increase to 89 cm. The mass is pulled down an additional 3 cm and released. What is the amplitude of the resulting oscillation?

66. A mass oscillates up and down on a vertical spring with an amplitude of 4 cm and a period of 2 s. What total distance does the mass travel in 10 s?

67. What is the period of a 0.4-kg mass suspended from a spring with a spring constant of 40 N/m?

68. A boy with a mass of 50 kg is hanging from a spring with a spring constant of 200 N/m. With what frequency does the boy bounce up and down?

69. By what factor would you have to increase the mass to double the period for a mass on a spring?

70. By what factor would you have to increase the spring constant to triple the frequency for a mass on a spring?

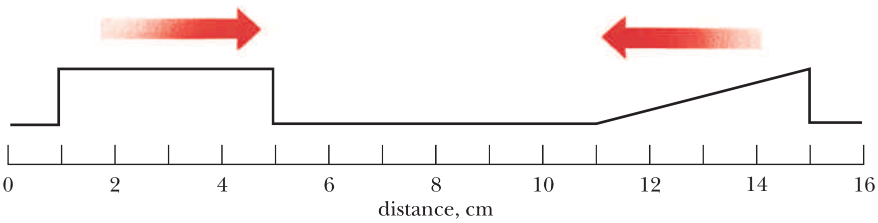
71. A pendulum has a length of 5 m. What is its period?

72. A girl with a mass of 40 kg is swinging from a rope with a length of 2.5 m. What is the frequency of her swinging?

73. The highly idealized wave pulses shown in the figure below at a time equal to zero have the same amplitudes and travel at 1 cm/s. Draw the shape of the rope at 2, 4, 5, and 8 s.

74. Work Exercise 73 but change the rectangular pulse from a crest to a trough.

75. A train consisting of identical 10-m boxcars passes you such that 25 boxcars pass you each minute. Find the speed of the train.



EXERCISE 73

76. You observe that 25 crests of a water wave pass you each minute. If the wavelength is 10 m, what is the speed of the wave?

77. A periodic wave on a string has a wavelength of 25 cm and a frequency of 3 Hz. What is the speed of the wave?

78. If the breakers at a beach are separated by 5 m and hit shore with a frequency of 0.3 Hz, at what speed are they traveling?

79. What is the distance between adjacent crests of ocean waves that have a frequency of 0.2 Hz if the waves have a speed of 3 m/s?

80. Sound waves in iron have a speed of about 5100 m/s. If the waves have a frequency of 400 Hz, what is their wavelength?

81. For sound waves, which travel at 343 m/s in air at room temperature, what frequency corresponds to a wavelength of 1 m?

82. What is the period of waves on a rope if their wavelength is 0.8 m and their speed is 2 m/s?

83. A rope is tied between two posts separated by 3 m. What possible wavelengths will produce standing waves on the rope?

84. A 3-m-long rope is tied to a thin string so that one end is essentially free. What possible wavelengths will produce standing waves on this rope?

85. What is the fundamental frequency on a 6-m rope that is tied at both ends if the speed of the waves is 18 m/s?

86. Tweety Bird hops up and down at a frequency of 0.5 Hz on a power line at the midpoint between the poles, which are separated by 20 m. Assuming Tweety is exciting the fundamental standing wave, find the speed of transverse waves on the power line.