25 VIBRATIONS AND WAVES

Objectives

- Describe the period of a pendulum. (25.1)
- Describe the characteristics and properties of waves. (25.2)
- Describe wave motion. (25.3)
- Describe how to calculate the speed of a wave. (25.4)
- Give examples of transverse waves. (25.5)
- Give an example of a longitudinal wave. (25.6)
- Explain what causes interference patterns. (25.7)
- Describe how a standing wave occurs. (25.8)
- Describe how the apparent frequency of waves change as a wave source moves. (25.9)
- Describe bow waves. (25.10)
- Describe sonic booms. (25.11)

discover!

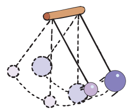
MATERIALS foam cup, water

EXPECTED OUTCOME Regions of still water, nodes, and regions of choppy water, antinodes, should be observable. This pattern is the result of the interference of traveling waves reflecting from the vibrating walls of the cup.

ANALYZE AND CONCLUDE

1. Students should observe regions of still water and regions of choppy water.
2. The pattern changes because the cup vibrates differently on different surfaces.
3. Yes, because waves travel in all media and interference is a characteristic of waves.

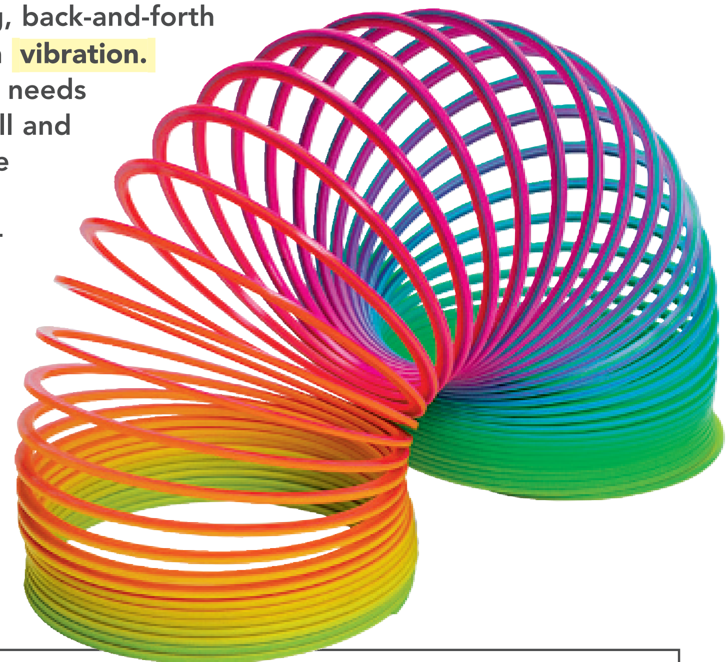
25 VIBRATIONS AND WAVES



THE BIG IDEA Waves transmit energy through space and time.

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

A disturbance that is transmitted progressively from one place to the next with no actual transport of matter is a **wave.** A wave cannot exist in one place but must extend from one place to another. Light and sound are both forms of energy that move through space as waves. This chapter is about vibrations and waves, and the following chapters continue with the study of sound and light.



discover!

What Are Standing Waves?

1. Fill a foam cup nearly to the top with water. Place the cup on a smooth, dry surface.
2. While applying a moderate downward pressure, drag the cup across the surface.
3. Adjust the downward pressure on the cup until a pattern of waves, called standing waves, appears on the surface of the water.
4. Now try to change the pattern by altering both the speed of the cup and the downward pressure.

Analyze and Conclude

1. **Observing** Describe the patterns that you produced on the surface of the water.
2. **Predicting** What do you think might happen if you were to drag the cup on a different kind of surface?
3. **Making Generalizations** Do you think standing waves can be produced in other media? Explain.

25.1 Vibration of a Pendulum

Suspend a stone at the end of a string and you have a simple pendulum. Pendulums like the one in Figure 25.1 swing back and forth with such regularity that they have long been used to control the motion of clocks. Galileo discovered that the time a pendulum takes to swing back and forth through small angles depends only on the length of the pendulum—the mass has no effect. The time of a back-and-forth swing of the pendulum is called the **period.** **The period of the pendulum depends only on the length of a pendulum and the acceleration of gravity.** [25.1]

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

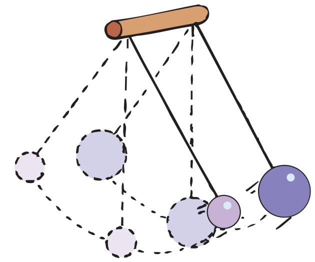


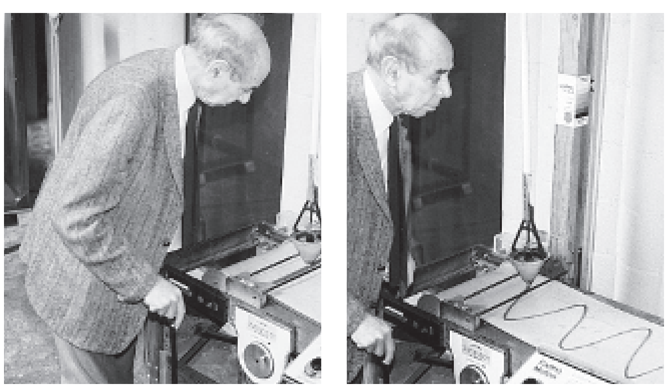
FIGURE 25.1 ▲
Two pendulums of the same length have the same period regardless of mass.

CONCEPT CHECK What determines the period of a pendulum?

25.2 Wave Description

The back-and-forth vibratory motion (often called oscillatory motion) of a swinging pendulum is called **simple harmonic motion.** [25.2] The pendulum bob filled with sand in Figure 25.2 exhibits simple harmonic motion above a conveyor belt. When the conveyor belt is stationary, the sand traces out a straight line. More interestingly, when the conveyor belt is moving at constant speed, the sand traces out a special curve known as a sine curve. A **sine curve** is a pictorial representation of a wave. **The source of all waves is something that vibrates.**

think!
What is the frequency in vibrations per second of a 100-Hz wave?
Answer: 25.2.1



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

25.1 Vibration of a Pendulum

Key Terms
period, vibration, waves

▶ **Teaching Tip** Distinguish between a simple pendulum (the bob is very small compared to the length of string) and a physical pendulum (the stick makes up a significant part of the mass). Explain that their rotational inertias are different.

Ask What principle of mechanics accounts for the different periods of pendulums of different lengths? *Rotational inertia*

Demonstration

Attach a small heavy weight to the end of a piece of string about 1 m long. Swing it to and fro: this is a simple pendulum. Identify frequency and period. Time how long the pendulum takes to make 10 complete cycles. Repeat to show that the result does not change from trial to trial. Divide the time by 10 to get the period. Add more mass to the end of the string without changing the overall length of the pendulum. Time 10 more cycles to show that weight does not affect the period.

CONCEPT CHECK The period of the pendulum depends only on the length of a pendulum and the acceleration of gravity.

Teaching Resources

- **Problem-Solving Exercises in Physics** *12-1, 12-2*
- **Laboratory Manual** *68, 69*
- **Probeware Lab Manual** *13*

25.2 Wave Description

Key Terms
simple harmonic motion, sine curve, crest, trough, amplitude, wavelength, frequency, hertz

▶ **Teaching Tip** Begin by tapping your lecture table or the chalkboard. Call attention to how frequently you tap and relate this to the term *frequency.* Call attention to the time interval between taps and relate this to the period. Establish the reciprocal relationship between frequency and period.

▶ **Teaching Tip** Move a piece of chalk up and down on the board, tracing and retracing a vertical straight line. Call attention to how "frequently" you oscillate the chalk, again tying this to the definition of frequency. Discuss the idea of displacement and amplitude (maximum displacement). With appropriate motions, show different frequencies and different amplitudes. Then do the same while walking across the front of the board tracing out a sine wave. Repeat showing waves of different wavelengths.

▶ **Teaching Tip** Point out that since a vibration is also called a cycle, one hertz is also one cycle per second.

(1 kHz = 10^3 cycles/s;

1 MHz = 10^6 cycles/s)

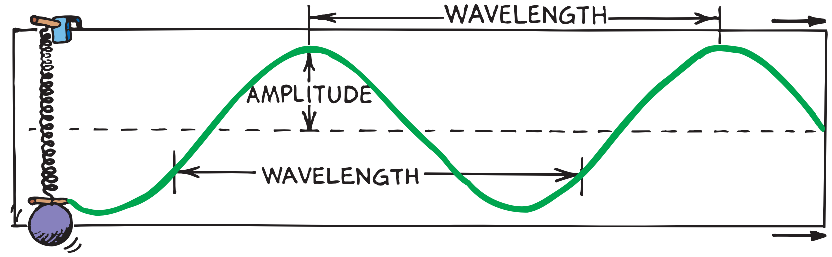
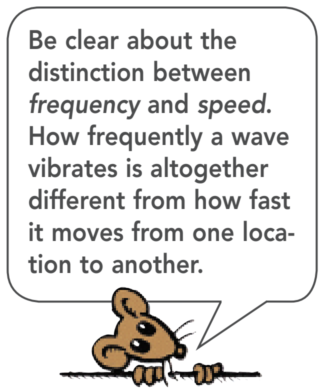


FIGURE 25.3 ▶
A sine curve is a pictorial representation of a wave.

The Parts of a Wave A weight attached to a spring undergoes vertical simple harmonic motion as shown in Figure 25.3. A marking pen attached to the bob traces a sine curve on a sheet of paper that is moving horizontally at constant speed. Like a water wave, the high points on a wave are called **crests.** The low points on a wave are called **troughs.** The straight dashed line represents the "home" position, or midpoint of the vibration. The term **amplitude** refers to the distance from the midpoint to the crest (or trough) of the wave. So the amplitude equals the maximum displacement from equilibrium.

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



Frequency The number of vibrations an object makes in a unit of time is an object's **frequency.** The frequency of a vibrating pendulum, or object on a spring, specifies the number of back-and-forth vibrations it makes in a given time (usually one second). A complete back-and-forth vibration is one cycle. If it occurs in one second, the frequency is one vibration per second or one cycle per second. If two vibrations occur in one second, the frequency is two vibrations or two cycles per second. The frequency of the vibrating source and the frequency of the wave it produces are the same.

The unit of frequency is called the **hertz** (Hz). A frequency of one cycle per second is 1 hertz, two cycles per second is 2 hertz, and so on. Higher frequencies are measured in kilohertz (kHz—thousands of hertz), and still higher frequencies in megahertz (MHz—millions of hertz) or gigahertz (GHz—billions of hertz). AM radio waves are broadcast in kilohertz, while FM radio waves are broadcast in megahertz; radar and microwave ovens operate at gigahertz. A station at 960 kHz broadcasts radio waves that have a frequency of 960,000 hertz. A station at 101 MHz broadcasts radio waves with a frequency of 101,000,000 hertz. As Figure 25.4 shows, these radio-wave frequencies are the frequencies at which electrons vibrate in the transmitting antenna of a radio station.

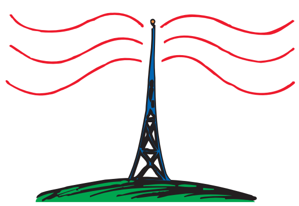


FIGURE 25.4 ▲
Electrons in the transmitting antenna of a radio station at 960 kHz on the AM dial vibrate 960,000 times each second and produce 960-kHz radio waves.

If the frequency of a vibrating object is known, its period can be calculated, and vice versa. Suppose, for example, that a pendulum makes two vibrations in one second. Its frequency is 2 Hz. The time needed to complete one vibration—that is, the period of vibration—is 1/2 second. Or if the vibration period is 3 Hz, then the period is 1/3 second. As you can see below, frequency and period are inverses of each other:

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

CONCEPT CHECK What is the source of all waves?

25.3 Wave Motion

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

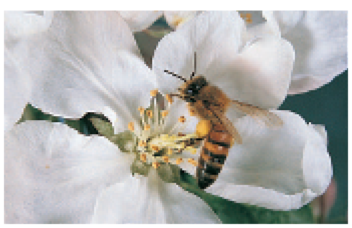
When energy is transferred by a wave from a vibrating source to a distant receiver, there is no transfer of matter between the two points. To see this, think about the very simple wave produced when one end of a horizontally stretched string is shaken up and down as shown in Figure 25.5. After the end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

think!

The Sears Tower in Chicago sways back and forth at a frequency of about 0.1 Hz. What is its period of vibration?
Answer: 25.2.2

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

Link to ENTOMOLOGY



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

CONCEPT CHECK The source of all waves is something that vibrates.

Teaching Resources

- Reading and Study Workbook
- Transparency *50*
- Presentation*EXPRESS*
- Interactive Textbook

25.3 Wave Motion

Common Misconception
When a wave travels in a medium, the medium moves with the wave.

FACT As a wave travels through a medium, there is no transfer of matter.

▶ **Teaching Tip** Point out that if a leaf is floating in a pond as a wave passes, the leaf will move up and down with the water but will not move along with the wave.

Demonstration

Have a student hold one end of a stretched spring or a Slinky while you hold the other. Send transverse pulses along it, stressing the idea that the disturbance rather than the medium moves along the spring. Shake the spring and produce a sine wave. Then send a stretch and squeeze (elongation and compression) down the spring, showing a longitudinal pulse. Send a sequence of pulses and you have a wave. After some discussion, produce standing waves.

discover!

MATERIALS pen, paper, wide pan, water

EXPECTED OUTCOME In Part 1, students will create a pictorial representation of a wave. They will observe the same pattern as in Figure 25.2. In Part 2, students will actually make waves.

THINK, PART 1 The wavelength increases.

THINK, PART 2 The wavelength decreases.

CONCEPT CHECK The energy transferred by a wave from a vibrating source to a receiver is carried by a disturbance in a medium.

Teaching Resources

- Reading and Study Workbook
- Problem-Solving Exercises in Physics *13-1*
- Presentation*EXPRESS*
- Interactive Textbook

FIGURE 25.6 ▶
A circular water wave in a still pond moves out from the center in an expanding circle.

Go Online SCILINKS NSTA

For: Links on wave motion
Visit: www.SciLinks.org
Web Code: csn – 2503

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

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

CONCEPT CHECK How does a wave transfer energy?

discover!

Making Waves

Part 1

1. Oscillate a marking pen back and forth across a piece of paper as you slowly pull the paper in a direction perpendicular to your oscillation.
2. Repeat Step 1, but pull the paper faster this time.
3. **Think** What happens to the wavelength of the curves when you pull the paper faster?

Part 2

1. Repeatedly dip your finger into a wide pan of water to make circular waves on the surface.
2. Repeat Step 1, but dip your finger more frequently.
3. **Think** What happens to the wavelength of the waves when you dip your finger more frequently?

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think!

If a water wave vibrates up and down two times each second and the distance between wave crests is 1.5 m, what is the frequency of the wave? What is its wavelength? What is its speed? *Answer: 25.4.1*

25.4 Wave Speed

The speed of a wave depends on the medium through which the wave moves. Sound waves, for example, move at speeds of about 330 m/s to 350 m/s in air (depending on temperature), and about four times faster in water. Whatever the medium, the speed, wavelength, and frequency of the wave are related. Consider the simple case of water waves, as shown in Figure 25.7. Imagine that you fix your eyes at a stationary point on the surface of water and observe the waves passing by this point. If you observe the distance between crests (the wavelength) and also count the number of crests that pass each second (the frequency), then you can calculate the horizontal distance a particular crest moves each second. For example, in Figure 25.7, one crest passes by the bird every second. The waves therefore move at 1 meter per second.

You can calculate the speed of a wave by multiplying the wavelength by the frequency. For example, if the wavelength is 3 meters and if two crests pass a stationary point each second, then 3 meters × 2 waves pass by in 1 second. The waves therefore move at 6 meters per second. In equation form, this relationship is written as

$$v = \lambda f$$

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

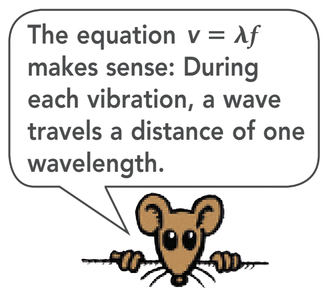
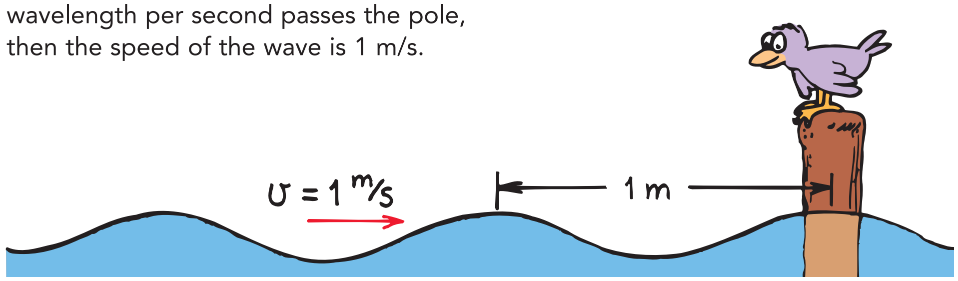


FIGURE 25.7 ▼
If the wavelength is 1 meter, and one wavelength per second passes the pole, then the speed of the wave is 1 m/s.



25.4 Wave Speed

▶ **Teaching Tip** Explain that the frequency of a vibrating source is the same as the frequency of the wave it produces.

▶ **Teaching Tip** Explain or derive wave speed: Speed = wavelength × frequency. Support this with the freight car example.

▶ **Teaching Tip** Have students calculate the wavelengths of their favorite local radio stations. Wavelength = speed/frequency. For example, 1000-kHz waves have wavelengths = (3×10^8 m/s)/(10^6 Hz) = 300 m. Surprisingly long!

Be sure to distinguish electromagnetic waves from longitudinal sound waves. Consider discussing Chapter 27 and Chapter 37 material here to lead into the family of electromagnetic waves. Show how electromagnetic waves are grouped according to their wavelengths and frequencies.

PAUL

Table 25.1 Sound Waves

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

think!

What is the wavelength of a 340-Hz sound wave when the speed of sound in air is 340 m/s?
Answer: 25.4.2

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

CONCEPT CHECK **How do you calculate the speed of a wave?**

do the math!

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

You can look at this problem in two ways, the Chapter 4 way and the Chapter 25 way.

From Chapter 4 recall:

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

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

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

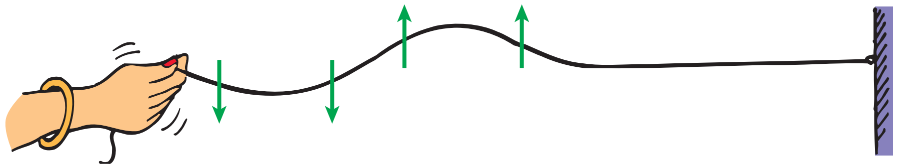
$$\begin{aligned} \text{wave speed} &= \text{wavelength} \times \text{frequency} \\ &= (10 \text{ m}) \times (2 \text{ Hz}) = 20 \text{ m/s} \end{aligned}$$

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

CONCEPT CHECK You can calculate the speed of a wave by multiplying the wavelength by the frequency.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**



◀ FIGURE 25.8
A person creates a transverse wave by shaking the free end of a rope up and down. The arrows represent the motion of the rope.

25.5 Transverse Waves

Suppose you create a wave along a rope by shaking the free end up and down, as shown in Figure 25.8. The motion of the rope is at right angles to the direction in which the wave is moving. Whenever the motion of the medium is at right angles to the direction in which a wave travels, the wave is a **transverse wave.** ✓ **Waves in the stretched strings of musical instruments and the electromagnetic waves that make up radio waves and light are transverse.**

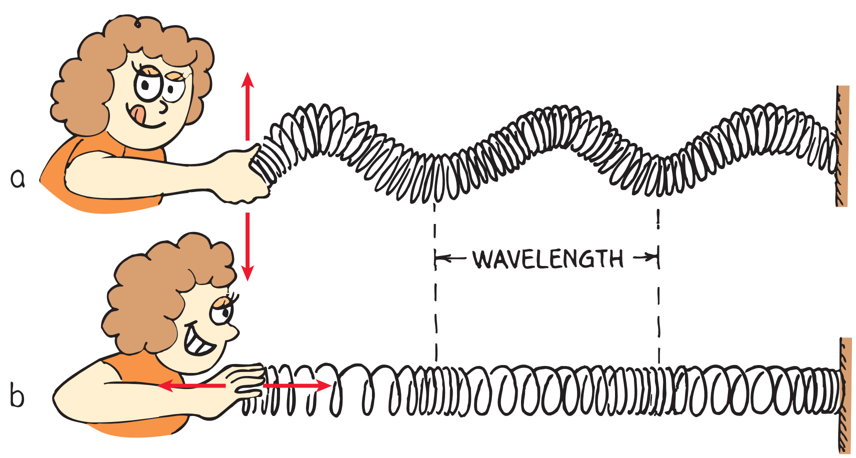
CONCEPT CHECK What are some examples of transverse waves?

25.6 Longitudinal Waves

Not all waves are transverse. Sometimes the particles of the medium move back and forth in the same direction in which the wave travels. When the particles oscillate parallel to or *along* the direction of the wave rather than at right angles to it, the wave is a **longitudinal wave.** ✓ **Sound waves are longitudinal waves.**

Both transverse and longitudinal waves can be demonstrated with a loosely-coiled spring, as shown in Figure 25.9. A transverse wave is demonstrated by shaking the end of a coiled spring up and down. A longitudinal wave is demonstrated by shaking the end of the coiled spring in and out. In this case we see that the medium vibrates parallel to the direction of energy transfer.

CONCEPT CHECK What is an example of a longitudinal wave?



◀ FIGURE 25.9
Transverse and longitudinal waves transfer energy from left to right.
a. When the end of a coiled spring is shaken up and down, a transverse wave is produced.
b. When it is shaken in and out, a longitudinal wave is produced.

25.5 Transverse Waves

Key Term
transverse wave

CONCEPT CHECK Waves in the stretched strings of musical instruments and the electromagnetic waves that make up radio waves and light are transverse.

25.6 Longitudinal Waves

Key Term
longitudinal wave

▶ **Teaching Tip** Allow students to play with large springs or Slinkys until they can demonstrate and explain the difference between transverse and longitudinal waves.

Ask **With respect to the direction of the wave's motion, how do the directions of vibrations differ for transverse and longitudinal waves?** *Perpendicular for transverse; parallel for longitudinal*

CONCEPT CHECK Sound waves are longitudinal waves.

Teaching Resources
- Reading and Study Workbook
- Transparency *51*
- Presentation*EXPRESS*
- Interactive Textbook

25.7 Interference

Key Terms
interference pattern, constructive interference, destructive interference, out of phase, in phase

▶ **Teaching Tip** Describe interference by drawing Figure 25.10 on the board. If you have a ripple tank, show the overlapping of water waves and interference.

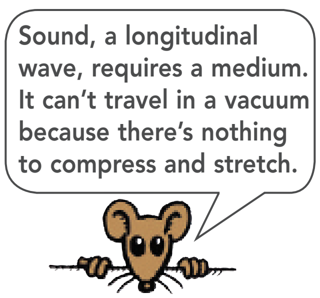
Physics on the Job

Seismologist
When an earthquake occurs, the sudden release of energy produces waves. Seismologists study and interpret those waves in order to determine the strength and location of the earthquake. They compare the speed, amplitude, and reception of primary longitudinal waves with secondary transverse waves. Because they understand how waves travel and the materials through which they pass, seismologists are able to describe earthquakes, learn about the composition of Earth, and possibly predict future earthquakes. Seismologists conduct research from university and government facilities, such as the National Earthquake Information Service (NEIS) in Colorado.

25.7 Interference

A material object such as a rock will not share its space with another rock. But more than one vibration or wave can exist at the same time in the same space. If you drop two rocks in water, the waves produced by each can overlap and form an interference pattern. An **interference pattern** is a regular arrangement of places where wave effects are increased, decreased, or neutralized. ✓ **Interference patterns occur when waves from different sources arrive at the same point—at the same time.**

In **constructive interference,** the crest of one wave overlaps the crest of another and their individual effects add together. The result is a wave of increased amplitude. As Figure 25.10a shows, this is called reinforcement. In **destructive interference,** the crest of one wave overlaps the trough of another and their individual effects are reduced. The high part of one wave simply fills in the low part of another. As Figure 25.10b shows, this is called cancellation.



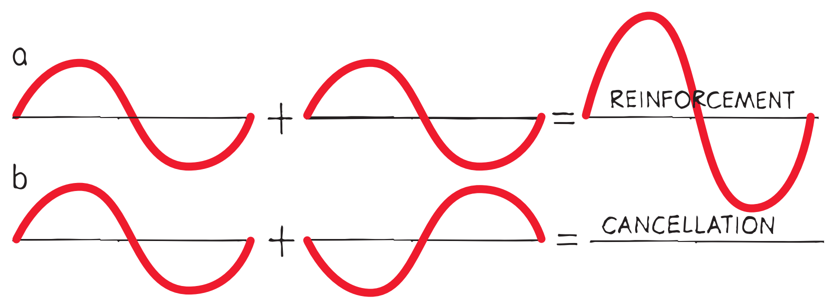


FIGURE 25.10 ▶
There are two types of wave interference. **a.** In constructive interference, the waves reinforce each other to produce a wave of increased amplitude. **b.** In destructive interference, the waves cancel each other and no wave is produced.

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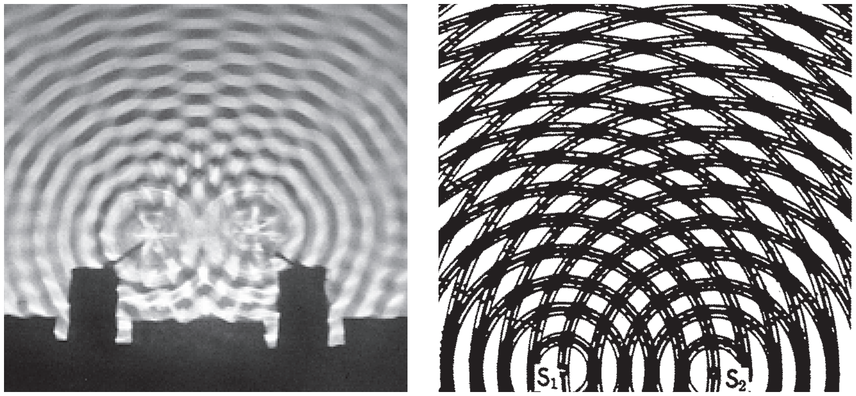


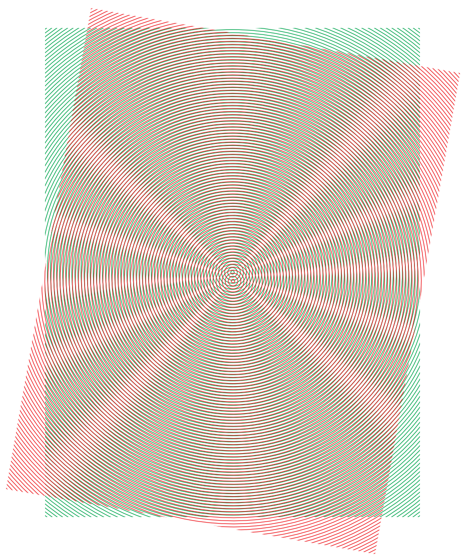
◀ **FIGURE 25.11**
a. Two overlapping water waves produce an interference pattern.
b. Overlapping concentric circles produce a pictorial representation of an interference pattern.

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

Interference patterns are nicely illustrated by the overlapping of concentric circles printed on a pair of clear sheets, as shown in Figures 25.11b and 25.12. When the sheets overlap with their centers slightly apart, a so-called *moiré pattern* is formed that is very similar to the interference pattern of water waves (or any kind of waves). A slight shift in either of the sheets produces noticeably different patterns. If a pair of such sheets is available, be sure to try this and see the variety of patterns for yourself.

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

FIGURE 25.12 ▼
A moiré pattern is very similar to an interference pattern.



CONCEPT CHECK What causes interference patterns?

▶ **Teaching Tip** Make a pair of transparencies of concentric circles. Superimpose them on your overhead projector and show the variety of interference patterns that result when their centers are displaced. One example is shown in Figure 25.12.

Ask Can waves overlap in such a way as to produce a zero amplitude? *Yes, that is the destructive interference characteristic of all waves.*

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

Teaching Resources

- **Reading and Study Workbook**
- **Laboratory Manual** ***71***
- **Presentation*EXPRESS***
- **Interactive Textbook**

25.8 Standing Waves

Key Terms
standing wave, node, antinode

▶ **Teaching Tip** Emphasize that a standing wave is the result of interference.

▶ **Teaching Tip** Use a long thin spring or a rope to demonstrate standing waves. Have students identify the nodes and come up close to inspect them. Change the frequency and show that only specific frequencies allow the creation of standing waves.

▶ **Teaching Tidbit** Figure 25.14a shows the lowest frequency of vibration of a standing wave—the *fundamental frequency*.

▶ **Teaching Tip** Point out that for a string free at one end and a tube open at one end and closed at the other end, standing waves form when odd integer multiples of quarter wavelengths fit into the vibrating medium. A soda-pop bottle is an example of a tube open at one end and closed at the other end.

CONCEPT CHECK A standing wave forms only if half a wavelength or a multiple of half a wavelength fits exactly into the length of the vibrating medium.

Teaching Resources
- **Reading and Study Workbook**
- **Problem-Solving Exercises in Physics** *13-3*
- **Transparency** *52*
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Question** *25-1*

think!

Is it possible for one wave to cancel another wave so that the combined amplitude is zero? Explain your answer.
Answer: 25.8

25.8 Standing Waves

If you tie a rope to a wall and shake the free end up and down, you will produce a wave in the rope. The wall is too rigid to shake, so the wave is reflected back along the rope to you. By shaking the rope just right, you can cause the incident (original) and reflected waves to form a standing wave. A **standing wave** is a wave that appears to stay in one place—it does not seem to move through the medium. Certain parts of a standing wave remain stationary. **Nodes** are the stationary points on a standing wave.

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

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

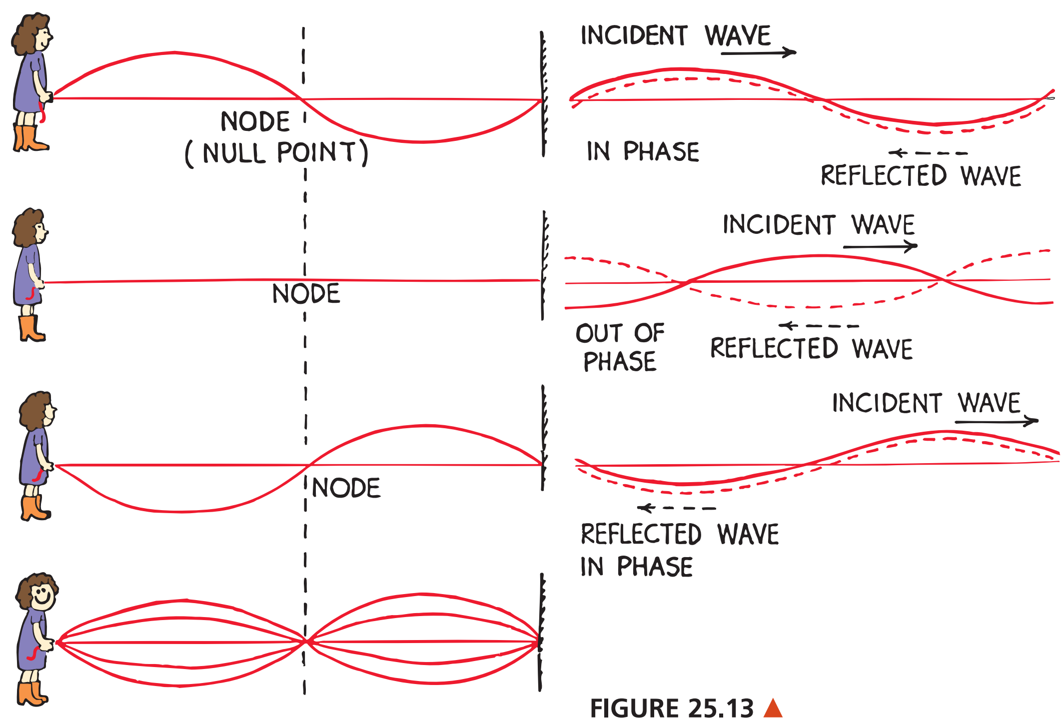


FIGURE 25.13 ▲
The incident and reflected waves interfere to produce a standing wave. The nodes are places that remain stationary.

You can produce a variety of standing waves by shaking the rope at different frequencies. Once you find a frequency that produces a standing wave, doubling or tripling the frequency will also produce a standing wave. **A standing wave forms only if half a wavelength or a multiple of half a wavelength fits exactly into the length of the vibrating medium.** In Figure 25.14a, the rope length equals half a wavelength. In Figure 25.14b, the rope length equals one wavelength. In Figure 25.14c, the rope length equals one and one-half wavelengths. If you keep increasing the frequency, you'll produce more interesting waves.

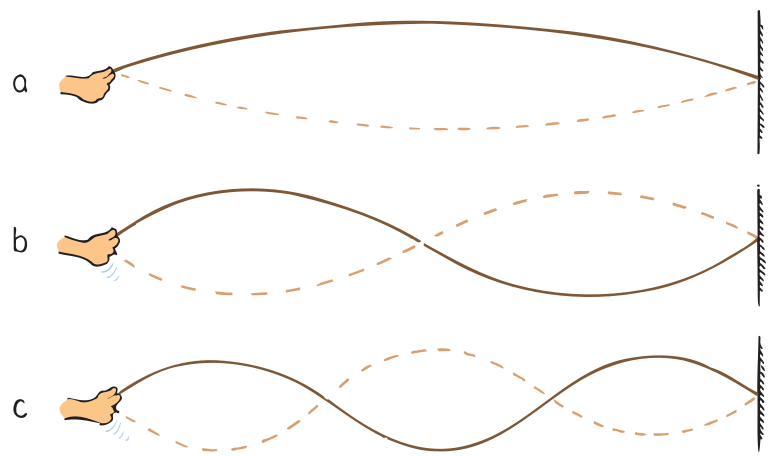


FIGURE 25.14
You can produce a variety of standing waves.
a. Shake the rope until you set up a standing wave of $\frac{1}{2}$ wavelength.
b. Shake with twice the frequency and produce a standing wave of 1 wavelength.
c. Shake with three times the frequency and produce a standing wave of $1\frac{1}{2}$ wavelengths.

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

CONCEPT CHECK At what wavelengths can a standing wave form in a vibrating medium?

25.9 The Doppler Effect

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

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25.9 The Doppler Effect

Key Terms
Doppler effect, blue shift, red shift

Common Misconception
Changes in wave speed cause the Doppler effect.

FACT The Doppler effect is an apparent change in frequency due to the motion of the source.

Teaching Tip Place an electronic whistle that emits a sound of about 3000 Hz into a sponge, rubber, or foam ball. Introduce the Doppler effect by throwing the ball around the room. Ask students to describe what they hear as the ball moves through the air. Then ask if the frequency of the sound that the whistle emits actually changes.

▶ **Teaching Tip** Describe the pattern that a stationary bug jiggling in still water makes as shown in Figure 25.15. Draw circles to show the top view of circular ripples made by a bug bobbing in the water. Stress that wave speed, wavelength, and frequency are the same in all directions, as shown by the circular shape.

▶ **Teaching Tip** Now consider a moving bug and the pattern it makes (Figure 25.16). Explain how the frequency of waves is increased in front of the bug; waves would be encountered more often (more frequently) by your hand placed in the water in front of the bug. (The observer would also encounter a shorter wavelength; since *v* is a constant for a given medium, then as *f* increases, λ decreases.) Similarly waves would be encountered less often (less frequently) behind the bug.

FIGURE 25.15 ▼
A stationary bug jiggling in still water produces a circular water wave.

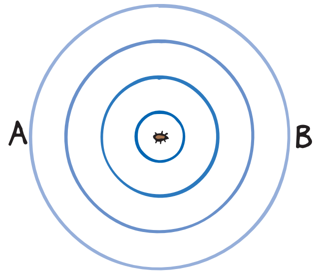
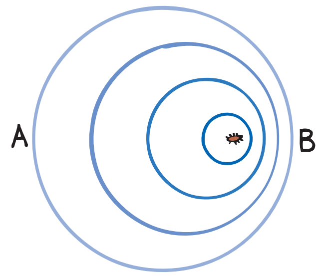


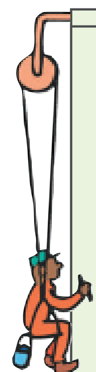
FIGURE 25.16 ▼
A bug swimming in still water produces a wave pattern that is no longer concentric.



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

An observer at A, on the other hand, encounters a *lower* frequency because of the longer time between wave-crest arrivals. To reach A, each crest has to travel farther than the one ahead of it due to the bug's motion. ✓ **As a wave source approaches, an observer encounters waves with a higher frequency. As the wave source moves away, an observer encounters waves with a lower frequency.** This apparent change in frequency due to the motion of the source (or receiver) is called the **Doppler effect** (after the Austrian scientist Christian Doppler, 1803–1853). The greater the speed of the source, the greater will be the Doppler effect.

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



Physics on the Job

Police Officer
Police officers are responsible for protecting people. While that involves catching criminals and solving crimes, it also requires that police officers prevent drivers from speeding. In this way, police officers protect pedestrians and people in vehicles. One way that police officers prevent speeding is by using radar equipment. Radar equipment sends waves toward a moving vehicle and uses the Doppler effect to determine the speed of the vehicle. By knowing how to operate the device, police officers can determine when a driver is not obeying the speed limit.

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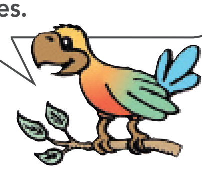
FIGURE 25.17
The pitch of sound is higher when the source moves toward you, and lower when the source moves away.

Sound The Doppler effect is evident when you hear the changing pitch of a siren as a firetruck passes you. Look at Figure 25.17. When the firetruck approaches, the pitch sounds higher than normal. This occurs because the sound wave crests are encountering you more frequently. When the firetruck passes and moves away, you hear a drop in pitch because the wave crests are encountering you less frequently.

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

Bats hunt moths in darkness by echo location and the Doppler effect. Some moths are protected by a thick covering of fuzzy scales that deaden the echoes.



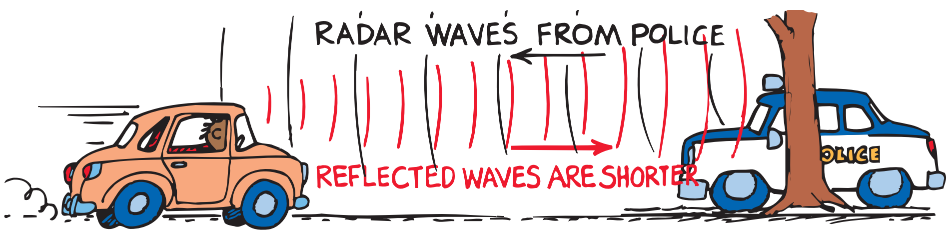


FIGURE 25.18
The police calculate a car's speed by measuring the Doppler effect of radar waves.

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

CONCEPT CHECK How does the apparent frequency of waves change as a wave source moves?

think!

When a source moves toward you, do you measure an increase or decrease in wave speed?
Answer: 25.9

Teaching Tip Relate the concept of the moving bug to the waves from the moving sources in Figures 25.17 and 25.18.

Ask The waves are more crowded in front of the swimming bug and more spread out behind. Is the wave speed greater in front of the bug (and less behind the bug)? *No! Frequency, not speed, is greater in front of the bug and less behind.*

Teaching Tip Emphasize the distinction between wave speed and wave frequency.

Teaching Tip Swing a sound source at the end of a string in a horizontal circle. Relate this to the siren of a fire engine and the radar of the highway patrol (Figures 25.17 and 25.18). (Mention that sound requires a medium; radar doesn't.)

Teaching Tip Point out that light, radar, TV, and radio waves are all electromagnetic in nature. The waves differ only in frequency (and hence wavelength) and energy per photon.

Teaching Tip Relate the pitch of sound to the color of light. Both depend on frequency.

CONCEPT CHECK As a wave source approaches, an observer encounters waves with a higher frequency. As the wave source moves away, an observer encounters waves with a lower frequency.

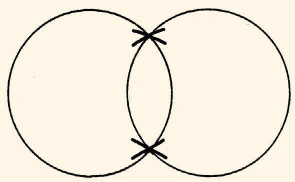
Teaching Resources

- **Concept-Development Practice Book** *25-1*
- **Problem-Solving Exercises in Physics** *13-2*
- **Laboratory Manual** *70*

25.10 Bow Waves

Key Term
bow wave

▶ **Teaching Tip** Ask the class to consider the waves made by two stones thrown in the water. Sketch the overlapping waves as shown below.



Ask where the water is highest above the normal water level, and then indicate the two places where the waves overlap with X's. This is constructive interference. Extend the swimming bug concept to speeds greater than wave speeds and show the regions of overlap that produce the bow wave (sketching Figures 25.15, 25.16, and 25.19). Show how a series of overlaps makes up the V-shaped envelope shown in Figure 25.21.

▶ **Teaching Tip** Explain that the formation of the bow wave in Figure 25.20 is another example of constructive interference, with an appreciable resulting amplitude.

CONCEPT CHECK A bow wave occurs when a wave source moves faster than the waves it produces.

Teaching Resources
- Reading and Study Workbook
- Transparency *53*
- Presentation*EXPRESS*
- Interactive Textbook

25.10 Bow Waves

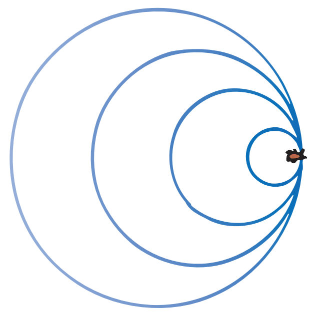
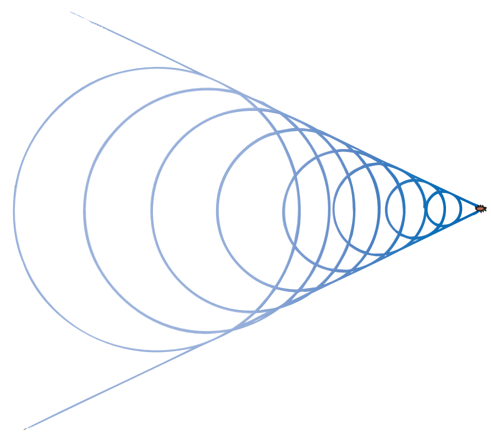


FIGURE 25.19 ▲
A bug swimming at the wave speed "keeps up" with the wave crests it produces.

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

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

FIGURE 25.20 ▶
A bug swimming faster than the wave speed produces a wave pattern in which the wave crests overlap at the edges.



When the bug swims faster than wave speed, ideally it produces a wave pattern as shown in Figure 25.20. It outruns the wave crests it produces. The crests overlap at the edges, and the pattern made by these overlapping crests is a V shape, called a **bow wave,** which appears to be dragging behind the bug. ✓ **A bow wave occurs when a wave source moves faster than the waves it produces.** The familiar bow wave generated by a speedboat knifing through the water is produced by the overlapping of many circular wave crests.

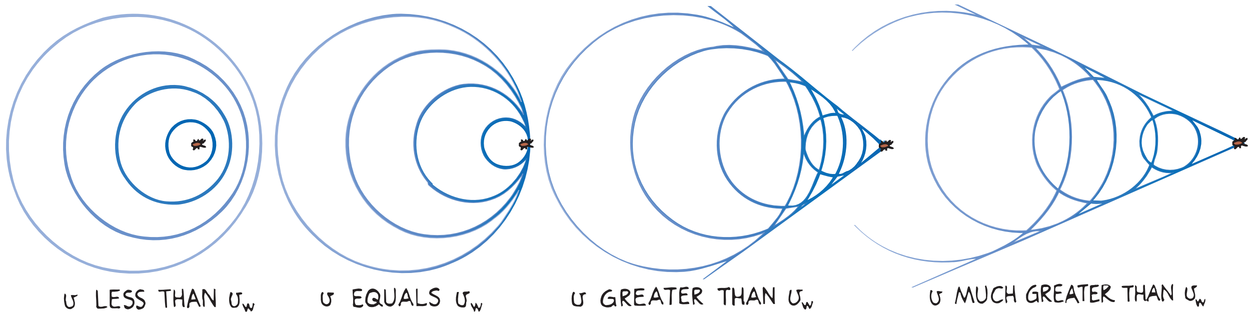


FIGURE 25.21 ▲
The wave patterns made by a bug swimming at successively greater speeds change. Overlapping at the edges occurs only when the source travels faster than wave speed.

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

CONCEPT CHECK What causes a bow wave?

25.11 Shock Waves

A speedboat knifing through the water generates a two-dimensional bow wave. A supersonic aircraft similarly generates a shock wave. A **shock wave** is a three-dimensional wave that consists of overlapping spheres that form a cone. ✓ **A shock wave occurs when an object moves faster than the speed of sound.** Just as the bow wave of a speedboat spreads until it reaches the shore of a lake, the conical shock wave generated by a supersonic craft spreads until it reaches the ground, as shown in Figure 25.22.

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, a conical shell of compressed air sweeps behind a supersonic aircraft. The sharp crack heard when the shock wave that sweeps behind a supersonic aircraft reaches the listeners is called a **sonic boom.**

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

Don't confuse *supersonic* with *ultrasonic.* Supersonic has to do with speed—faster than sound. Ultrasonic involves frequency—higher than we can hear.

25.11 Shock Waves

Key Terms
shock wave, sonic boom

Common Misconception
A sonic boom is a momentary burst of high pressure produced when something exceeds the speed of sound.

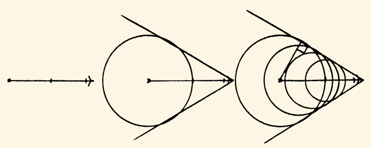
FACT A sonic boom is actually a continuous front of high pressure generated by faster-than-sound sources.

The analogy between bow waves in water and shock waves in air is useful when discussing the shock waves produced by supersonic aircraft.
PAUL

▶ Teaching Tip Questions raised by students about shock waves and the sonic boom can be effectively answered by substituting the example of an aircraft in the air for the example of a speedboat knifing through the water. If you're enjoying a picnic lunch at the edge of a river when a speedboat comes by and drenches you, you won't attribute this to the idea that the speedboat just exceeded the speed of the water waves. You know the boat is generating a continuous bow wave so long as it travels faster than waves in water. Likewise for aircraft.

Ask **Why can't a subsonic aircraft, no matter how loud it may be, produce a shock wave or sonic boom?** *There will be no overlapping of spherical waves to form a cone unless the aircraft moves faster than the waves it generates.*

Teaching Tip Construct a shock wave on the board as follows: First place your chalk anywhere on the board to signify time zero. Draw a 1-m-long horizontal line to the right to represent how far an aircraft has moved in a certain time. Suppose it moves at twice the speed of sound (Mach 2).



During the time it moves 1 m, the sound it initially made has moved half this distance, which you mark on the midpoint of your line. Explain that the initial sound has expanded spherically, which you represent two-dimensionally by drawing a circle. Explain that this circle represents only one of the nearly infinite number of circles that make up the shock wave, which you draw by making tangents from the end point to the circle. The shock wave should be a 60° wedge (30° above your horizontal line, and 30° below). Move the center 10 cm at a time in the direction of travel and draw circles (reduce the radius each time) within the two tangents. Explain how the speed of the craft is simply the ratio of the horizontal line (1 m) to the radial distance (0.5 m) of the big circle (and likewise the respective horizontal lines to radii of smaller circles).

CONCEPT CHECK A shock wave occurs when an object moves faster than the speed of sound.

Teaching Resources

- **Concept-Development Practice Book** *25-2, 25-3*
- **Next-Time Question** *25-2*

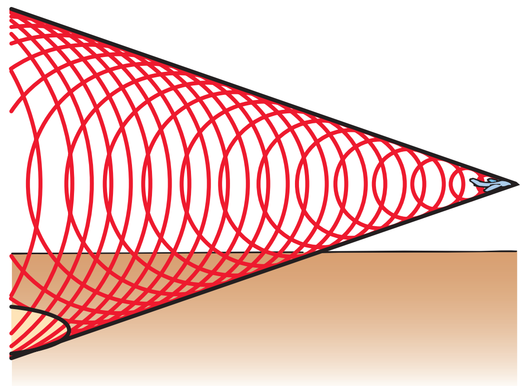
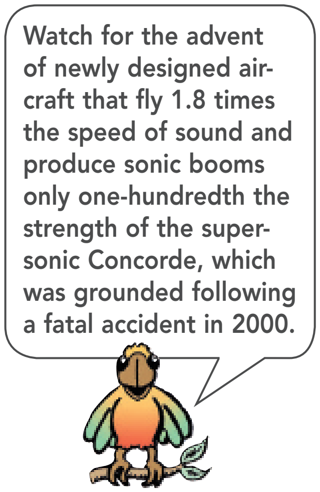


FIGURE 25.22 ▶
A shock wave is swept continuously behind a supersonic aircraft.



A common misconception is that sonic booms are produced at the moment that an aircraft flies through the "sound barrier"—that is, just as the aircraft surpasses the speed of sound. This is equivalent to saying that a boat produces a bow wave only when it first overtakes its own waves. This is not so. The fact is that a shock wave and its resulting sonic boom are swept continuously behind an aircraft traveling faster than sound, just as a bow wave is swept continuously behind a speedboat. In Figure 25.23, listener B is in the process of hearing a sonic boom. Listener A has already heard it, and listener C will hear it shortly. The aircraft that generated this shock wave may have broken through the sound barrier hours ago!

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

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

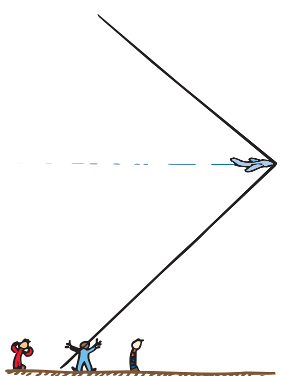


FIGURE 25.23 ▲
The shock wave has not yet encountered listener C, but is now encountering listener B, and has already passed listener A.

CONCEPT CHECK What causes a shock wave?

25 REVIEW

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Concept Summary

- The period of a pendulum depends only on the length of the pendulum and the acceleration of gravity.
- The source of all waves is a vibration.
- The energy in waves is carried by a disturbance in a medium.
- Calculate the wave speed by multiplying the wavelength and the frequency.
- Waves in the stretched strings of musical instruments and electromagnetic waves are transverse. Sound waves are longitudinal.
- Interference patterns occur when waves from different sources arrive at the same point—at the same time.
- A standing wave forms if a multiple of half a wavelength fits into the length of the medium.
- As a wave source approaches, an observer encounters waves with a higher frequency. As a wave source moves away, an observer encounters waves with a lower frequency.
- A bow wave occurs when a wave source moves faster than the waves it produces.
- A shock wave occurs when an object moves faster than the speed of sound.

Key Terms

vibration *(p. 490)*
wave *(p. 490)*
period *(p. 491)*
simple harmonic motion *(p. 491)*
sine curve *(p. 491)*
crest *(p. 492)*
trough *(p. 492)*
amplitude *(p. 492)*
wavelength *(p. 492)*
frequency *(p. 492)*
hertz *(p. 492)*
transverse wave *(p. 497)*
longitudinal wave *(p. 497)*
interference pattern *(p. 498)*
constructive interference *(p. 498)*
destructive interference *(p. 498)*
out of phase *(p. 499)*
in phase *(p. 499)*
standing wave *(p. 500)*
node *(p. 500)*
antinodes *(p. 500)*
Doppler effect *(p. 502)*
blue shift *(p. 503)*
red shift *(p. 503)*
bow wave *(p. 504)*
shock wave *(p. 505)*
sonic boom *(p. 505)*

think! Answers

25.2.1 A 100-Hz wave vibrates 100 times/s.

25.2.1 The period is $= \frac{1 \text{ vib}}{0.1 \text{ Hz}} = \frac{1 \text{ vib}}{0.1 \text{ vib/s}} = 10$ s.

25.4.1 The frequency of the wave is 2 Hz; its wavelength is 1.5 m; and its wave speed is $\lambda \times f = (1.5 \text{ m}) \times (2 \text{ Hz}) = 3$ m/s.

25.4.2 The wavelength must be 1 m. Then wave speed $= (1 \text{ m}) \times (340 \text{ Hz}) \times 340$ m/s.

25.8 Yes. This is called destructive interference. In a standing wave, for example, parts of the wave have no amplitude—the nodes.

25.9 Neither! It is the *frequency* of a wave that undergoes a change, not the wave *speed*.

25 REVIEW

Teaching Resources
- Teacher*EXPRESS*

25 ASSESS

Check Concepts

1. A wave spreads out through space.
2. 1 s
3. 1.5 s
4. longer
5. A sine curve is a pictorial representation of a wave.
6. Amplitude—maximum displacement; crest—point of greatest positive displacement; trough—point of greatest negative displacement; wavelength—distance from one crest to the next
7. Period—time to complete one cycle; frequency—how many cycles occur in a given time
8. No. The disturbance, not the material itself, moves.
9. Speed = wavelength × frequency
10. Decreases; smaller musical instruments produce higher frequency sounds.
11. Transverse—medium moves perpendicular to wave direction; longitudinal—medium moves back and forth parallel to wave direction.
12. Constructive—causes an additive effect; destructive—canceling effect
13. All. It is a prime test for wave properties.
14. Interference of original wave with reflected wave
15. Increase in frequency only
16. All

25 ASSESS

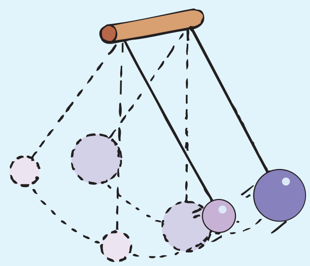
Check Concepts

Section 25.0

1. Does a vibration or a wave spread out through space?

Section 25.1

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



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

Section 25.2

5. How is a sine curve related to a wave?
6. Distinguish among these different parts of a wave: amplitude, crest, trough, and wavelength.
7. Distinguish between the *period* and the *frequency* of a vibration or a wave. How do they relate to one another?

Section 25.3

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

Section 25.4

9. How does the speed of a wave relate to its wavelength and frequency?
10. As the frequency of sound is increased, does the wavelength increase or decrease? Give an example.

Sections 25.5 and 25.6

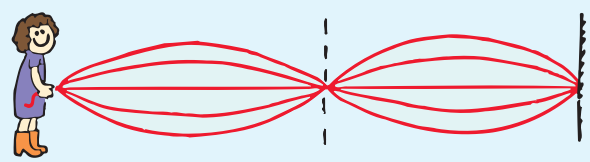
11. Distinguish between a *transverse* wave and a *longitudinal* wave.

Section 25.7

12. Distinguish between *constructive* interference and *destructive* interference.
13. Is interference a property of only some types of waves or of all types of waves?

Section 25.8

14. What causes a standing wave?



Section 25.9

15. When a wave source moves toward a receiver, does the receiver encounter an increase in wave frequency, wave speed, or both?
16. Does the Doppler effect occur for only some types of waves or all types of waves?

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Section 25.10

17. Compared with the speed of water waves how fast must a bug swim to keep up with the waves it produces? How fast must a boat move to produce a bow wave?

18. Distinguish a *bow* wave from a *shock* wave.

Section 25.11

19. **a.** What is a sonic boom?
b. How fast must an aircraft fly in order to produce a sonic boom?

20. If you encounter a sonic boom, is that evidence that an aircraft just exceeded the speed of sound to become supersonic?

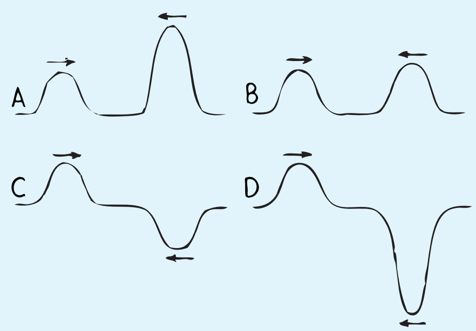
Think and Rank

Rank each of the following sets of scenarios in order of the quantity or property involved. List them from left to right. If scenarios have equal rankings, then separate them with an equal sign. (e.g., A = B)

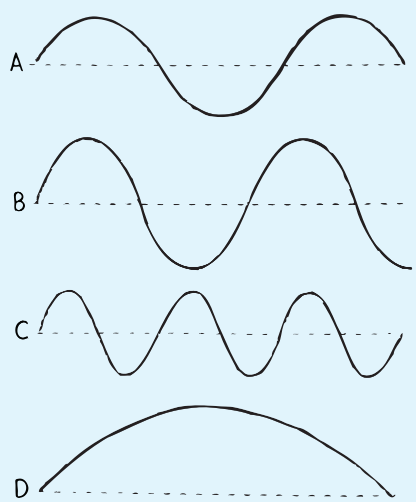
21. A fire engine's siren emits a certain frequency. Rank from greatest to least the *apparent* frequency heard by the stationary listener in each scenario.

(A) The fire engine is traveling toward a listener at 30 m/s.
(B) The fire engine is traveling away from a listener at 5 m/s.
(C) The fire engine is traveling toward a listener at 5 m/s.
(D) The fire engine is traveling away from a listener at 30 m/s.

22. Shown below 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 greatest to least on the basis of the height of the peak that results when the centers of the pairs coincide.



23. All the waves below have the same speed in the same medium. Use a ruler and rank these waves from greatest to least according to amplitude, wavelength, frequency, and period.



17. As fast as the waves move; faster than the waves move

18. Bow—a 2-D "V" on the water surface; shock—a 3-D cone in the air

19. **a.** Incident shock wave
b. Faster than sound

20. No; it could have been any time ago. It depends on speed, not time.

Think and Rank

21. A, C, B, D

22. A, B, D, C

23. Amplitude: D, B, A, C
Wavelength: D, A, B, C
Frequency: C, B, A, D
Period: D, A, B, C

24. D, C, B, A
25. A, C, B

Plug and Chug

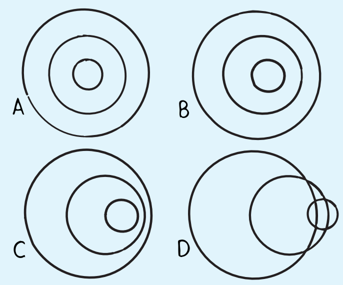
26. $T = (1/76)$ min; $f = 76$/min
27. $f = 1/(6.80\text{ s}) = 0.15$ Hz
28. $v = \lambda f = (0.15\text{ m})(2/\text{s}) = 0.3$ m/s
29. $v = \lambda f = (0.4\text{ m})(2/\text{s}) = 0.8$ m/s
30. $\lambda = v/f = (340\text{ m/s})/(20/\text{s}) =$ 17 m or 56 ft

Think and Explain

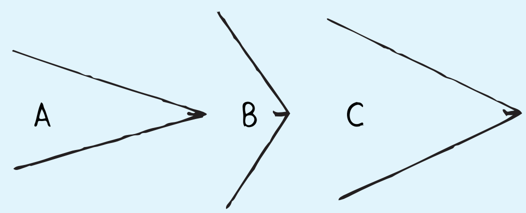
31. Pendulum period depends on its length, but not its mass.
32. Shorter pendulum, higher frequency, shorter period
33. Disagree with both. CG of "bob" is closer to pivot, so shorter pendulum has shorter period.
34. Higher frequency of dip makes shorter wavelength.
35. $f = 1/T$, and $T = 1/f$. Double one, then other is half. So $2f$ gives $1/2\ T$.
36. Both are the same.
37. f and T are reciprocals of each other, so tripling the frequency results in one third the period.

25 ASSESS *(continued)*

24. The four sets of waves below are a top view of circular wave patterns made by a bug jiggling on the surface of water. Rank them from greatest to least based on the speed of the bug.



25. The shock waves depicted below are produced by supersonic aircraft. Rank them from greatest to least based on the speed of the aircraft.



Plug and Chug

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

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

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

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

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

Think and Explain

31. Does the period of a pendulum depend of the mass of the bob? On the length of the string?

32. If a pendulum is shortened, does the frequency increase or decrease? What about its period?

33. Carmelita swings to and fro in a sitting position on a playground swing. William says that if she stands while swinging, a longer time will occur between back-and-forth swings. Carlos says no, that the to-and-fro time of the swing will be unaffected. Who, if either, do you agree with?

34. You dip your finger repeatedly into a puddle of water and make waves. What happens to the wavelength if you dip your finger more frequently?

35. If you double the frequency of a vibrating object, what happens to its period?

36. How does the frequency of vibration of a small object floating in water compare to the number of waves passing it each second?

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

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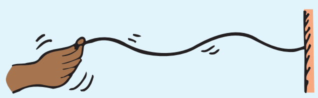
38. Red light has a longer wavelength than violet light. Which has the greater frequency?

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

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



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

42. Sound from Source A has a frequency twice as great as the frequency of sound from Source B. Compare the wavelengths of sound from the two sources.

43. What kind of motion should you impart to a stretched coiled spring to produce a transverse wave? A longitudinal wave?

44. Would it be correct to say that the Doppler effect is the apparent change in the speed of a wave due to the motion of the source? (Why is this question a test of reading comprehension as well as a test of physics knowledge?)

45. In the Doppler effect, does frequency change? Does wavelength change? Does wave speed change?

46. Can the Doppler effect be observed with longitudinal waves, with transverse waves, or with both?

47. A railroad locomotive is at rest with its whistle shrieking, and then it starts moving toward you.
 a. Does the frequency that you hear increase, decrease, or stay the same?
 b. Does the wavelength that reaches your ear increase, decrease, or stay the same?
 c. How about the speed of sound in the air between you and the locomotive?

48. When a driver blows his horn while approaching a stationary listener, the listener hears an increase in the frequency of the horn. Would the listener hear an increase in the frequency of the horn if she were also in a car traveling at the same speed in the same direction as the first driver? Explain.

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

38. The speeds are the same, so the wave with the shorter wavelength has the greater frequency—violet.

39. A wave takes a time equal to one period to travel a distance of one wavelength. Distance = speed × time = (wavelength × frequency) × period = (wavelength × 1/period) × period = wavelength

40. 2 Hz; 20 m/s

41. The waves travel at the same speed in all directions.

42. Source A has half wavelength of Source B sound.

43. Transverse wave shakes back-and-forth perpendicular to coiled spring. Longitudinal wave shakes back-and-forth along length.

44. No, it is the change in the observed *frequency* of a wave due to motion of the observer with respect to the source. There is no change in wave speed when the source moves.

45. Frequency and wavelength change; not wave speed.

46. Both

47. **a.** Frequency increases.
 b. Wavelength decreases.
 c. No change in speed.

48. No. There is no relative motion between source and listener.

49. The sun is spinning, since point A must be moving toward the observer and point B must be moving away.

50. If the speed of the boat exceeds wave speed, yes. If slower, no.

51. It takes negligible time for light to get to you from the airplane, but it takes a noticeable time for sound to reach you. When sound from a fast-moving source reaches you, the source is farther along.

52. The narrower the angle, the faster the source

53. At subsonic speeds, there is no overlapping of waves to produce high-pressure regions; where there is no shock wave, there is no sonic boom.

54. False; a sonic boom occurs continuously for supersonic source.

55. From difference in arrival times, each scientist calculates distance, and draws a circle of possible sources. Origin of quake is where 3 such circles drawn by different scientists overlap.

Think and Solve

56. No, don't agree. $T \sim \sqrt{L}$ so $L \sim T^2$. To double T, L must be 4 times as long.

57. $T = 2\pi\sqrt{L/g} = 2\pi\sqrt{(0.31\text{ m})/(10\text{ m/s}^2)} = 1.1\text{ s}$

58. $T = 2\pi\sqrt{L/g} = 2\pi\sqrt{(12.2\text{ m})/(10\text{ m/s}^2)} = 6.9\text{ s}$ (or 7.0 s using $g = 9.8\text{ m/s}^2$)

59. Yes. From $T = 2\pi\sqrt{L/g}$, $L = gT^2/4\pi^2 = [(10\text{ m/s}^2) \times (4.0\text{ s})^2]/4\pi^2 = 4.0\text{ m}$

60. From $T = 2\pi\sqrt{L/g}$, $L = gT^2/4\pi^2 = [(9.8\text{ m/s}^2) \times (2.00\text{ s})^2]/4\pi^2 = 0.99\text{ m}$

25 ASSESS *(continued)*

50. Does a boat moving through the water always produce a bow wave? Defend your answer.

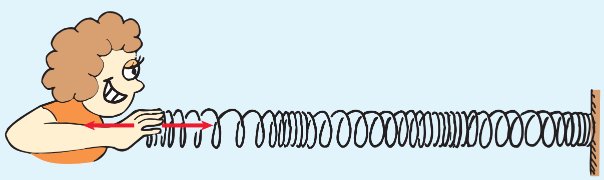
51. Whenever you watch a high-flying aircraft overhead, it seems that its sound comes from behind the craft rather than from where you see it. Why is this?

52. How does the angle of the V shape of a bow wave depend on the speed of the wave source?

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

54. True or false: A sonic boom occurs only when an aircraft is breaking through the sound barrier. Defend your answer.

55. Consider an earthquake caused by a single disturbance, which sends out both transverse and longitudinal waves that travel with distinctly different speeds in the ground. How can earth scientists in different locations determine the earthquake origin?



Think and Solve

56. The period of a simple pendulum is given by $T = 2\pi\sqrt{\frac{L}{g}}$, where g is the acceleration of gravity and L is the length of the pendulum. In a lab, you want to double the period of a certain pendulum. Your friend says you'll have to make the pendulum twice as long. Do you agree with your friend?

57. Maria shows her friends a simple 31-cm-long pendulum. Her teacher, looking on, asks if she can predict the period of the pendulum before she demonstrates it. What's your prediction?

58. The Foucault pendulum in the rotunda of the Griffith Observatory in Los Angeles has a 110-kg brass ball at the end of a 12.2-m-long cable. What is the period of this pendulum?

59. You are looking through your grandparents' window and notice a hummingbird feeder hanging by a rope. You can't see the top of the rope, but you notice that in a gentle breeze the feeder moves back and forth with a period of 4.0 seconds. You make a calculation and announce to your grandparents that the rope is 4 m long. Your grandparents go outside and measure the rope. Should they be impressed with you?

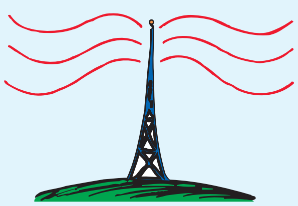
60. For your science fair project you decide to make a simple pendulum for a grandfather clock, such that the period of the pendulum is 2.00 seconds. Show that the length of your pendulum should be just slightly less than the length of a meterstick. (Use $g = 9.8\text{ m/s}^2$ here.)

61. Melanie is new to the nursing program. With a patient she counts 84 heartbeats in one minute. She calculates that the period and frequency of the heartbeats are 0.71 s and 1.4 Hz respectively. Is she correct?

62. A design engineer figures that a proposed new skyscraper will swing to and fro in strong winds at a frequency of 0.15 Hz. A new assistant asks how much time a person in the skyscraper will experience during each complete swing. What's your answer?

63. In lab you strike a tuning fork that has a frequency of 340 Hz. For a speed of sound of 340 m/s, how does the wavelength of the resulting sound wave compare with the length of a meter stick?

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

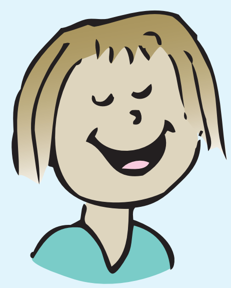


65. While watching ocean waves at the dock of the bay, Otis notices that 10 waves pass beneath him in 30 seconds. He also notices that the crests of successive waves exactly coincide with the posts that are 5 meters apart. What are the period, frequency, wavelength, and speed of the ocean waves?

66. The crests on a long surface water wave are 20 m apart, and in 1 minute 10 crests pass by. What is the speed of this wave?

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

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



69. The half-angle of the shock-wave cone generated by a supersonic aircraft is 45°. What is the speed of the plane relative to the speed of sound?

Activity

70. Tie a rubber tube, a spring, or a rope to a fixed support and produce standing waves, as Figure 25.14 suggests. How many nodes can you produce? How can you change the number of nodes?

More Problem-Solving Practice
Appendix F

61. She is correct. f = (84 beats)/(60 s) = 1.4 Hz.; $T = 1/f = 1/(1.4\ s^{-1}) = 0.71$ s

62. $T = 1/f = 1/(0.15\ s^{-1}) = 6.7$ s

63. The same; from $v = \lambda f$, $\lambda = v/f$ = (340 m/s)/(340 Hz) = 1.0 m.

64. f = 3 Hz; T = 1/3 s; $v = \lambda f$ = (2 m)(3/s) = 6 m/s

65. T = (30 s)/10 = 3 s; f = 1/3 Hz; λ = 5 m; $v = \lambda f$ = (5 m)(1/3 Hz) = 1.67 m/s

66. $v = \lambda f$ = (20 m)(10/min) = 200 m/min, or 3.3 m/s

67. $\lambda = v/f$ = (300,000 km/s) ÷ (100,000,000/s) = 0.003 km, or 3 m

68. $f = v/\lambda = (3 \times 10^8$ m/s) ÷ $(7 \times 10^{-7}$ m) $= 4.3 \times 10^{14}$ Hz, an extraordinarily high frequency by ordinary standards

69. The plane's speed is 1.41 times the speed of sound. In right triangle, the distance AB is $\sqrt{2}$ or 1.41 times the distance AC.

Activity

70. Check students' work. The frequency of the incident wave determines the number of nodes produced.

Teaching Resources

- Computer Test Bank
- Chapter and Unit Tests