chapter 10

Waves

BIG Idea
Waves transfer energy from place to place without transferring matter.

10.1 The Nature of Waves

MAIN Idea Waves move through matter as energy is transferred from particle to particle.

10.2 Wave Properties

MAIN Idea Wave properties depend on the vibrations of the wave source and the material in which the wave moves.

10.3 The Behavior of Waves

MAIN Idea Waves can change direction when they interact with matter.

Hanging In

This surfer in Hawaii is surrounded by an ocean wave that forms a huge tube of water. But even sitting at your desk, you are also surrounded by waves. Everything you see or hear is brought to you by waves. Easy to see-like this ocean wave-or invisible, all waves carry energy.

Science Journal

Write down three things you already know about waves and one thing you would like to learn about waves.

Jason Childs/Getty Images

Start-Up Activities

Launch LAB

How do waves transfer energy?

Light enters your eyes and sound strikes your ears, enabling you to sense the world around you. Light and sound are waves that transfer energy from one place to another. Do waves transfer anything else along with their energy? Does a wave transfer matter, too? In this activity, you'll observe one way that waves can transfer energy.

1. Complete the safety form.
2. Place your textbook flat on your desk. Line up four marbles on the groove at the edge of the textbook so that the marbles are touching each other.
3. Hold the first three marbles in place using three fingers of one hand.
4. Tap the first marble with a pen or pencil.
5. Observe the behavior of the fourth marble.
6. **Think Critically** Write a paragraph explaining how the fourth marble reacted to the pen tap. Diagram how energy was transferred through the marbles.

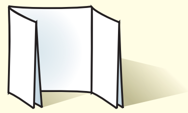
Science Online — Preview this chapter's content and activities at gpescience.com

FOLDABLES™ Study Organizer

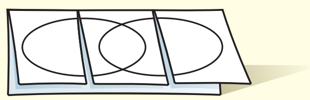
Types of Waves Make the following Foldable to compare and contrast two types of waves.

STEP 1 **Fold** one sheet of paper lengthwise.

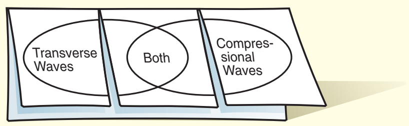
STEP 2 **Fold** into thirds.



STEP 3 **Unfold and draw** overlapping ovals. Cut the top sheet along the folds.



STEP 4 **Label** the ovals as shown.



Construct a Venn Diagram As you read this chapter, list properties and characteristics unique to transverse waves under the left tab, those unique to compressional waves under the right tab, and those common to both under the middle tab.

Jason Childs/Getty Images

section 1

The Nature of Waves

Reading Guide

What You'll Learn

- **Recognize** that waves transfer energy but not matter.
- **Define** mechanical waves.
- **Compare and contrast** transverse waves and compressional waves.

Why It's Important

You can see and hear the world around you because of the energy transferred by waves.

Review Vocabulary

energy: the ability to do work

New Vocabulary

- wave
- medium
- transverse wave
- compressional wave

What's in a wave?

A surfer bobs in the ocean waiting for the perfect wave, microwaves warm up your leftover pizza, and sound waves from your CD player bring music to your ears. Do these and other types of waves have anything in common with one another?

A **wave** is a repeating disturbance or movement that transfers energy through matter or space. For example, ocean waves disturb the water and transfer energy through it. During earthquakes, energy is transferred in powerful waves that travel through Earth. Light is a type of wave that can travel through empty space to transfer energy from one place to another, such as from the Sun to Earth.

Figure 1 Falling pebbles transfer their kinetic energy to the particles of water in a pond, forming waves.

Waves and Energy

Kerplop! A pebble falls into a pool of water and ripples form. As **Figure 1** shows, the pebble causes a disturbance that moves outward in the form of a wave. Because it is moving, the falling pebble has energy. As it splashes into the pool, the pebble transfers some of its energy to nearby water molecules, causing them to move. These molecules then pass the energy along to neighboring water molecules, which, in turn, transfer it to their neighbors. The energy moves farther and farther from the source of the disturbance. What you see is energy traveling in the form of a wave on the surface of the water.

Waves and Matter Imagine that you're in a boat on a lake. Approaching waves bump against your boat, but they don't carry it along with them as they pass. The boat does move up and down and maybe even a short distance back and forth because the waves transfer some of their energy to it. However, after the waves have moved on, the boat is still in nearly the same place. The waves don't even carry the water along with them. Only the energy transferred by the waves moves forward. All waves have this property—they transfer energy without transporting matter from place to place.

Reading Check *What do waves transfer?*

Making Waves A wave will travel only as long as it has energy to transfer. For example, when you drop a pebble into a puddle, the ripples soon die out and the surface of the water becomes still again.

Suppose you are holding a rope at one end, and you give it a shake. You would create a pulse that would travel along the rope to the other end, and then the rope would be still again, as **Figure 2** shows. Now suppose you shake your end of the rope up and down for a while. You would make a wave that would travel along the rope. When you stop shaking your hand up and down, the rope will be still again. It is the up-and-down motion of your hand that creates the wave.

Anything that moves up and down or back and forth in a rhythmic way is vibrating. The vibrating movement of your hand at the end of the rope created the wave. In fact, all waves are produced by something that vibrates.

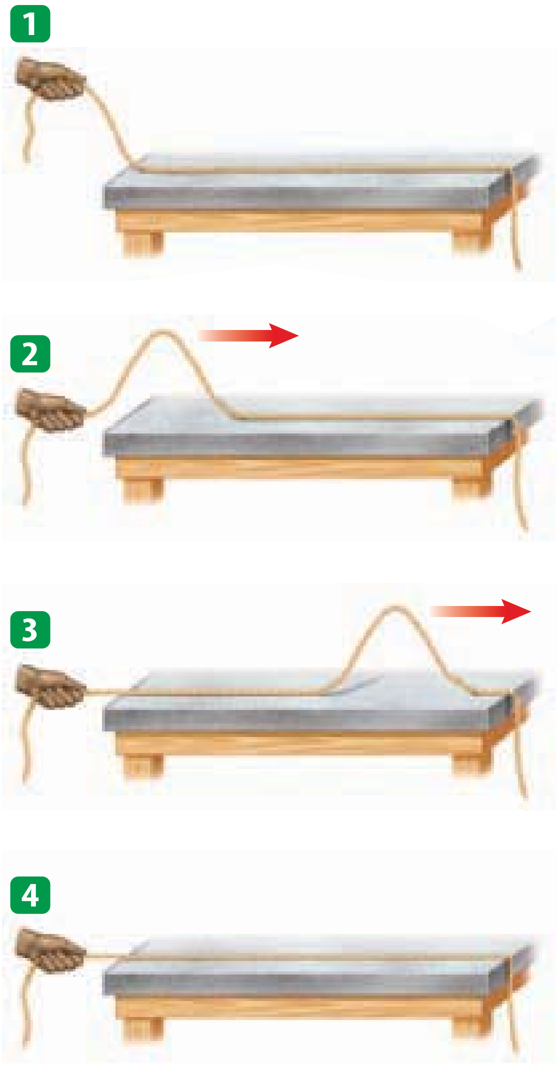


Figure 2 A wave will exist only as long as it has energy to transfer. **Explain** *what happened to the energy that was transferred by the wave in this rope.*

Mechanical Waves

Sound waves travel through the air to reach your ears. Ocean waves move through water to reach the shore. In both cases, the matter the waves travel through is called a **medium.** A medium can be a solid, a liquid, a gas, or a combination of these. For sound waves, the medium is air, and for ocean waves, the medium is water. Not all waves need a medium. Some waves, such as light and radio waves, can travel through space. Waves that can travel only through matter are called mechanical waves. The two types of mechanical waves are transverse waves and compressional waves.

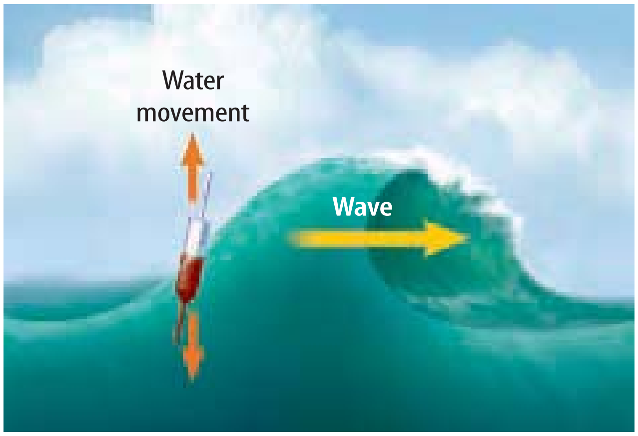


Figure 3 A water wave travels horizontally as the water moves vertically up and down.

Transverse Waves In a **transverse wave**, matter in the medium moves back and forth at right angles to the direction that the wave travels. For example, **Figure 3** shows how a wave in the ocean moves horizontally, but the water that the wave passes through moves up and down. When you shake one end of a rope while your friend holds the other end, you are making transverse waves. The wave and its energy travel from you to your friend as the rope moves up and down.

Compressional Waves In a **compressional wave**, matter in the medium moves back and forth along the same direction that the wave travels. You can model compressional waves with a coiled-spring toy, as shown in **Figure 4.** Squeeze several coils together at one end of the spring. Then let go of the coils, still holding onto coils at both ends of the spring. A wave will travel along the spring. As the wave moves, it looks as if the whole spring is moving toward one end. Suppose you watched the coil with yarn tied to it, as in **Figure 4.** You would see that the yarn moves back and forth as the wave passes, and then it stops moving after the wave has passed. The wave transfers energy, but not matter, forward along the spring. Compressional waves also are called longitudinal waves.

Sound Waves Sound waves are compressional waves. When a noise is made, such as when a locker door slams shut and vibrates, nearby air molecules are pushed together by the vibrations. The air molecules are squeezed together like the coils in a coiled-spring toy are when you make a compressional wave with it. The compressions travel through the air to make a wave.

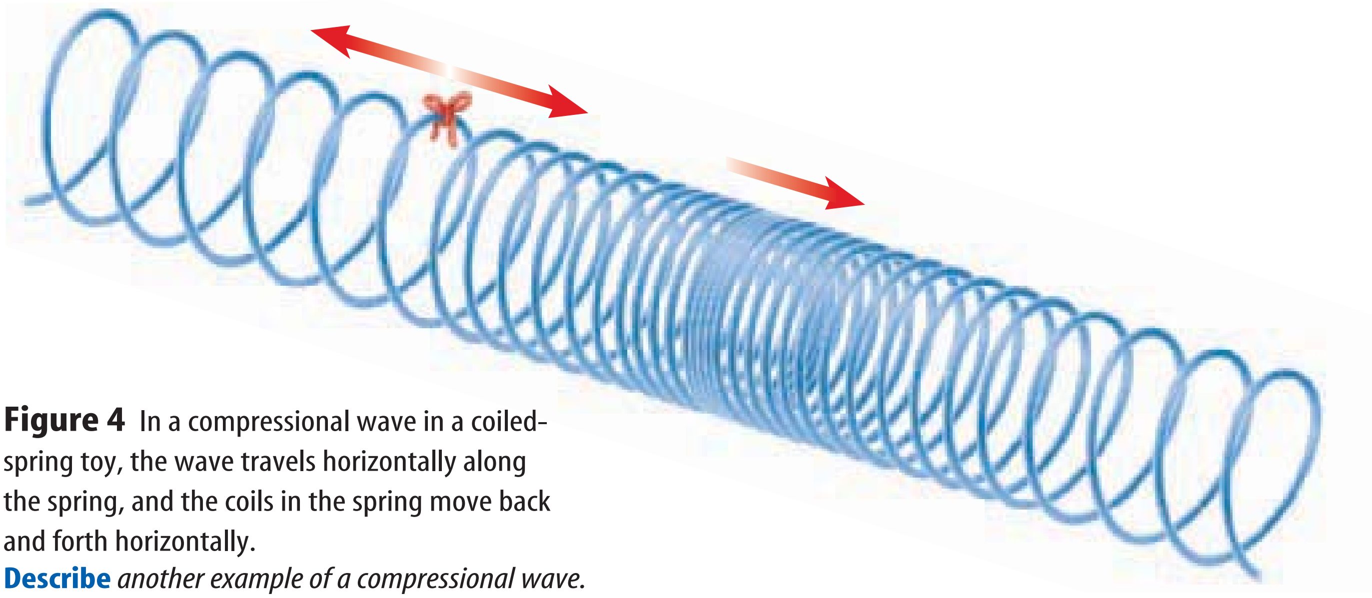


Figure 4 In a compressional wave in a coiled-spring toy, the wave travels horizontally along the spring, and the coils in the spring move back and forth horizontally.
Describe *another example of a compressional wave.*

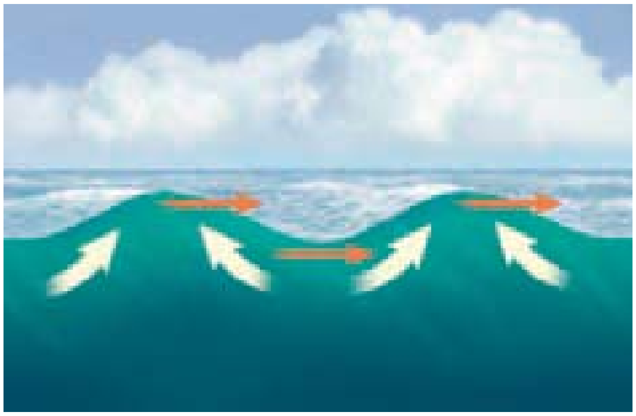
Sound in Other Materials Sound waves also can travel through other mediums, such as water and wood. Particles in these mediums also are pushed together and move apart as the sound waves travel through them. When a sound wave reaches your ear, it causes your eardrum to vibrate. Your inner ear then sends signals to your brain, and your brain interprets the signals as sound.

Reading Check *How do sound waves travel in solids?*

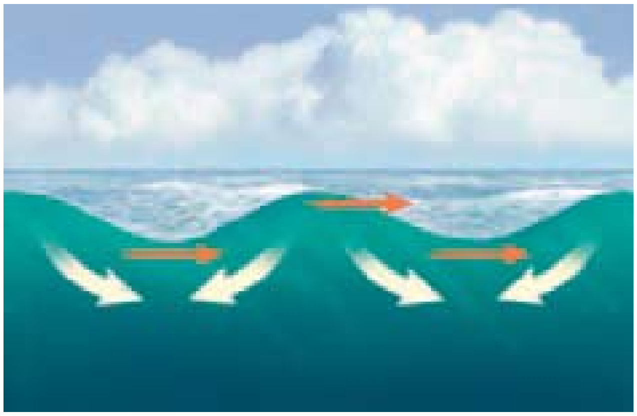
Water Waves Water waves are not purely transverse waves. The water moves up and down as the waves go by. However, the water also moves a short distance back and forth along the direction the wave is moving. This movement happens because the low part of the wave can be formed only by pushing water forward or backward toward the high part of the wave, as in **Figure 5A.** Then, as the wave passes, the water that was pushed aside moves back to its initial position, as in **Figure 5B.** In fact, if you looked closely, you would see that the combination of this up-and-down and back-and-forth motion causes water to move in circles. Anything floating on the surface of the water absorbs some of the waves' energy and bobs in a circular motion.

Ocean waves are formed most often by wind blowing across the ocean surface. As the wind blows faster and slower, the changing wind speed is like a vibration. The size of the waves that are formed depends on the wind speed, the distance over which the wind blows, and how long the wind blows. **Figure 6** on the next page shows how ocean waves are formed.

Figure 5 A water wave causes water to move back and forth, as well as up and down. Water is pushed back and forth to form the crests and troughs.



A The low point of a water wave is formed when water is pushed aside and up to the high point of the wave.



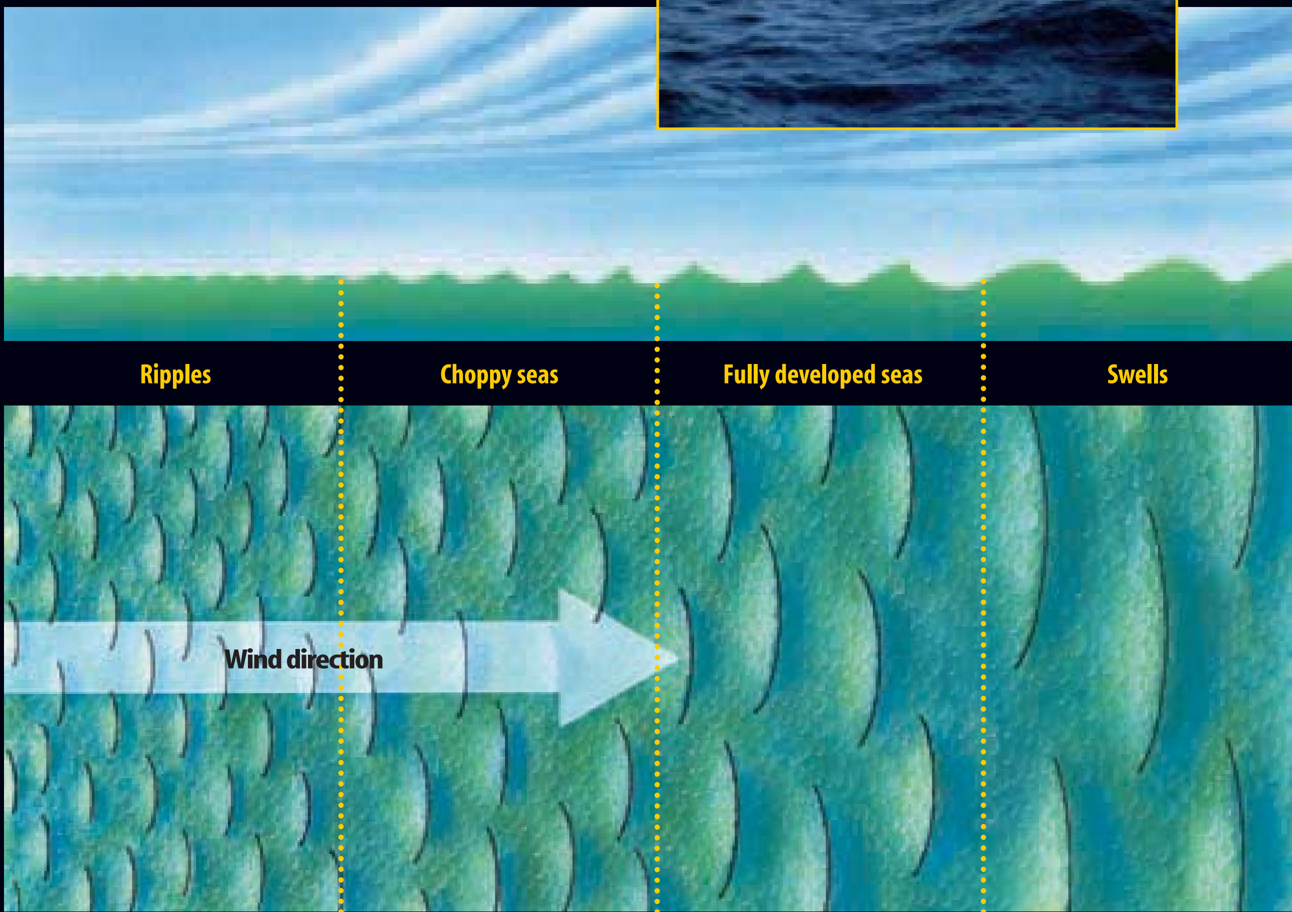
B The water that is pushed aside returns to its initial position.

NATIONAL GEOGRAPHIC

VISUALIZING FORMATION OF OCEAN WAVES

Figure 6

When wind blows across an ocean, friction between the moving air and the water causes the water to move. As a result, energy is transferred from the wind to the surface of the water. The waves that are produced depend on the length of time and the distance over which the wind blows, as well as the wind speed.



▲ Wind causes ripples to form on the surface of the water. As ripples form, they provide an even larger surface area for the wind to strike, and the ripples increase in size.

▲ Waves that are higher and have longer wavelengths grow faster as the wind continues to blow, but the steepest waves break up, forming whitecaps. The surface is said to be choppy.

▲ The shortest-wavelength waves break up, while the longest-wavelength waves continue to grow. When these waves have reached their maximum height, they form fully developed seas.

▲ After the wind dies down, the waves lose energy and become lower and smoother. These smooth, long-wavelength ocean waves are called swells.

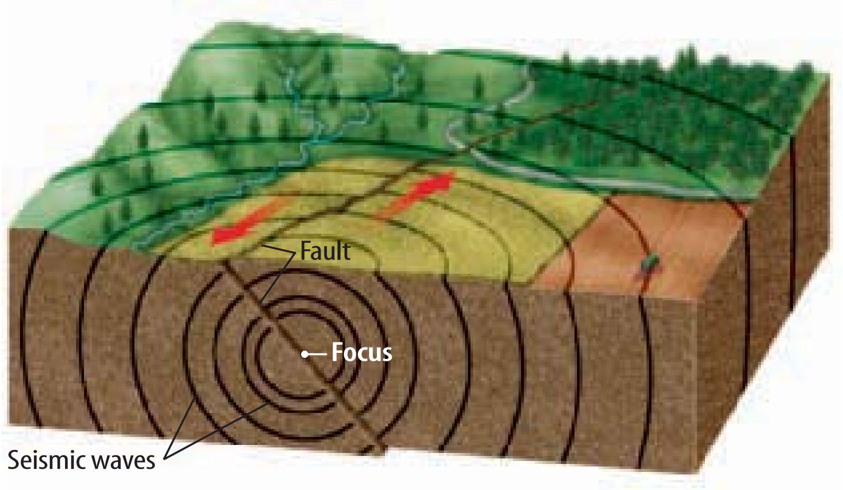


Figure 7 When Earth's crust shifts or breaks, the energy that is released is transmitted outward, causing an earthquake.
Explain *why earthquakes are mechanical waves.*

INTEGRATE Earth Science

Seismic Waves A guitar string makes a sound when it breaks. The string vibrates for a short time after it breaks and produces sound waves. In a similar way, forces in Earth's crust can cause regions of the crust to shift, bend, or even break. The breaking crust vibrates, creating seismic waves that transfer energy outward, as shown in **Figure 7.** Seismic waves are a combination of compressional and transverse waves. They can travel through Earth and along Earth's surface. When objects on Earth's surface absorb some of the energy transferred by seismic waves, they move and shake. The more the crust moves during an earthquake, the more energy is released.

Science Online

Topic: Seismic Waves
Visit gpescience.com for Web links to information about seismic waves.

Activity Write a summary of how seismic waves are used to map Earth's interior.

section 1 review

Summary

Waves and Energy

- A wave is a repeating disturbance or movement that transfers energy through matter or space.
- Waves transfer energy without transporting matter.
- Waves are produced by something that is vibrating.

Mechanical Waves

- Mechanical waves must travel in matter.
- Mechanical waves can be transverse waves or compressional waves.
- In a transverse wave, matter in the medium moves at right angles to the wave motion.
- In a compressional wave, matter in the medium moves back and forth along the direction of the wave motion.

Self Check

1. **Compare and contrast** a transverse wave and a compressional wave. Give an example of each type.
2. **Describe** the motion of a buoy when a water wave passes. Does it move the buoy forward?
3. **Explain** how you could model a compressional wave using a coiled-spring toy.
4. **List** the characteristics of a mechanical wave.
5. **Think Critically** Why do boats need anchors if ocean waves do not carry matter forward?

Applying Math

6. **Calculate Time** The average speed of sound in water is 1,500 m/s. How long would it take a sound wave to travel 9,000 m?

section 2

Wave Properties

Reading Guide

What You'll Learn

- **Define** wavelength, frequency, period, and amplitude.
- **Describe** the relationship between frequency and wavelength.
- **Explain** how a wave's energy and amplitude are related.
- **Calculate** wave speed.

Why It's Important

Waves with different properties can be used in different ways.

Review Vocabulary

vibration: a back and forth movement

New Vocabulary

- crest
- trough
- rarefaction
- wavelength
- frequency
- period
- amplitude

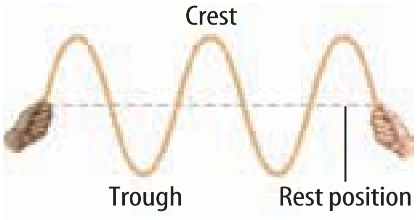
The Parts of a Wave

What makes sound waves, water waves, and seismic waves different from each other? Waves can differ in how much energy they transfer and in how fast they travel. Waves also have other characteristics that make them different from each other.

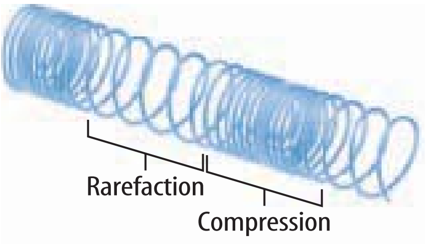
Suppose you shake the end of a rope and make a transverse wave. The transverse wave in **Figure 8** has alternating high points, called **crests,** and low points, called **troughs.**

On the other hand, a compressional wave has no crests and troughs. When a compressional wave passes through a medium, it creates regions where the medium becomes crowded together and more dense, as in **Figure 8.** These regions are compressions. When you make compressional waves in a coiled spring, the compressions are regions where the coils are close together. **Figure 8** also shows that the coils in the regions next to a compression are spread apart, or less dense. These less-dense regions of a compressional wave are called **rarefactions.**

Figure 8 Transverse and compressional waves have different features that travel through a medium and form the wave.

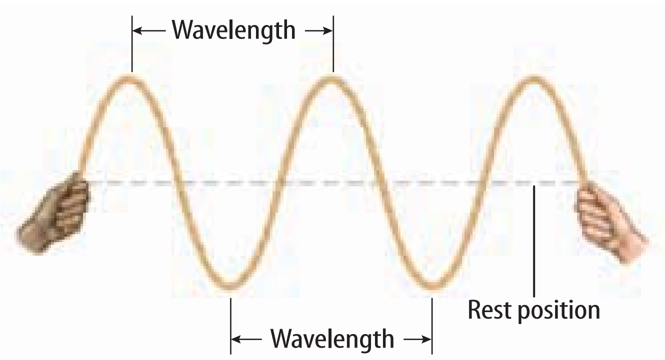


A transverse wave is made of crests and troughs that travel through the medium.

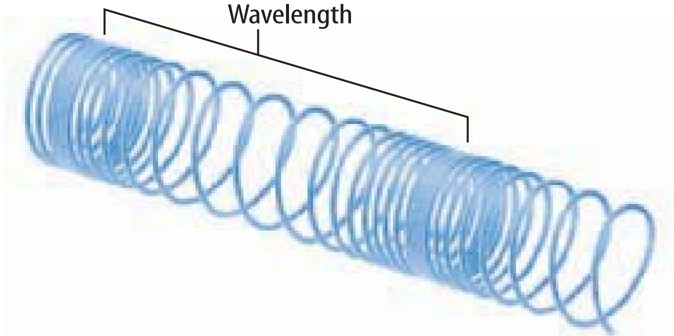


A compressional wave is made of compressions and rarefactions that travel through the medium.

Figure 9 One wavelength starts at any point on a wave and ends at the nearest point just like it.



For transverse waves, a wavelength can be measured from crest to crest or trough to trough.



The wavelength of a compressional wave can be measured from compression to compression or from rarefaction to rarefaction.

Wavelength

Waves also have a property called wavelength. A **wavelength** is the distance between one point on a wave and the nearest point just like it. **Figure 9** shows that for transverse waves, the wavelength is the distance from crest to crest or trough to trough.

A wavelength in a compressional wave is the distance between two neighboring compressions or two neighboring rarefactions, as shown in **Figure 9.** You can measure from the start of one compression to the start of the next compression or from the start of one rarefaction to the start of the next rarefaction. The wavelengths of sound waves that you can hear range from a few centimeters for the highest-pitched sounds to about 15 m for the deepest sounds.

Reading Check *How is wavelength measured in transverse and compressional waves?*

Frequency and Period

When you tune your radio to a station, you are choosing radio waves of a certain frequency. The **frequency** of a wave is the number of wavelengths that pass a fixed point each second. You can find the frequency of a transverse wave by counting the number of crests or troughs that pass by a point each second. The frequency of a compressional wave is the number of compressions or rarefactions that pass a point every second. Frequency is expressed in hertz (Hz). A frequency of 1 Hz means that one wavelength passes by in 1 s. In SI units, 1 Hz is the same as 1/s. The **period** of a wave is the amount of time it takes one wavelength to pass a point. As the frequency of a wave increases, the period decreases. Periods are measured in units of seconds.

Mini LAB

Observing Wavelength

Procedure

1. Complete the safety form.
2. Fill a **pie plate or other wide pan** with **water** about 2 cm deep.
3. Lightly tap your finger once per second on the surface of the water and observe the spacing of the water waves.
4. Increase the rate of your tapping, and observe the spacing of the water waves.

Analysis

1. How is the spacing of the water waves related to their wavelength?
2. How does the spacing of the water waves change when the rate of tapping increases?

Try at Home

Wavelength Is Related to Frequency If you make transverse waves with a rope, you increase the frequency by moving the rope up and down faster. Moving the rope faster also makes the wavelength shorter. This relationship is always true: as frequency increases, wavelength decreases. **Figure 10** compares the wavelengths and frequencies of two different waves.

The frequency of a wave is always equal to the rate of vibration of the source that creates it. If you move the rope up, down, and back up in 1 s, the frequency of the wave you generate is 1 Hz. If you move the rope up, down, and back up five times in 1 s, the resulting wave has a frequency of 5 Hz.

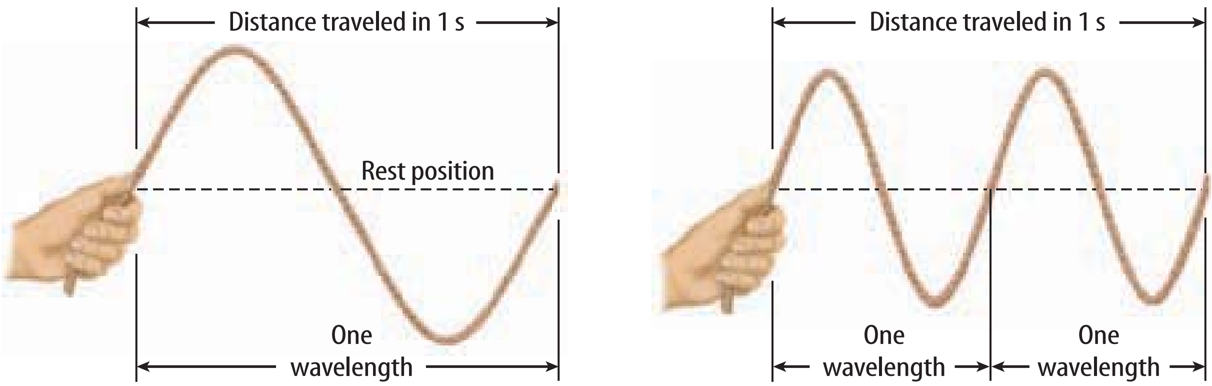
Reading Check ***How are the wavelength and frequency of a wave related?***

Wave Speed

You're at a large stadium watching a baseball game, but you're high up in the bleachers, far from the action. The batter swings and you see the ball rise. An instant later, you hear the crack of the bat hitting the ball. You see the impact before you hear it because light waves travel much faster than sound waves. Therefore, the light waves reflected from the flying ball reach your eyes before the sound waves created by the crack of the bat reach your ears.

The speed of a wave depends on the medium it is traveling through. Sound waves usually travel faster in liquids and solids than they do in gases. However, light waves travel more slowly in liquids and solids than they do in gases or in empty space. Also, sound waves usually travel faster in a material when the temperature of the material is increased. For example, sound waves travel faster in air at 20°C than in air at 0°C.

Figure 10 The wavelength of a wave decreases as the frequency increases.



The rope is moved down, up, and down again one time in 1 s. One wavelength is created on the rope.

The rope is shaken down, up, and down again twice in 1 s. Two wavelengths are created on the rope.

Calculating Wave Speed You can calculate the speed of a wave, represented by v, by multiplying its frequency times its wavelength. Wavelength is represented by the Greek letter *lambda* (λ), and frequency is represented by f.

Wave Speed Equation

speed (in m/s) = frequency (in Hz) × wavelength (in m)

$$v = f\lambda$$

Why does multiplying the frequency unit Hz by the distance unit m give the unit for speed, m/s? Recall that the SI unit Hz is the same as 1/s. Multiplying m × Hz equals m × 1/s, which equals m/s.

INTEGRATE Social Studies

Deadly Ocean Waves Tsunamis can cause serious damage when they hit land. These waves can measure up to 30 m tall and can travel faster than 700 km/h. Research which areas of the world are most vulnerable to tsunamis. Describe the effects of a tsunami that has occurred in these areas.

Applying Math — Solve a Simple Equation

THE SPEED OF SOUND What is the speed of a sound wave that has a wavelength of 2.00 m and a frequency of 170.5 Hz?

IDENTIFY known values and the unknown value

Identify the known values:

wavelength of 2.0 m — means → $\lambda = 2.00$ m

frequency of 170.5 Hz — means → $f = 170.5$ Hz

Identify the unknown value:

the speed of a sound wave — means → $v = ?$ m/s

SOLVE the problem

Substitute the known values $\lambda = 2.00$ m and $f = 170.5$ Hz into the wave speed equation:

$$v = f\lambda = (170.5 \text{ Hz})\ (2.00 \text{ m}) = 341 \text{ m/s}$$

CHECK the answer

Does your answer seem reasonable? Check your answer by dividing the wave speed you calculated by the wavelength given in the problem. The result should be the frequency given in the problem.

Practice Problems

1. A wave traveling in water has a frequency of 500.0 Hz and a wavelength of 3.0 m. What is the speed of the wave?
2. The lowest-pitched sounds humans can hear have a frequency of 20.0 Hz. What is the wavelength of these sound waves if their wave speed is 340.0 m/s?
3. The highest-pitched sound humans can hear have a wavelength of 0.017 m in air. What is the frequency of these sound waves if their wave speed is 340.0 m/s?

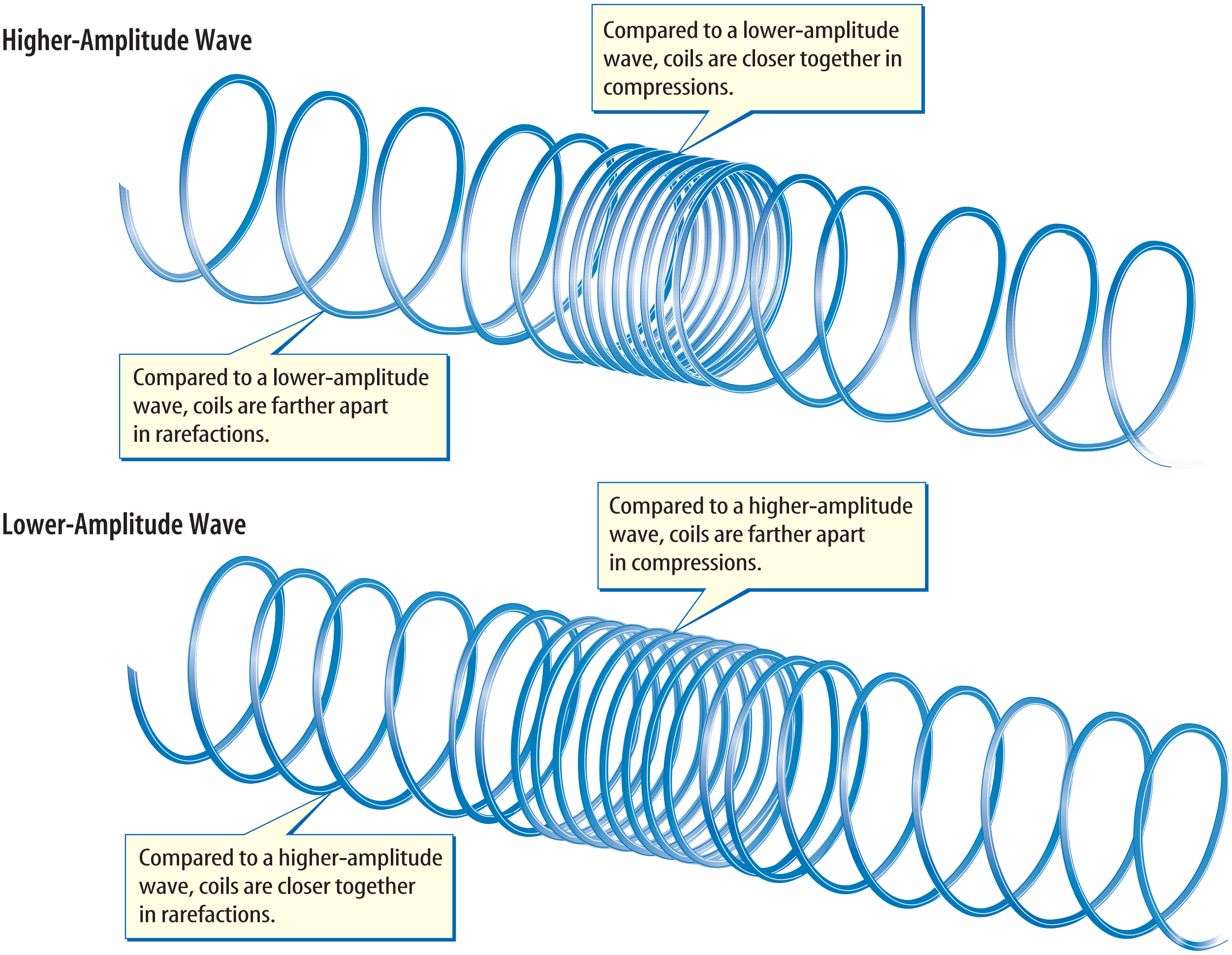
For more practice problems go to page 879, and visit Math Practice at gpescience.com.

Amplitude and Energy

Why do some earthquakes cause terrible damage, while others are hardly felt? This is because the amount of energy a wave transfers can vary. **Amplitude** is related to the energy transferred by a wave. The greater the wave's amplitude, the more energy the wave transfers. Amplitude is measured differently for compressional and transverse waves.

Amplitude of Compressional Waves The amplitude of a compressional wave is related to how tightly the medium is pushed together at the compressions. The denser the medium is at the compressions, the larger its amplitude is and the more energy the wave transfers. For example, it takes more energy to push the coils in a coiled-spring toy tightly together than to barely move them. The closer the coils are in a compression, the farther apart they are in a rarefaction. So, the less dense the medium is at the rarefactions, the more energy the wave transfers. **Figure 11** shows compressional waves with different amplitudes.

Figure 11 The amplitude of a compressional wave depends on the density of the medium in the compressions and rarefactions.



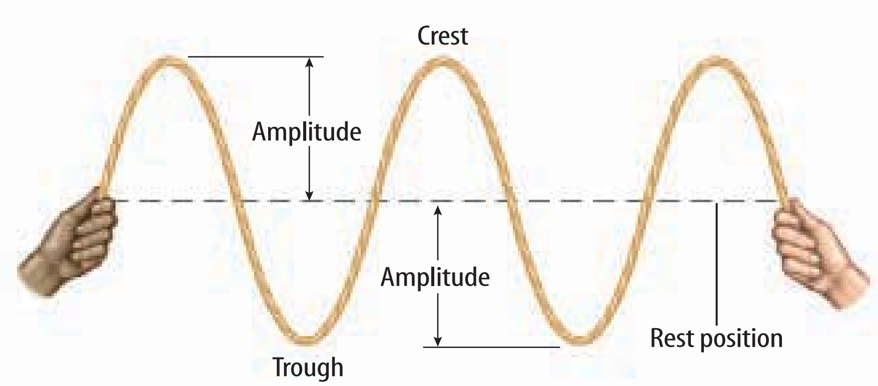


Figure 12 The amplitude of a transverse wave is the distance between a crest or a trough and the position of the medium at rest. **Describe** *how you could create waves with different amplitudes in a piece of rope.*

Amplitude of Transverse Waves If you've ever been knocked over by an ocean wave, you know that the higher the wave, the more energy it transfers. Remember that the amplitude of a wave increases as the energy transferred by the wave increases. So a tall ocean wave has a greater amplitude than a short ocean wave does. The amplitude of any transverse wave is the distance from the crest or trough of the wave to the rest position of the medium, as shown in **Figure 12.**

section 2 review

Summary

The Parts of a Wave

- Transverse waves have repeating high points called crests and low points called troughs.
- Compressional waves have repeating high-density regions called compressions, and low-density regions called rarefactions.

Wavelength, Frequency, and Period

- Wavelength is the distance between a point on a wave and the nearest point just like it.
- A wave's frequency is the number of wavelengths passing a fixed point each second.
- A wave's period is the amount of time it takes one wavelength to pass a fixed point.

Wave Speed and Amplitude

- The speed of a wave depends on the material it is traveling in, and on the temperature.
- The speed of a wave is the product of its frequency and its wavelength:

$$v = f\lambda$$

- As the amplitude of a wave increases, the energy transferred by the wave increases.

Self Check

1. **Describe** the difference between a compressional wave with a large amplitude and one with a small amplitude.
2. **Describe** how the wavelength of a wave changes when the wave slows down but its frequency doesn't change.
3. **Explain** how the frequency of a wave changes when the period of the wave increases.
4. **Form a hypothesis** to explain why a sound wave travels faster in a solid than in a gas.
5. **Think Critically** You make a transverse wave by shaking the end of a long rope up and down. Explain how you would shake the end of the rope to make the wavelength shorter. How would you shake the end of the rope to increase the energy transferred by the wave?

Applying Math

6. **Calculate** the frequency of a water wave that has a wavelength of 0.5 m and a speed of 4.0 m/s.
7. **Calculate Wavelength** An FM radio station broadcasts radio waves with a frequency of 100,000,000 Hz. What is the wavelength of these radio waves if they travel at a speed of 300,000 km/s?

LAB

Wave Speed and Tension

Before playing her violin, a violinist must adjust the tension, or the amount of force pulling on each string, to tune the violin.

Real-World Problem

How does the tension in a material affect the waves traveling in the material?

Goal

- **Determine** the relationship between tension and wave speed.

Materials

coiled-spring toy
meterstick
stopwatch

Safety Precautions

Procedure

1. Complete the safety form.
2. Attach one end of the spring to a chair leg so that the spring rests on a smooth floor.
3. Stretch the spring along the floor to a length of 1 m.
4. Make a compressional wave by squeezing together several coils and then releasing them.
5. Have your partner time how long the wave takes to travel two or three lengths of the spring. Record the time in your data table. Record the distance the wave traveled in your data table.
6. Repeat steps 4 and 5 two more times for waves 2 and 3.
7. Stretch the spring to a length of 1.5 m.
8. Repeat steps 4 and 5 for waves 4, 5, and 6.

Data Table

	Distance (m)	Wave Time (s)	Wave Speed (m/s)
Wave 1			
Wave 2			
Wave 3	Do not write in this book.		
Wave 4			
Wave 5			
Wave 6			

Analyze Your Data

1. **Calculate** the wave speed for each wave using the formula:

   speed = distance/time

2. Calculate the average speed of the waves on the spring with a length of 1.0 m by adding the measured wave speeds and dividing by 3.
3. Calculate the average speed of the waves on the spring with a length of 1.5 m.

Conclude and Apply

1. How did the tension in the spring change as the length of the spring increased?
2. How did the wave speed depend on the tension? How could you make the waves travel even faster? Test your prediction.

Communicating Your Data

Compare your results with those of other students in your class. Discuss why results might be different.

section 3

The Behavior of Waves

Reading Guide

What You'll Learn

- **State** the law of reflection.
- **Explain** why waves change direction when they travel from one material to another.
- **Compare and contrast** refraction and diffraction.
- **Describe** how waves interfere with each other.

Why It's Important

You can hear an echo, see shadows, and check your reflection in a mirror because of how waves behave.

Review Vocabulary

perpendicular: a line that forms a 90-degree angle with another line

New Vocabulary

- refraction
- diffraction
- interference
- standing wave
- resonance

Reflection

If you are one of the last people to leave your school building at the end of the day, you'll probably find the hallways quiet and empty. When you close your locker door, the sound echoes down the empty hall. Your footsteps also make a hollow sound. Thinking you're alone, you may be startled by your own reflection in a classroom window. The echoes and your image looking back at you from the window are caused by wave reflection.

Reflection occurs when a wave strikes an object and bounces off it. All types of waves—including sound, water, and light waves—can be reflected. How does the reflection of light allow the boy in **Figure 13** to see himself in the mirror? It happens in two steps. First, light strikes his face and bounces off. Then, the light reflected off his face strikes the mirror and is reflected into his eyes.

Echoes A similar thing happens to sound waves when your footsteps echo. Sound waves form when your foot hits the floor and the waves travel through the air to both your ears and other objects. Sometimes, when the sound waves hit another object, they reflect off it and come back to you. Your ears hear the sound again, a few seconds after you first heard your footstep.

Bats and dolphins use echoes to learn about their surroundings. A dolphin makes a clicking sound and listens to the echoes. These echoes enable the dolphin to locate nearby objects.

Figure 13 The light that strikes the boy's face is reflected into the mirror. The light then reflects off the mirror into his eyes.
List *examples of waves that can be reflected.*

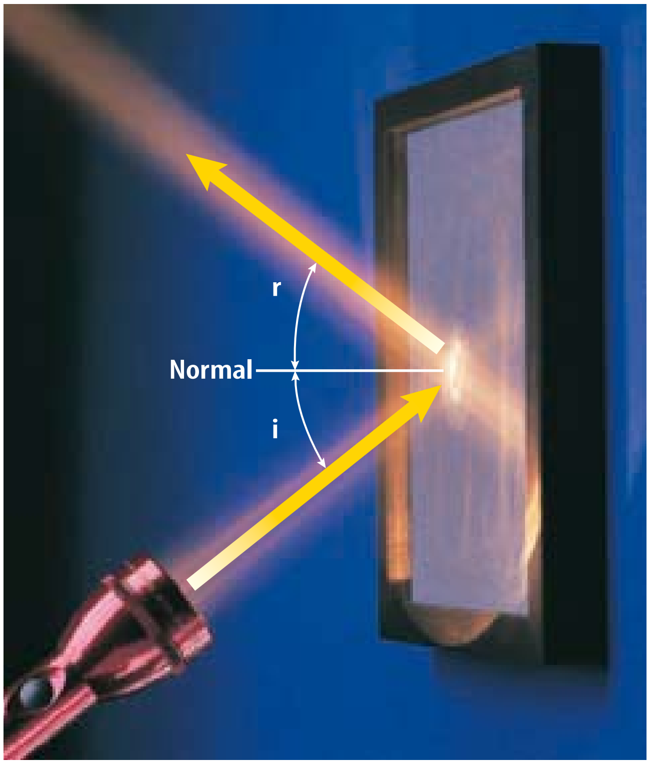


Figure 14 A flashlight beam is made of light waves. When any wave is reflected, the angle of incidence, *i*, equals the angle of reflection, *r*.

The Law of Reflection Look at the two light beams in **Figure 14.** The beam striking the mirror is called the incident beam. The beam that bounces off the mirror is called the reflected beam. The line drawn perpendicular to the surface of the mirror is called the normal. The angle formed by the incident beam and the normal is the angle of incidence, labeled *i.* The angle formed by the reflected beam and the normal is the angle of reflection, labeled *r.* According to the law of reflection, the angle of incidence is equal to the angle of reflection. All reflected waves obey this law. Objects that bounce from a surface sometimes behave like waves that are reflected from a surface. For example, suppose you throw a bounce pass while playing basketball. The angle between the ball's direction and the normal to the floor is the same before and after it bounces.

Refraction

Do you notice anything unusual in **Figure 15?** The pencil looks as if it is broken into two pieces. But if you pulled the pencil out of the water, you would see that it is unbroken. This illusion is caused by refraction. How does it work?

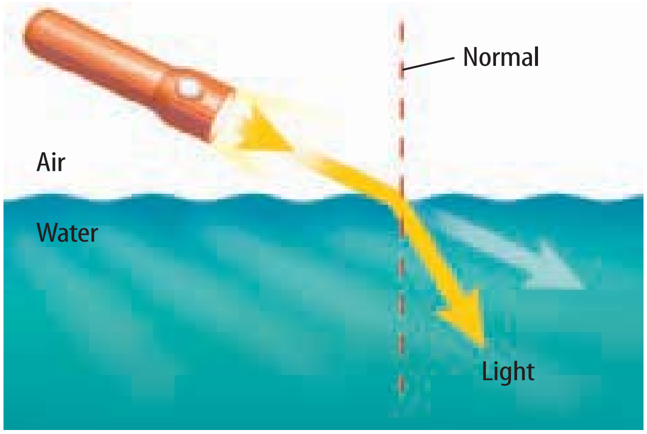
Remember that a wave's speed depends on the medium it is moving through. When a wave passes from one medium to another—such as when a light wave passes from air to water—it changes speed. If the wave is traveling at an angle when it passes from one medium to another, it changes direction, or bends, as it changes speed. **Refraction** is the bending of a wave caused by a change in its speed as it moves from one medium to another. The greater the change in speed is, the more the wave bends.

Reading Check *When does refraction occur?*

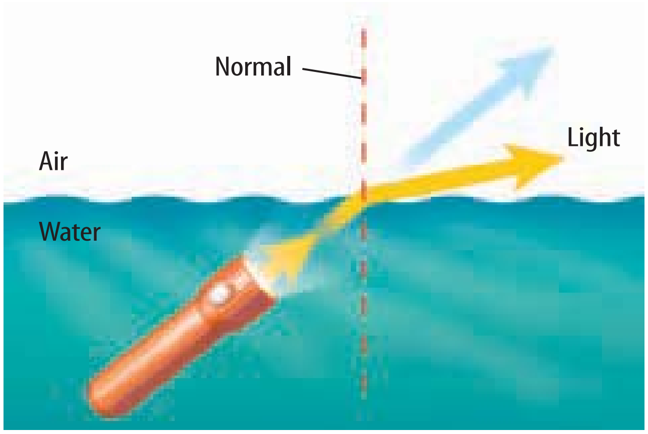
Figure 16A on the next page shows what happens when a wave passes into a material in which it slows down. The wave is refracted (bent) toward the normal. **Figure 16B** shows what happens when a wave passes into a medium in which it speeds up. Then the wave is refracted away from the normal.

Figure 15 The pencil looks like it is broken at the surface of the water because of refraction.

Figure 16 Light waves travel more slowly in water than in air. This causes light waves to change direction when they move from water to air or air to water.
Predict *how the beam would bend if the speed were the same in both air and water.*



A When light waves travel from air to water, they slow down and bend toward the normal.



B When light waves travel from water to air, they speed up and bend away from the normal.

Refraction of Light in Water You may have noticed that objects that are under water seem closer to the surface than they really are. **Figure 17** shows how refraction causes this illusion. In the figure, the light waves reflected from the boy's foot are refracted away from the normal and enter your eyes. However, your brain assumes that all light waves have traveled in a straight line. The light waves that enter your eyes seem to have come from a foot that was higher in the water. This is also why the pencil in **Figure 15** seems broken. The light waves coming from the part of the pencil that is under water are refracted, but your brain interprets them as if they have traveled in a straight line. However, the light waves coming from the part of the pencil above the water are not refracted. So, the part of the pencil that is under water looks as if it has shifted.

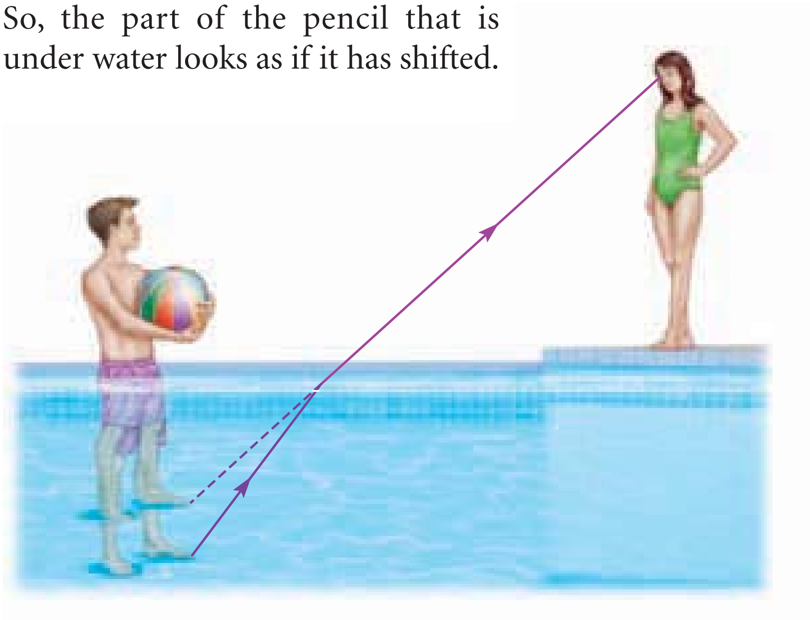


Figure 17 Light waves from the boy's foot bend away from the normal as they pass from water to air. This makes his foot look closer to the surface than it really is.
Infer *whether the boy's knee would seem closer to the surface than it is.*

Figure 18 Diffraction causes ocean waves to change direction as they pass a group of islands.

Diffraction

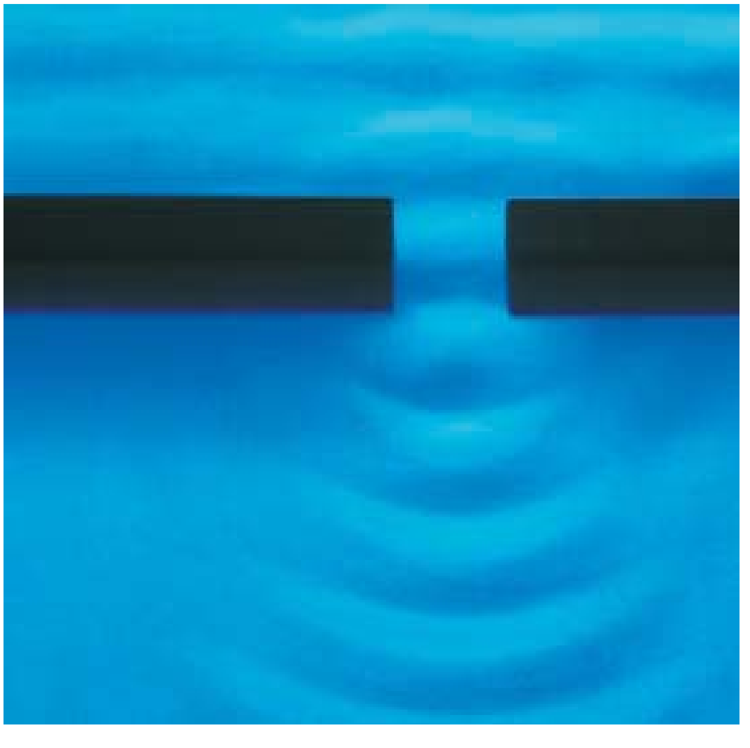
When waves strike an object, several things can happen. Some of the wave's energy can be absorbed by the object. The waves can also be reflected. If the object is transparent, light waves can be refracted as they pass through it. Sometimes, the waves may be both reflected and refracted. If you look into a glass window, sometimes you can see your reflection in the window, as well as objects behind it.

Waves also can behave another way when they strike an object. The waves can bend around the object. **Figure 18** shows how ocean waves change direction and bend after they strike an island. **Diffraction** occurs when an object causes a wave to change direction and bend around it. Diffraction and refraction both cause waves to bend. The difference is that refraction occurs when waves pass through an object, while diffraction occurs when waves pass around an object.

Reading Check *How do diffraction and refraction differ?*

Waves also can be diffracted when they pass through a narrow opening, as shown in **Figure 19.** After they pass through the opening, the waves spread out. In this case, the waves are bending around the corners of the opening.

Figure 19 When water waves pass through a small opening in a barrier, they diffract and spread out after they pass through the hole.



Diffraction and Wavelength How much does a wave bend when it strikes an object or an opening? The amount of diffraction that occurs depends on how big the obstacle or opening is compared to the wavelength, as shown in **Figure 20.** When an obstacle is smaller than the wavelength, the waves bend around it. But if the obstacle is larger than the wavelength, the waves do not diffract as much. In fact, if the obstacle is much larger than the wavelength, almost no diffraction occurs. The obstacle casts a shadow because almost no waves bend around it.

Hearing Around Corners For example, suppose that you're walking down a hallway and hear sounds coming from the lunchroom before you reach the open lunchroom door. However, you can't see into the room until you reach the doorway. Why can you hear the sound waves but not see the light waves while you're still in the hallway? The wavelengths of sound waves are similar in size to a door opening. Sound waves diffract around the door and spread out down the hallway. Light waves have a much shorter wavelength. They are hardly diffracted at all by the door. This is why you can't see into the room until you get close to the door.

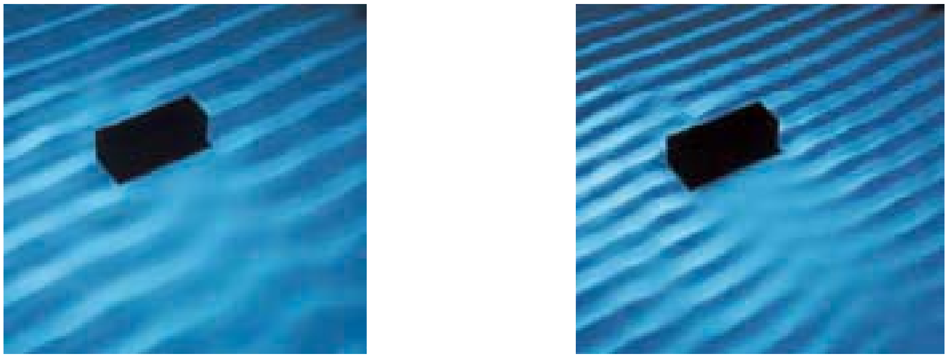
Diffraction of Radio Waves Diffraction also affects your radio's reception. AM radio waves have longer wavelengths than FM radio waves do. Because of their longer wavelengths, AM radio waves diffract around obstacles such as buildings and mountains. The FM waves with their short wavelengths do not diffract as much. As a result, AM radio reception is often better than FM reception around tall buildings and natural barriers such as hills.

Science Online

Topic: Diffraction
Visit gpescience.com for Web links to information about diffraction.

Activity Research the wave lengths of several types of waves. For each wave type, give an example of an object that could cause diffraction to occur.

Figure 20 The diffraction of waves around an obstacle depends on the wavelength and the size of the obstacle.



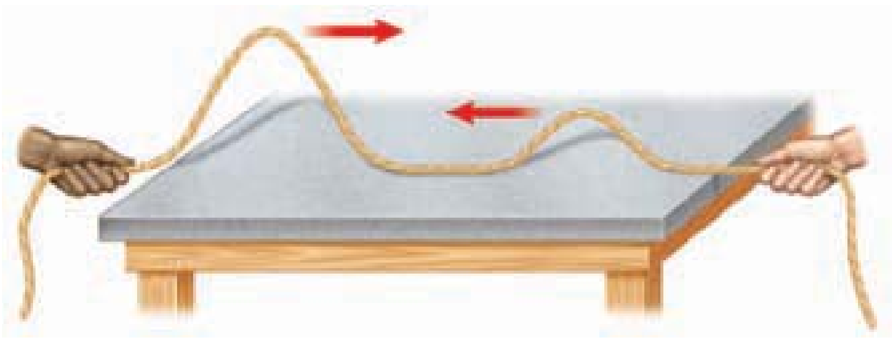
More diffraction occurs when the wavelength is the same size as the obstacle.

Less diffraction occurs when the wavelength is smaller than the obstacle.

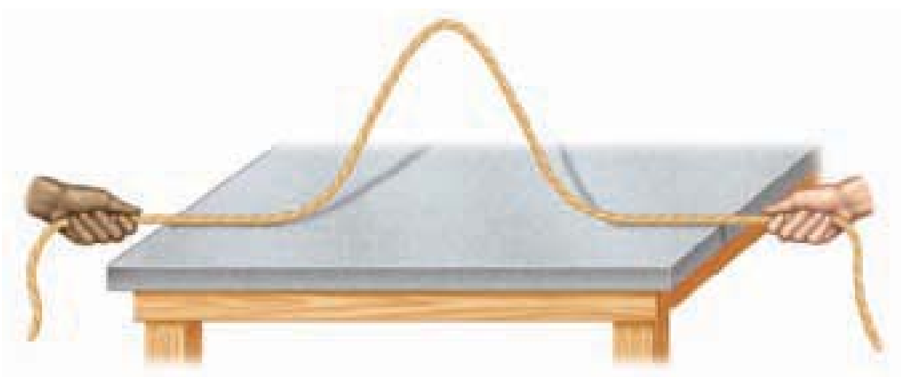
Interference

Suppose two waves are traveling toward each other on a long rope, as in **Figure 21A.** What will happen when the two waves meet? If you did this experiment, you would find that the two waves pass right through each other, and each one continues to travel in its original direction, as shown in **Figure 21B** and **Figure 21C.** If you look closely at the waves when they meet each other in **Figure 21B,** you will see a wave that looks different from either of the two original waves. When the two waves arrive at the same place at the same time, they combine to form a new wave. When two or more waves overlap and combine to form a new wave, the process is called **interference.** This new wave exists only while the two original waves continue to overlap. The two ways that the waves can combine are called constructive interference and destructive interference.

Figure 21 Interference occurs while two waves are overlapping. Then the waves combine to form a new wave. Two waves traveling on a rope can interfere with each other.

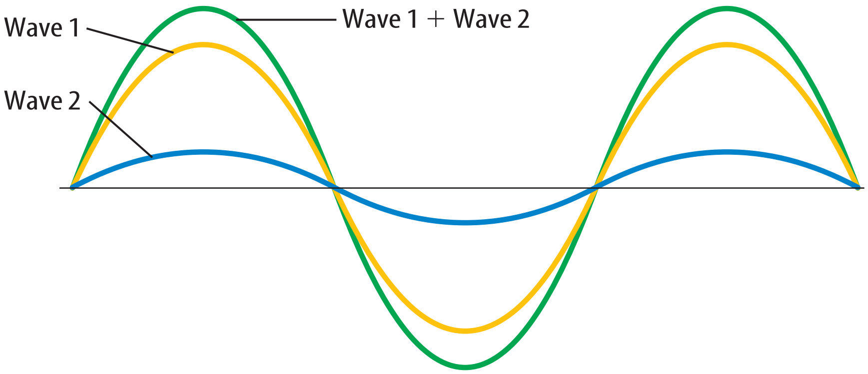


A Two waves move toward each other on a rope.



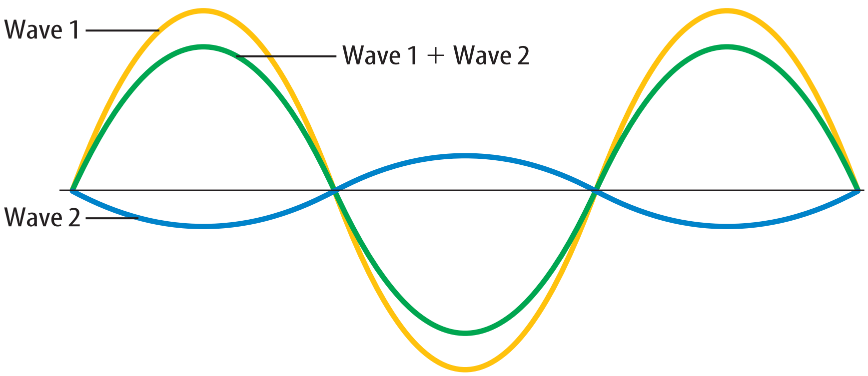
B As the waves overlap, they interfere to form a new wave.
Identify *What is the amplitude of the new wave?*

C While the two waves overlap, they continue to move right through each other. Afterward, they continue moving unchanged, as if they had never met.



Constructive Interference

A If Wave 1 and Wave 2 overlap, they constructively interfere and form the green wave. Wave 1 and Wave 2 are in phase.



Destructive Interference

B If Wave 1 and Wave 2 overlap, they destructively interfere and form the green wave. Wave 1 and Wave 2 are out of phase.

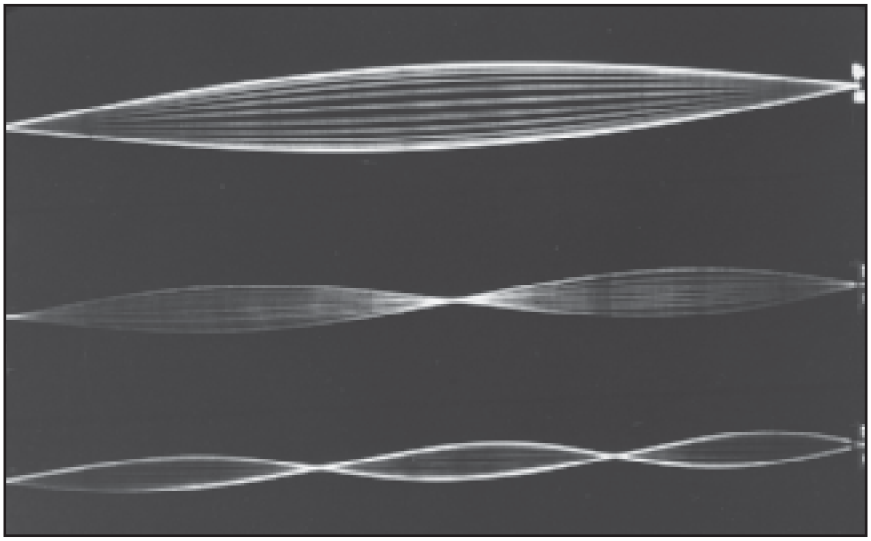
Figure 22 When waves interfere with each other, constructive and destructive interference can occur. **Infer** *how the energy transferred by each wave changes when interference occurs.*

Constructive Interference In constructive interference, shown in **Figure 22A,** the waves add together. This happens when the crests of two or more transverse waves arrive at the same place at the same time and overlap. The amplitude of the new wave that forms is equal to the sum of the amplitudes of the original waves. Constructive interference also occurs when the compressions of different compressional waves overlap. If the waves are sound waves, for example, constructive interference produces a louder sound. Waves undergoing constructive interference are said to be in phase.

Destructive Interference In destructive interference, the waves subtract from each other as they overlap. This happens when the crests of one transverse wave meet the troughs of another transverse wave, as shown in **Figure 22B.** The amplitude of the new wave is the difference between the amplitudes of the waves that overlapped. With compressional waves, destructive interference occurs when the compression of one wave overlaps with the rarefaction of another wave. The compressions and rarefactions combine and form a wave with reduced amplitude. When destructive interference happens with sound waves, it causes a decrease in loudness. Waves undergoing destructive interference are said to be out of phase.

Noise Damage People who are exposed to constant loud noises, such as those made by airplane engines, can suffer hearing damage. Special ear protectors have been developed that use destructive interference to cancel damaging noise. With a classmate, list all the jobs you can think of that require ear protectors.

Figure 23 Standing waves form a wave pattern that seems to stay in the same place.
Explain *how nodes form in a standing wave.*



Standing Waves

When you make transverse waves with a rope, you might shake one end while your friend holds the other end still. What would happen if you both shook the rope continuously to create identical waves moving toward each other? As the two waves travel in opposite directions down the rope, they continually pass through each other. Interference takes place as the waves from each end overlap along the rope. At any point where a crest meets a crest, a new wave with a larger amplitude forms. However, at points where crests meet troughs, the waves cancel each other and no motion occurs.

The interference of the two identical waves makes the rope vibrate in a special way, as shown in **Figure 23.** The waves create a pattern of crests and troughs that do not seem to be moving. Because the wave pattern stays in one place, it is called a standing wave. A **standing wave** is a special type of wave pattern that forms when waves equal in wavelength and amplitude, but traveling in opposite directions, continuously interfere with each other. The places where the two waves always cancel are called nodes. The nodes always stay in the same place on the rope. Meanwhile, the wave pattern vibrates between the nodes.

Standing Waves in Music When the string of a violin is played with a bow, it vibrates and creates standing waves. The standing waves in the string help produce a rich, musical tone. Other instruments also rely on standing waves to produce music. Some instruments, such as flutes, create standing waves in a column of air. In other instruments, such as drums, a tightly stretched piece of material vibrates in a special way to create standing waves. As the material in a drum vibrates, nodes are created on the surface of the drum.

Resonance

You might have noticed that bells of different sizes and shapes create different notes. When you strike a bell, the bell vibrates at certain frequencies called the natural frequencies. All objects have their own natural frequencies of vibration, which depend on the object's size, shape, and the material it is made from.

There is another way to make something vibrate at its natural frequencies. Suppose you have a tuning fork that has a single natural frequency of 440 Hz. Imagine that a sound wave of the same frequency strikes the tuning fork. Because the sound wave has the same frequency as the natural frequency of the tuning fork, the tuning fork will vibrate. The process by which an object is made to vibrate by absorbing energy at its natural frequencies is called **resonance.**

Sometimes, resonance can cause an object to absorb a large amount of energy. Recall that the amplitude of a wave increases as the energy it transfers increases. In the same way, an object vibrates more strongly as it continues to absorb energy at its natural frequencies. If enough energy is absorbed, the object can vibrate so strongly that it breaks apart.

Mini LAB

Experimenting with Resonance

Procedure

1. Complete the safety form.
2. Strike a **tuning fork** with a **mallet.**
3. Hold the vibrating tuning fork 1 cm from a **second tuning fork** that has the same frequency.
4. Strike the tuning fork again. Hold it 1 cm from a **third tuning fork** that has a different frequency.

Analysis

How did the vibrating tuning fork affect the other tuning forks? Explain.

section 3 review

Summary

Reflection and Refraction

- When reflection of a wave occurs, the angle of incidence equals the angle of reflection.
- Refraction occurs when a wave changes direction as it moves from one medium to another.

Diffraction

- Diffraction occurs when a wave changes direction by bending around an obstacle.
- The effects of diffraction are greatest when the wavelength is nearly the obstacle's size.

Interference and Resonance

- Interference occurs when two or more waves overlap and form a new wave.
- Interference between two waves with the same wavelength and amplitude, but moving in opposite directions, produces a standing wave.
- Resonance occurs when an object is made to vibrate by absorbing energy from vibrations at its natural frequencies.

Self Check

1. **Compare** the loudness of sound waves that are in phase when they interfere with the loudness of sound waves that are out of phase when they interfere.
2. **Describe** how the reflection of light waves enables you to see your image in a mirror.
3. **Describe** the energy transformations that occur when one tuning fork makes another tuning fork resonate.
4. **Think Critically** Suppose the speed of light were greater in water than in air. Draw a diagram to show whether an object under water would seem deeper or closer to the surface than it really is.

Applying Math

5. **Use Percentages** You aim a flashlight at a window. The radiant energy in the reflected beam is two-fifths of the energy in the incident beam. What percentage of the incident beam energy passed through the window?
6. **Calculate Angle of Incidence** The angle between a flashlight beam that strikes a mirror and the reflected beam is 80°. What is the angle of incidence?

LAB

Measuring Wave Properties

Goals

- **Measure** the speed of a transverse wave.
- **Create** waves with different amplitudes.
- **Measure** the wavelength of a transverse wave.

Materials

long spring, rope, or hose
meterstick
stopwatch

Safety Precautions

Real-World Problem

Some waves travel through space; others pass through a medium such as air, water, or earth. Each wave has a wavelength, speed, frequency, and amplitude. How can the speed of a wave be measured? How can the wavelength be determined from the frequency?

Procedure

1. Complete the safety form before you begin.
2. With a partner, stretch your spring across an open floor and measure the length of the spring. Record this measurement in the data table. Make sure the spring is stretched to the same length for each step.
3. Have your partner hold one end of the spring. Create a single wave pulse by shaking the other end of the spring back and forth.
4. Have a third person use a stopwatch to measure the time needed for the pulse to travel the length of the spring. Record this measurement in the *Wave Time* column of your data table.
5. Repeat steps 3 and 4 two more times.
6. **Calculate** the speed of waves 1, 2, and 3 in your data table by using the formula speed = distance/time. Average the speeds of waves 1, 2, and 3 to find the speed of waves on your spring.
7. **Create** a wave with several wavelengths. You make one wavelength when your hand moves left, right, and left again. Count the number of wavelengths that you generate in 10 s. Record this measurement for wave 4 in the *Wavelength Count* column in your data table.
8. **Repeat** step 7 two more times. Each time, create a wave with a different wavelength by shaking the spring faster or slower.

Analyze Your Data

1. **Calculate** the frequency of waves 4, 5, and 6 by dividing the number of wavelengths by 10 s.
2. Calculate the wavelength of waves 4, 5, and 6 using the formula
   wavelength = wave speed/frequency.
   Use the average speed calculated in step 5 for the wave speed.

Wave Property Measurement

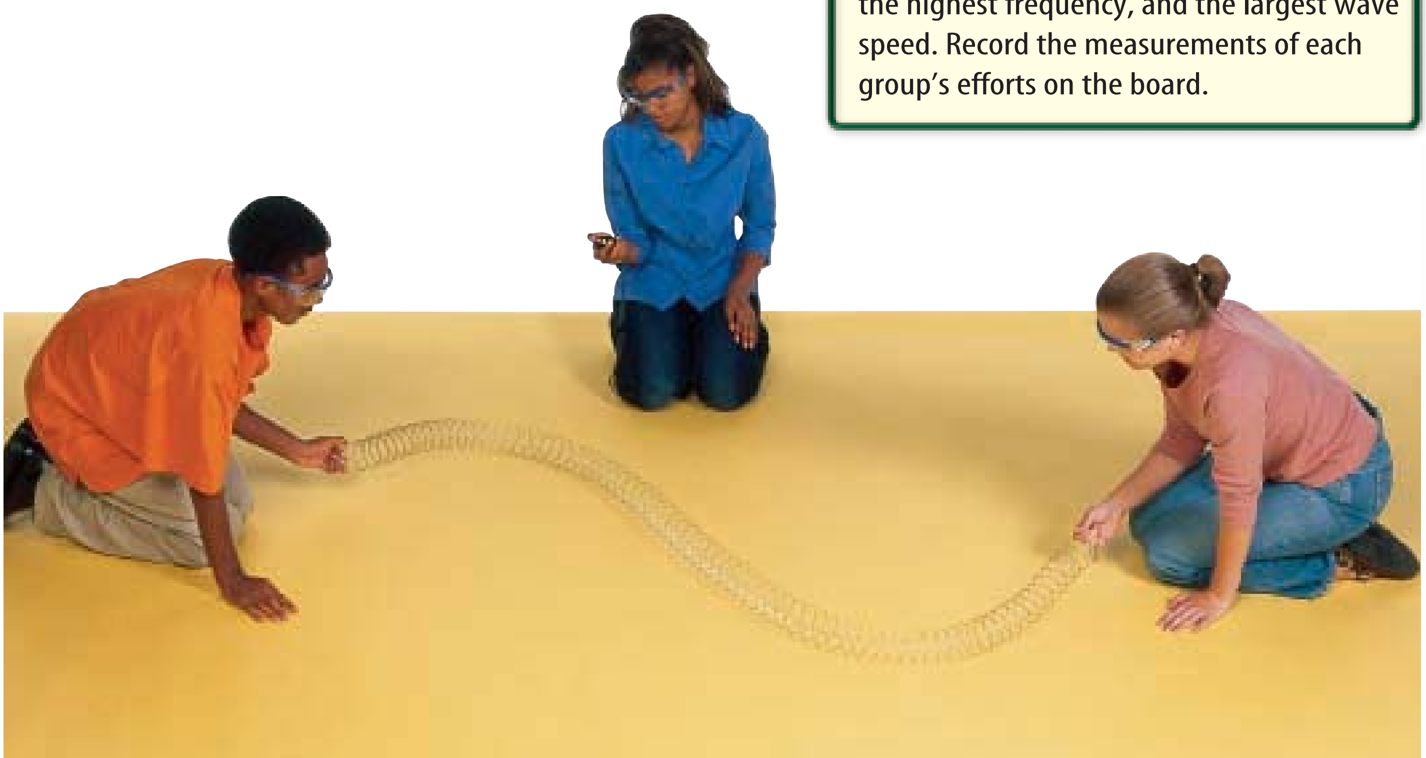
	Spring Length	Wave Time	Wave Speed
Wave 1			
Wave 2			
Wave 3	Do not write in this book.		
	Wavelength Count	**Frequency**	**Wavelength**
Wave 4			
Wave 5			
Wave 6			

Conclude and Apply

1. Was the wave speed different for the three different pulses you created? Why or why not?
2. Why would you average the speeds of the three different pulses to calculate the speed of waves on your spring?
3. How did the wavelength of the waves you created depend on the frequency of the waves?

Communicating Your Data

Ask your teacher to set up a contest between the groups in your class. Have each group compete to determine who can create waves with the longest wavelength, the highest frequency, and the largest wave speed. Record the measurements of each group's efforts on the board.



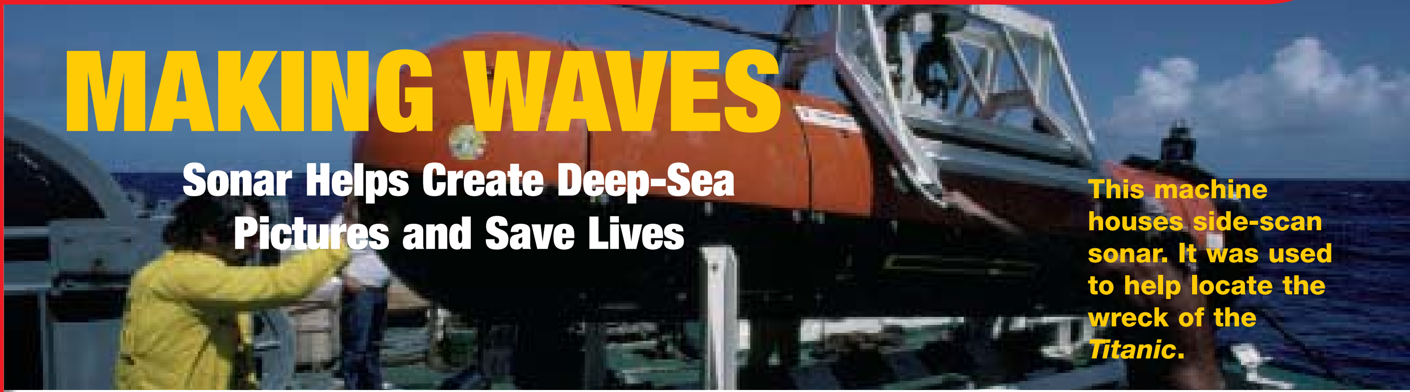
TIME

SCIENCE AND HISTORY

SCIENCE CAN CHANGE THE COURSE OF HISTORY!

MAKING WAVES

Sonar Helps Create Deep-Sea Pictures and Save Lives



This machine houses side-scan sonar. It was used to help locate the wreck of the *Titanic*.

What is sonar?

Sonar is a device that uses sound waves to locate and measure the distance to underwater objects. Its name is a shortened version of SOund NAvigation and Ranging.

How does sonar work?

Sonar sends out a ping sound that reflects back when it hits an underwater object. Because sound travels through water at a known speed (about 1,500 m/s), scientists measure how long the sound takes to return, then they calculate the distance.

Why was it invented?

Sonar was developed by scientists in the early twentieth century as a way to detect icebergs and prevent boating disasters. Its technical advancement was hurried by the Allies' need to detect German submarines in World War I. By 1918, the United States and Great Britain had developed an active sonar system placed in submarines sent to attack other subs.

By World War II, sonar allowed ships to defend themselves effectively from enemy subs. The strategy was to use sonar to find subs and then fire depth charges at them from a safe distance. After the war, sonar-absorbing hulls and quiet engines and machinery ensured that subs could partly shield themselves from sonar.

Sonar is now used to help find schools of fish. Oceanographers also use it to map ocean and lake floors. Sonar has been vital, too, in the discovery of sunken airplanes and ships.

In 1985, a French and American team used a new type of sonar device called side-scan sonar to locate the *Titanic,* the passenger liner that sank in 1912. This kind of sonar projects a tight beam of sound to create detailed images of the sea bed. Members of the expedition towed this sonar device about 170 m above the seabed across a section of the Atlantic Ocean where the *Titanic* went down. Weeks later, video cameras finally spotted the wreck.

The *Titanic* was found thanks to sonar.

Report Research how sonar was used by navies in World War I and World War II. Did sonar affect each war's outcome? How did it save lives? What uses can you think of for sonar if it could be used in everyday life?

Reviewing Main Ideas

Section 1 The Nature of Waves

1. Waves are rhythmic disturbances that transfer energy through matter or space.
2. Waves transfer only energy, not matter.

3. Mechanical waves need matter to travel through. Mechanical waves can be compressional or transverse.
4. When a transverse wave travels in a medium, matter in the medium moves at right angles to the direction the wave travels.
5. When a compressional wave travels in a medium, matter moves back and forth along the same direction that the wave travels.

Section 2 Wave Properties

1. The movement of high points in a medium, called crests, and low points, called troughs, forms a transverse wave.
2. The movement of more-dense regions, called compressions, and less-dense regions, called rarefactions, forms a compressional wave.
3. Transverse and compressional waves can be described by their wavelengths, frequencies, periods, and amplitudes. As frequency increases, wavelength always decreases.
4. The greater a wave's amplitude is, the more energy it transfers.

5. A wave's velocity can be calculated by multiplying its frequency times its wavelength.

Section 3 The Behavior of Waves

1. For all waves, the angle of incidence equals the angle of reflection.
2. A wave is bent, or refracted, when it changes speed as it enters a new medium.

3. When two or more waves overlap, they combine to form a new wave. This process is called interference.

FOLDABLES™ Use the Foldable that you made at the beginning of this chapter to help you review waves.

chapter 10 Review

Using Vocabulary

amplitude p. 288	rarefaction p. 294
compressional wave p.290	refraction p. 302
crest p. 294	resonance p. 309
diffraction p. 304	standing wave p. 308
frequency p. 295	transverse wave p. 290
interference p. 306	trough p. 294
medium p. 289	wave p. 298
period p. 295	wavelength p. 295

Answer the following questions using complete sentences.

1. Compare and contrast reflection and refraction.
2. Which type of wave has points called nodes that do not move?
3. Which part of a compressional wave has the lowest density?
4. Find two words in the vocabulary list that describe the bending of a wave.
5. What occurs when waves overlap?
6. What is the relationship among amplitude, crest, and trough?
7. What does frequency measure?
8. What does a mechanical wave always travel through?

Checking Concepts

Choose the word or phrase that best answers each question.

9. Which of the following do waves transfer?
   A) matter
   B) energy
   C) matter and energy
   D) the medium
10. What is the formula for calculating wave speed?
    A) $v = \lambda f$
    B) $v = f - \lambda$
    C) $v = \lambda / f$
    D) $v = \lambda + f$
11. When a compressional wave travels through a medium, which way does matter in the medium move?
    A) backward
    B) forward
    C) perpendicular to the rest position
    D) along the same direction the wave travels
12. What is the highest point of a transverse wave called?
    A) crest
    B) compression
    C) wavelength
    D) trough
13. If the frequency of the waves produced by a vibrating object increases, how does the wavelength of the waves produced change?
    A) It stays the same.
    B) It decreases.
    C) It vibrates.
    D) It increases.
14. If the amplitude of a wave changes, which of the following changes?
    A) wave energy
    B) frequency
    C) wave speed
    D) refraction
15. Which term describes the bending of a wave around an object?
    A) resonance
    B) interference
    C) diffraction
    D) reflection
16. What is equal to the angle of reflection?
    A) refraction angle
    B) normal angle
    C) bouncing angle
    D) angle of incidence

Use the table below to answer question 17.

Speed of Sound in Air

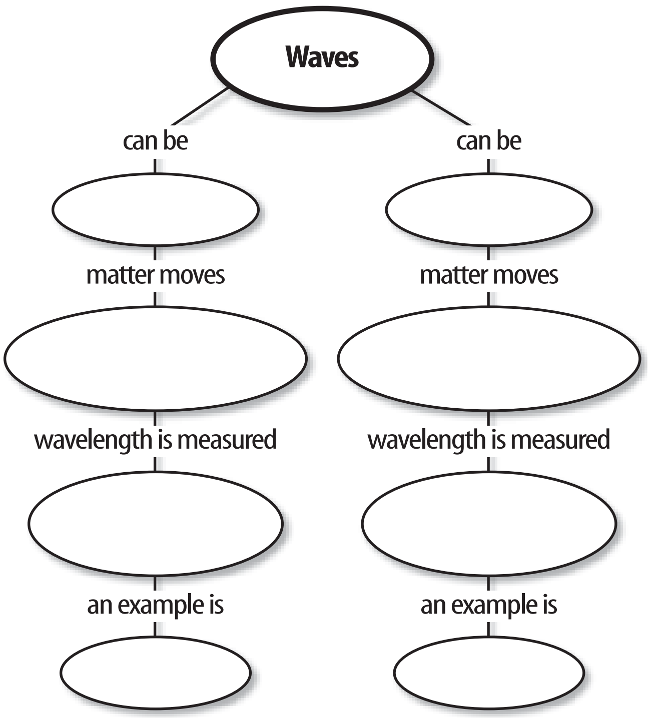
Temperature (°C)	Sound Speed (m/s)
0	331.4
10	337.4
20	343.4

17. Based on the data in the table above, which of the following would be the speed of sound in air at 30°C?
    A) 340.4 m/s
    B) 346.4 m/s
    C) 353.4 m/s
    D) 349.4 m/s

Vocabulary PuzzleMaker gpescience.com

Interpreting Graphics

18. Copy and complete the following concept map.



Thinking Critically

19. Explain An earthquake on the ocean floor produces a tsunami that hits a remote island. Is the water that hits the island the same water that was above the earthquake on the ocean floor?

20. Compare Suppose waves with different amplitudes are produced by a vibrating object. How do the frequencies of the waves with different amplitudes compare?

21. Explain Use the law of reflection to explain why you see only a portion of the area behind you when you look in a mirror.

22. Explain why you can hear a fire engine coming around a street corner before you can see it.

23. Describe the objects or materials that vibrated to produce three of the sounds you've heard today.

24. Form a Hypothesis In 1981, people dancing on the balconies of a Kansas City, Missouri, hotel caused the balconies to collapse. Use what have you learned about wave behavior to form a hypothesis that explains why this happened.

25. Make and Use Tables Find information in newspaper articles or magazines describing five recent earthquakes. Construct a table that shows for each earthquake the date, location, magnitude, and whether the damage caused by the earthquake was light, moderate, or heavy.

26. Concept Map Design a concept map that shows the characteristics of transverse waves. Include the terms *crest, trough, medium, wavelength, frequency, period,* and *amplitude.*

Applying Math

27. Calculate Wavelength Calculate the wavelength of a wave traveling on a spring if the wave moves at 0.2 m/s and has a period of 0.5 s.

28. Calculate Wavespeed The microwaves produced inside a microwave oven have a wavelength of 12.0 cm and a frequency of 2,500,000,000 Hz. At what speed do the microwaves travel in units of m/s?

29. Calculate Frequency Water waves on a lake travel toward a dock with a speed of 2.0 m/s and a wavelength of 0.5 m. How many wave crests strike the dock each second?

Record your answers on the answer sheet provided by your teacher or on a sheet of paper.

Multiple Choice

1. When a transverse wave travels through a medium, which way does matter in the medium move?

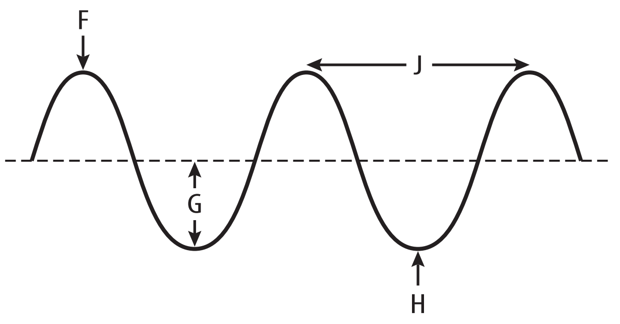
A. backward

B. in all directions

C. at right angles to the direction the wave travels

D. in the same direction the wave travels

Use the illustration below to answer questions 2 and 3.



2. What wave property is shown at G?

A. amplitude

B. wavelength

C. crest

D. trough

3. What property of the wave is shown at H?

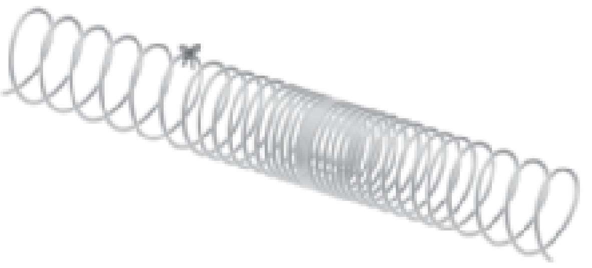
A. amplitude

B. wavelength

C. crest

D. trough

Use the illustration below to answer questions 4 and 5.



4. What kind of wave is shown?

A. mechanical

B. compressional

C. transverse

D. both A and B

5. What happens to the yarn tied to the coil?

A. It moves back and forth as the wave passes.

B. It moves up and down as the wave passes.

C. It does not move as the wave passes.

D. It moves to the next coil as the wave passes.

6. What kind of waves are the seismic waves produced during an earthquake?

A. transverse

B. compressional

C. combination of transverse and compressional

D. electromagnetic

7. What is the bending of a wave as it enters a new material called?

A. refraction

B. diffraction

C. reflection

D. interference

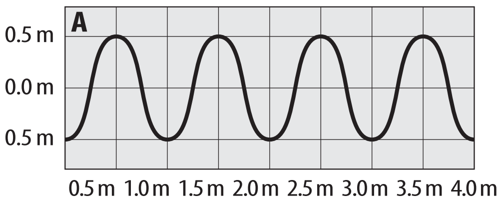
Gridded Response

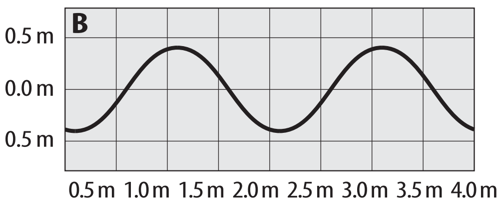
8. A tuning fork vibrates at a frequency of 256 Hz. The wavelength of the sound produced by the tuning fork is 1.32 m. What is the speed of the wave in m/s?

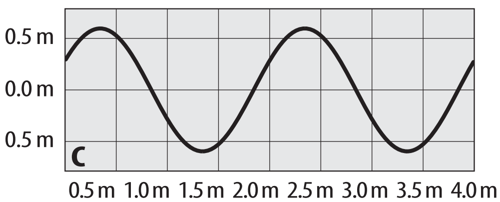
9. A wave has a speed of 345 m/s and its frequency is 2050 Hz. What is its wavelength in m?

Short Response

Use the illustration below to answer questions 10 and 11.







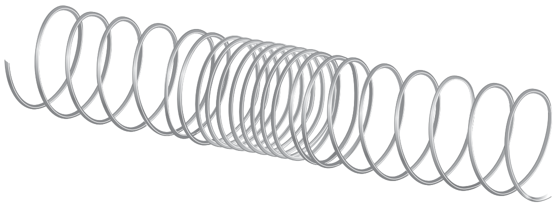
10. Determine the amplitudes and the wavelengths of each of the three waves.

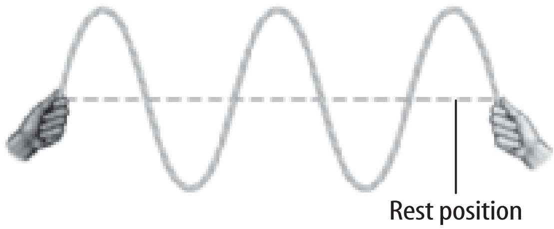
11. If the length of the *x*-axis on each diagram represents 2 s of time, what is the frequency of each wave?

Extended Response

12. In a science fiction movie, a huge explosion occurs on the surface of a planet. People in a spaceship heading toward the planet see and hear the explosion. Is this realistic? Explain.

Use the illustrations below to answer question 13.





13. The illustrations show two mechanical waves.

Part A Describe how the amplitude of each of the two waves shown is defined.

Part B Describe how you would change both drawings to show waves that transfer more energy.

Test-Taking Tip

Answer Every Question Never leave any open-ended answer blank. Answer each question as best you can. You can receive partial credit for partially correct answers.

Question 12 Before you answer the question, list what you know about light waves and sound waves.