CHAPTER 9
Introduction to Waves

Launch Lab
Energy of Waves

Light enters your eyes, and sound strikes your ears, enabling you to sense the world around you. Light waves and sound waves transfer energy from one place to another. Do waves transfer anything else along with their energy? Do waves transfer matter, too? In this activity, you will observe a model of how waves transfer energy.

For a lab worksheet, use your StudentWorks™ Plus Online.

Make a Venn diagram foldable. Label it as shown. Use it to organize your notes on transverse and longitudinal waves.
THEME FOCUS  **Energy**  
Waves are one of many ways to transfer energy.

**BIG IDEA**  Waves transfer energy from place to place without transferring matter.

**Section 1**  •  The Nature of Waves  
**Section 2**  •  Wave Properties  
**Section 3**  •  The Behavior of Waves
Section 1

The Nature of Waves

**Main Idea** Waves travel through matter as energy is transferred from particle to particle.

**Real-World Reading Link** When you catch a fastball from a baseball pitcher, you can feel the slight sting on your hand. The baseball carries both matter and energy as it travels to your hand. On the other hand, a wave carries only energy as it travels.

**Waves Defined**

Figure 1 shows a disturbance from a pebble splashing into a pond. This disturbance travels outward from the spot where the pebble splashed. The pebble produced a small wave in the pond. A wave is a repeating disturbance that transfers energy through matter or space. Other examples of waves include ocean waves, sound waves, seismic waves, and light waves. Do these and other types of waves have anything in common with one another?

**Waves and Energy**

Because a falling pebble is moving, the falling pebble has kinetic energy. As the falling pebble splashes into the pool in Figure 1, the pebble transfers some of its energy to nearby water molecules, causing them to move. Those molecules then pass the energy along to neighboring water molecules, which, in turn, transfer it to their neighbors. The energy travels farther and farther from the source of the disturbance. However, the water itself does not move outward. What you see is energy traveling in the form of a wave on the surface of the water.
Waves and matter  Imagine that you are in a boat on a lake. Approaching waves bump against your boat, but they do not 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 the boat.

But after the waves have passed, the boat is still in nearly the same place. The waves do not even carry the water along with them. The water that is around the boat after the wave passes is the same water as was there before the wave passed. Only the energy travels along with the waves. All waves, whether they are water waves, sound waves, light waves or earthquake waves, have this property: they carry energy without transporting matter from place to place.

Reading Check  Identify what waves carry.

Making waves  A wave will travel only as long as it has energy to carry. When you drop a pebble into a pond, small waves form, as shown in Figure 1. These waves carry energy. However, this energy is gradually transferred to the surrounding water and air. At the same time, the remaining energy in the waves spreads out as the waves spread out. As the energy spreads out and is transferred away from the waves, those waves shrink and disappear.

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 shown in Figure 2.

Now suppose you shake your end of the rope up and down for a while. You would make waves that 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.

Reading Check  Identify what produces waves.
Mechanical Waves

Sound waves travel through the air to reach your ears. Ocean waves travel through water to reach the shore. A medium is matter through which a wave travels. The medium can be a solid, a liquid, a gas, or a combination of these. Not all waves need a medium. Some waves, such as light and radio waves, can travel through a vacuum. Mechanical waves, such as sound waves, are waves that can travel only through matter. Mechanical waves can be either transverse waves or longitudinal waves.

Transverse waves In a transverse wave, particles in the medium move back and forth at right angles to the direction that the wave travels. For example, Figure 3 shows how a wave along a rope travels horizontally, but the portions of the rope that the wave passes through move up and down. When you shake one end of a rope while your friend holds the other end, you are making transverse waves.

Reading Check Compare the direction that a transverse wave travels with the direction that matter in that wave vibrates.

Water waves When the wind blows across the surface of the ocean, water waves form. Water waves are often thought of as transverse waves, but this is not entirely correct. The water in water waves does move up and down as the waves go by. But the water also moves short distances back and forth along the direction that the wave is traveling.

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 shown on the left in Figure 4. This is much like a child pushing sand into a pile. Sand must be pushed in from the sides to make the pile. As the wave passes, the water that was pushed aside moves back to its initial position, as shown on the right in Figure 4.
Longitudinal waves  In a longitudinal wave, matter in the medium moves back and forth along the same direction that the wave travels. You can model longitudinal waves with a coiled spring toy, as shown in Figure 5. 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 5. You would see that the yarn moves back and forth as the wave passes and then stops moving after the wave has passed. The wave carries energy, but not matter, forward along the spring. Longitudinal waves are sometimes called compressional waves.

Sound waves  Sound waves are longitudinal waves. When a noise is made, such as when a locker door slams shut, nearby molecules in the air are pushed together by the vibrations caused by the slamming door. The molecules in the air are squeezed together similar to the coils in the coiled spring toy in Figure 5. These compressions travel through the air to make a sound wave. The sizes of a sound wave’s compressions, as well as the distances between those compressions, determines the nature of that sound.

Sound waves in liquids and solids  Sound waves can also travel through liquids and solids, such as water and wood. Particles in these mediums are pushed together and move apart as the sound waves travel through them.

Reading Check  Describe how sound waves travel through solids.

Vocabulary

Science Usage v. Common Usage

**Medium**

Science usage  the matter through which waves travel
Common usage  something in a middle position

Air is often the medium through which a sound wave travels.

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Seismic waves can cause regions of Earth’s crust to move, bend, or even break. Movement in the crust, which occurs along faults, can result in a rapid release of energy. This energy travels away from the fault in the form of seismic waves, as shown in Figure 6. Seismic waves can be longitudinal waves or transverse waves. Scientists have found out much about Earth’s interior by studying these seismic waves.

Seismic waves can travel through Earth, as well as along Earth’s surface. When the energy from seismic waves is transferred to objects on Earth’s surface, those objects move and shake.

Seismic waves

Figure 6 A fault is a break in Earth’s crust. The red arrows show the direction that Earth’s crust is moving at a fault. When Earth’s crust shifts or breaks, the energy that is released is transmitted outward, causing an earthquake. The point where the earthquake originates is called the focus.

Explain how earthquake waves and sound waves are similar.

Section 1 Review

Section Summary

A wave is a repeating disturbance that transfers energy through matter or space.

- Waves carry energy without transporting matter.
- In a transverse wave, matter in the medium moves at right angles to the direction that the wave travels.
- In a longitudinal wave, matter in the medium moves back and forth along the direction that the wave travels.

Apply Math

1. **Main Idea** Describe the motion of an unanchored rowboat when a water wave passes. Does the wave move the boat forward?

2. **Contrast** how you would move a spring to make a transverse wave with how you would move a spring to make a longitudinal wave.

3. **Identify** evidence that seismic waves transfer energy without transferring matter.

4. **Identify** a mechanical wave that is also a longitudinal wave.

5. **Think Critically** Describe how the world would be different if all waves were mechanical waves.

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 in water?

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Wave Properties

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

**Real-World Reading Link** When you adjust the volume on a stereo or adjust the brightness on a computer monitor, you are manipulating wave properties. Wave properties affect how we see objects and hear sounds. When we adjust color, brightness, pitch, or loudness, we are changing certain characteristics of the waves produced by the computer monitor or stereo system.

**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 carry 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 7* has alternating high points and low points. **Crests** are the high points of a transverse wave. **Troughs** are the low points of a transverse wave. The imaginary line that is half the vertical distance between a crest and a trough is called the rest position.

On the other hand, a longitudinal wave has no crests and troughs. When a longitudinal wave passes through a medium, it creates regions where the medium becomes crowded together and more dense, as in *Figure 7*. These regions are compressions. A **compression** is the more dense region of a longitudinal wave. *Figure 7* also shows that the coils in the region next to a compression are spread apart, or less dense. The less-dense region of a longitudinal wave is called a **rarefaction**.

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*Figure 7* Different types of waves are described in different ways. Transverse waves have crests and troughs, but longitudinal waves have compressions and rarefactions.
Wavelength

All waves have wavelength. Wavelength is the distance between one point on a wave and the nearest point just like it. Figure 8 shows that for transverse waves, the wavelength is the distance from crest to crest or trough to trough. These two distances are equal on a transverse wave.

A wavelength in a longitudinal wave is the distance from the middle of one compression to the middle of the next compression, as shown in Figure 8. The wavelength in a longitudinal wave is also the distance from the middle of one rarefaction to the middle of the next rarefaction. These two distances are equal on a longitudinal wave.

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. Frequency is also the number of times that a point on a wave moves up and down or back and forth each second. You can find the frequency of a transverse wave by counting the number of crests that pass a point each second. You can find the frequency of a longitudinal wave by counting the number of compressions that pass a point each 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. In SI units, period has units of seconds.
**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. If you double the frequency of a wave, you halve the wavelength of that wave. If you double the wavelength of a wave, you halve that wave’s frequency. **Figure 9** 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 that 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.** Describe how the wavelength and the frequency of a wave are related.

**Wave Speed**

Suppose you are at a large stadium watching a baseball game, but you are up high 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 through which it is traveling. 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 a vacuum. Also, sound waves usually travel faster in a material if 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 9** When frequency increases, the number of wavelengths that pass in one second increases. **Identify which of the waves in this figure has the higher frequency.**
Calculating wave speed  The speed of a wave depends on the medium in which the wave travels. However, the wave speed, wave frequency, and the wavelength are related. The speed of a wave can be calculated from the following equation.

Wave Speed Equation

\[ \text{speed (in m/s)} = \text{frequency (in Hz)} \times \text{wavelength (in m)} \]

\[ v = f \lambda \]

In this equation, \( v \) represents the wave speed, \( f \) is the frequency, and the Greek letter \( \lambda \) (lambda) represents the wavelength. 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. Therefore, m × Hz is the same as m × 1/s. Both are equivalent to m/s.

**EXAMPLE Problem 1**

**Solve for Wave Speed**  What is the speed of a sound wave that has a wavelength of 2.00 m and a frequency of 170.5 Hz?

**Identify the Unknown:**  wave speed: \( v \)

**List the Knowns:**  
- wavelength: \( \lambda = 2.00 \text{ m} \)
- frequency: \( f = 170.5 \text{ Hz} \)

**Set Up the Problem:**  \[ v = f \lambda \]

**Solve the Problem:**  
\[ v = (170.5 \text{ Hz})(2.00 \text{ m}) \]
\[ = (170.5 \text{ waves/s})(2.00 \text{ m}) \]
\[ = 341 \text{ m/s} \]

The speed of the sound wave is 341 m/s.

**Check the Answer:**  The speed of sound through air varies but is typically close to 340 m/s. Therefore, this answer seems reasonable.

**PRACTICE Problems**  Find Additional Practice Problems in the back of your book.

7. A wave traveling in water has a frequency of 250 Hz and a wavelength of 6.0 m. What is the speed of the wave?

8. The lowest-pitched sounds humans can generally hear have a frequency of roughly 20 Hz. What is the approximate wavelength of these sound waves if their wave speed is 340 m/s?

9. A particular radio station broadcasts radio waves at 100 MHz (100 million Hz). If radio waves travel at the speed of light (300 million m/s), then what is the wavelength of the radio waves that the station is broadcasting?

10. **Challenge** A sound wave with a frequency of 100.0 Hz travels in water with a speed of 1,500 m/s and then travels in air with a speed of 340 m/s. Approximately how many times larger is the wavelength in water than in air?
Amplitude

Why do some earthquakes cause terrible damage, while others are hardly felt? This is because the disturbance from a wave can vary. **Amplitude** is a measure of the size of the disturbance from a wave. If the wave’s amplitude is greater, then the disturbance from that wave is also greater. Amplitude is measured differently for longitudinal waves and transverse waves.

**Amplitude of longitudinal waves** The amplitude of a longitudinal wave is related to how tightly the medium is pushed together at the compressions and how much the medium is pulled apart at the rarefactions. The more tightly pushed together the medium is at the compressions, the denser the medium. The denser the medium is at the compressions, the larger the wave’s amplitude is and the greater the disturbance from the wave. The denser the medium is at the compressions, the less dense the medium is in the rarefactions. Therefore, another indication of high amplitude is whether the medium is stretched out more in the rarefactions. **Figure 10** shows longitudinal waves with different amplitudes.

![Figure 10](image)

**Figure 10** The coils in the high-amplitude wave’s compression are closer together than the coils in the low-amplitude wave’s compression.

**Vocabulary**

**Word Origin**

**Amplitude**

comes from the Latin word *amplitudinem*, which means “wide extent or width”

Waves with high amplitudes are usually very noticeable.
Amplitude of transverse waves If you have ever been knocked over by an ocean wave, you know that the higher the wave, the greater the disturbance from that wave. Remember that the amplitude of a wave increases as the disturbance from that 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 vertical distance from the crest or trough of the wave to the rest position of the medium, as shown in Figure 11. Tall waves have large amplitude, and short waves have small amplitude. The amplitude of any transverse wave is also half the vertical distance from crest to trough.

Amplitude of transverse waves

Describe how you could create waves with different amplitudes in a piece of rope.

Section 2 Review

Section Summary

- Wavelength is the distance between a point on a wave and the nearest point just like it.
- Wave frequency is the number of wavelengths passing a fixed point each second.
- Wave period is the amount of time it takes one wavelength to pass a fixed point.
- The speed of a wave is the product of its frequency and its wavelength.
- As the amplitude of a wave increases, the disturbance from that wave increases.

11. **Main IDEA** Identify a wave that speeds up when it passes from air to water as well as one that slows down.

12. **Describe** the difference between a longitudinal wave with a large amplitude and one with a small amplitude.

13. **Describe** how the wavelength of a wave changes if the wave slows down but its frequency does not change.

14. **Explain** how the frequency of a wave changes when the period of the wave increases.

15. **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.

Apply Math

16. **Calculate** the frequency of a water wave that has a wavelength of 0.5 m and a speed of 4 m/s.

17. **Calculate Speed** An FM radio station broadcasts radio waves with a frequency of 96,000,000 Hz. What is the speed of these radio waves if they have a wavelength of 3.1 m?
Objectives
- Determine the relationship between tension and wave speed.

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

Question: How does the tension in a material affect the waves traveling through that material?

Materials
- coiled-spring toy
- meterstick
- stopwatch

Safety Precautions

Procedure
1. Read the procedure and safety information, and complete the lab form.
2. Create a data table similar to the one shown.
3. Attach one end of the spring to a chair leg so that the spring rests on a smooth floor.
4. Stretch the spring to a length of 1.0 m.
5. Make a longitudinal wave by squeezing several coils together, and then releasing them.
6. 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.
7. Repeat steps 4 and 5 two more times for waves 2 and 3.
8. Stretch the spring to a length of 1.5 m. Repeat steps 4 and 5 for waves 4, 5, and 6.

Data Table

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Wave Time (s)</th>
<th>Wave Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave 3</td>
<td></td>
<td></td>
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<tr>
<td>Wave 4</td>
<td></td>
<td></td>
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<tr>
<td>Wave 5</td>
<td></td>
<td></td>
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<tr>
<td>Wave 6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Conclude and Apply
1. Calculate the speed of each wave. Use the formula speed = distance/time.
2. Calculate the average speed of the waves on the spring when the spring has a length of 1.0 m.
3. Calculate the average speed of the waves on the spring when the spring has a length of 1.5 m.
4. Describe how the tension in the spring changes as the length of the spring is increased.
5. Describe how the wave speed depends on the tension. How could you make the waves travel even faster? Test your prediction.
6. Predict how you could increase the speed of waves along a violin string.

Communicate Your Data
Compare your results with those of other students in your class. Form a hypothesis about what you might observe if the coiled-spring toy were made of another material. How would you test your hypothesis?
The Behavior of Waves

MAIN Idea  Waves interact with matter and with each other.

Real-World Reading Link  Think about what you might see when you look at the surface of a calm lake. You might see your reflection, or you might see distorted images of what is below the surface of the lake. Both of these examples are results of the behavior of light waves.

Reflection

If you are one of the last people to leave your school building at the end of the day, you will probably find that the hallways are 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 are all alone, you might 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. Without wave reflection, you could not even see the lockers in your school’s hallway.

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 girl in Figure 12 to see herself in the mirror? It happens in two steps. First, light strikes her face and bounces off her face. Then, the light reflected off her face strikes the mirror and is reflected into her eyes.

Figure 12  Some of the light that strikes this girl’s face is reflected into the mirror. Some of that light then reflects off the mirror into her eyes.

Describe how the path of the light reflected from the girl’s face would be different if the mirror was not present.
**Echoes** Surfaces often reflect sound waves as well as light waves. Echoes are a result of reflecting sound waves. Sound waves form when your foot hits the floor, and the waves travel through the air to both your ears and other objects. When sound waves reach another object, such as a row of lockers, they reflect off that object. Sometimes, those reflected waves travel back to your ears.

Some animals use echoes to learn about their surroundings. For example, dolphins make clicking sounds and listen to the echoes. These echoes enable the dolphin to locate objects.

**The law of reflection** Look at the two light beams in Figure 13. 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 always equal to the angle of reflection. All reflected waves, including light waves, sound waves, and water 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.
**Figure 14** Light waves refract as they enter the water. This results in the illusion of the broken straw.

**Refraction**

Do you notice anything unusual in **Figure 14**? The straw looks as if it is broken into two pieces. But if you pulled the straw out of the water, you would see that it is unbroken. This illusion is caused by refraction. How does refraction work?

Remember that a wave’s speed depends on the medium through which it is traveling. 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 travels from one medium to another. The greater the change in speed, the more the wave bends. The top panel in **Figure 15** shows how a wave refracts when it passes into a material in which that wave slows down. The wave is refracted (bent) toward the normal. The bottom panel in **Figure 15** shows how a wave refracts when it passes into a medium in which it speeds up. Then, the wave is refracted away from the normal.

**Figure 15** Light waves travel more slowly in water than in air. This causes light waves to refract when they move from water to air or air to water.

*Predict how the beam would bend if the speed of light were the same in both air and water.*
Refraction of light in water Have you ever gazed at fish in a pond, such as those in Figure 16? You may have noticed that objects that are underwater seem closer to the surface than they really are. Figure 17 shows how refraction causes this illusion.

In Figure 17, the light waves reflected from the swimmer’s foot are refracted away from the normal and enter the girl’s eyes. However, the brain assumes that all light waves have traveled in a straight line. The light waves that enter the girl’s eyes seem to have come from a foot that was higher in the water.

This is also why the straw in Figure 14 seems to be broken. The light waves coming from the part of the straw that is underwater 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 straw above the water are not refracted. So, the part of the straw that is underwater looks as if it has shifted.

Figure 16 The fish in this photo are farther from the surface of the water than they appear. Refraction causes this pond to appear to be much shallower than it actually is.

Figure 17 From the girl’s perspective, the boy appears to be shorter than he actually is due to refraction. Light rays from the boy’s foot refract downward at the water’s surface.
Diffraction

When waves strike an object, several things can happen. The waves can be reflected. If the object is transparent, light waves can be refracted as they pass through it. Often, some waves are reflected and some waves are refracted. If you look into a glass window, sometimes you can see your reflection in the window, as well as objects behind it. Light is passing through the window and is also being reflected at its surface.

Waves can also behave another way when they strike an object. The waves can bend around the object. Figure 18 shows ocean waves changing direction and bending after they strike an island. Diffraction is the bending of a wave around an object. 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. All waves, including water waves, sound waves, and light waves, can be diffracted.

Reading Check Contrast refraction with diffraction.

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.
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 roughly the same size as or smaller than the wavelength of a wave, the wave bends around it. But when the obstacle is much larger than the wavelength, the waves do not diffract as much. If the obstacle is much larger than the wavelength, almost no diffraction occurs. Instead, the obstacle casts a shadow.

Hearing around corners  Suppose you are walking down the hallway, and you hear sounds coming from a classroom on the left before you reach the open classroom door. However, you cannot see into the room until you reach the doorway.

Why can you hear the sound waves but not see the light waves while you are 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. So, you cannot see into the room until you get 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.

Figure 20  The diffraction of waves around an obstacle depends on how the wavelength compares with the size of the obstacle.
Interference

Suppose two waves travel toward each other on a long rope as in the top panel of Figure 21. What happens when the two waves meet? The two waves pass through each other, and each one continues to travel in its original direction, as shown in the middle and bottom panels of Figure 21. However, when the waves meet in the middle panel of Figure 21, they form a new wave that looks different from either of the original waves.

When two waves arrive at the same place at the same time, they combine to form a new wave. Interference is the process of two or more waves overlapping and combining to form a new wave. This new wave exists only while the two original waves continue to overlap. Two waves can combine through either constructive interference or destructive interference.
When waves pass through each other, constructive interference or destructive interference can occur. In both panels, the blue and yellow waves interfere to form the green wave.

**Constructive interference** In constructive interference, as shown in the top panel of Figure 22, 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 longitudinal 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 the bottom panel of Figure 22. The amplitude of the new wave is the difference between the amplitudes of the waves that overlapped.

With longitudinal waves, destructive interference occurs when the compression of one wave overlaps with the rarefaction of another wave. One way to think of this is that the compressions of one wave “fill in” the rarefactions 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.

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**Vocabulary**

**Academic Vocabulary**

**Sum**

the result of adding numbers

*The sum of 6 and 7 is 13.*
Standing waves

When you make transverse waves on a rope, you might attach one end to a fixed point, such as a doorknob, and shake the other end. The waves that you produce then reflect back from the doorknob. What happens when the incident and reflected waves meet?

As the two waves travel in opposite directions along 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. But 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. Standing waves have nodes, which are locations where the interfering waves always cancel. 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.

**MiniLab**

**Observe Standing Waves**

**Procedure**

1. Read the procedure and safety information, and complete the lab form.
2. Stretch a rope between two people.
3. Have one person shake the rope side to side to produce waves. Observe the waves.
4. Have the person shake the rope side to side faster. Observe the results again.

**Analysis**

1. Compare and contrast your results from step 3 with your results from step 4.
Resonance

When you were younger, you might have played on a swing like the one in Figure 24. You probably noticed that you could make the swing go higher by pumping your legs and arms. It was not necessary to pump hard, but timing was important. If you pumped in time to the swing’s rhythm, you could go quite high.

You can accomplish similar effects with sounds. Suppose you have a tuning fork that has a single natural frequency of 440 Hz, which means that the tuning fork naturally vibrates at 440 Hz when struck. Now think of a sound wave with a frequency of 440 Hz strikes the tuning fork. Because the sound wave has the same frequency as the natural frequency of the tuning fork, the tuning fork will begin to vibrate. Resonance is the process by which an object is made to vibrate by absorbing energy at its natural frequencies.

Sometimes resonance can cause an object to absorb a large amount of energy. An object vibrates more and more strongly as it absorbs energy at its natural frequencies. If the object absorbs enough energy, it might break.

Figure 24  This child times the movements of her arms and legs to make the swing go higher. Resonance is the process of increasing vibration through well-timed pushes and pulls on the object that is vibrating. This child uses resonance as she swings.

Section 3 Review

Section Summary

- 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 occurs when a wave changes direction by bending around an obstacle.
- Interference occurs when two or more waves overlap and form a new wave.

18. **Main Idea** Describe the path that light waves take when you see your image in a mirror.

19. Compare the loudness of sound waves that constructively interfere with the loudness of sound waves that destructively interfere.

20. Describe how one tuning fork’s vibrations can cause another tuning fork to vibrate.

21. Infer Sound waves often bend around columns in large concert halls. Is this a result of refraction or diffraction?

22. Think Critically Suppose the speed of light was 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 actually is.

Apply Math

23. Calculate Angle of Incidence The angle between a flashlight beam that strikes a mirror and the reflected beam is 80 degrees. What is the angle of incidence?
Wavelength, Frequency, and Wave Speed

Objectives

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

Background: 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.

Question: How can the speed of a wave be measured? How can the wavelength be determined from the frequency?

Preparation

Materials

long spring, rope, or hose
meterstick
stopwatch

Safety Precautions

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 Data Table 1.

5. Repeat steps 3 and 4 two more times.

6. Calculate the speed of waves 1, 2, and 3 in Data Table 1. Average the speeds of waves 1, 2, and 3 to find the speed of waves on your spring.

7. Make a copy of Data Table 2.

8. Create a series of waves with the same wavelength. 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 column marked Waves in 10 s in Data Table 2.

9. Repeat step 8 two more times. Each time, create a wave with a different wavelength by shaking the spring faster or slower.
1. Calculate the frequency of waves 4, 5, and 6. Remember that frequency is the same as the number of waves that pass in one second.

2. Calculate Use the equation $v = f\lambda$ to find the wavelength of waves 4, 5, and 6. Use the average speed calculated in step 6 for the wave speed.

3. Identify the potential sources of error in this lab.

### Data Table 1

<table>
<thead>
<tr>
<th></th>
<th>Length of Spring (m)</th>
<th>Time for Wave to Travel Spring Length (s)</th>
<th>Speed of Wave (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave 3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Data Table 2

<table>
<thead>
<tr>
<th></th>
<th>Waves in 10 s</th>
<th>Frequency (Hz)</th>
<th>Wavelength (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave 6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Analyze Your Data

1. **Calculate** the frequency of waves 4, 5, and 6. Remember that frequency is the same as the number of waves that pass in one second.

2. **Calculate** Use the equation $v = f\lambda$ to find the wavelength of waves 4, 5, and 6. Use the average speed calculated in step 6 for the wave speed.

3. **Identify** the potential sources of error in this lab.

### Conclude and Apply

1. **Compare** Were the three wave speeds that you calculated in step 6 significantly different from one another? Why or why not?

2. **Explain** why you would average the speeds of the three different pulses to calculate the speed of the waves on the spring.

3. **Describe** how the wavelength of the waves that you created depends on the frequency of the waves.

### Communicate Your Data

**Create** 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.
Invisibility is a common theme in science fiction and fantasy. Some recent developments in technology suggest that invisibility technology may really be possible.

**Bendable waves** All waves can be refracted, including light waves. One example is when light waves bend as they pass through air warmed by a hot road, forming a mirage. For most materials, waves refract in one direction only. But for a new class of materials, called metamaterials, refraction can occur in unprecedented ways.

**“Impossible” refraction** Most materials refract light waves from one side of the normal to the other. However, metamaterials can refract light waves so that they do not cross the normal. Both types of refraction are shown in Figure 1.

A metamaterial first refracts a light beam like an ordinary material would, and then refracts light in the other direction. As a result, a metamaterial can bend a light beam completely around an area, making that area invisible. Figure 2 shows how a wall composed of a metamaterial might conceal a person.

**Visible light** Early metamaterials made objects invisible only to microwaves. The wavelengths of visible light waves are about 50,000 times smaller than the wavelengths of microwaves. As a result, metamaterial components for visible light were not developed until 2010.

**Other Applications** While invisibility cloaks may still be in the far future, this research is leading in some surprising directions today. Tsunamis and earthquakes are powerful natural events that both involve wave motion. If metamaterials can render objects invisible to light waves, then similar materials might make buildings and even whole coastlines invisible to destructive water or seismic waves. In the future, destructive waves might be redirected harmlessly around vulnerable structures.

**WebQuest** Extend While an invisibility cloak might seem like an impractical device, the concepts are now being used to research ways to protect against earthquakes and tsunamis. Write a future news article or prepare a newscast about other unexpected uses of invisibility technology.
THEME FOCUS  **Energy**
Waves are one of many ways to transfer energy. All types of waves, including water waves, waves on a rope or spring, sound waves, and light waves, transfer energy without transferring matter.

### Section 1 The Nature of Waves

<table>
<thead>
<tr>
<th>Term</th>
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</tr>
</thead>
<tbody>
<tr>
<td>longitudinal wave</td>
<td>277</td>
</tr>
<tr>
<td>mechanical wave</td>
<td>276</td>
</tr>
<tr>
<td>medium</td>
<td>276</td>
</tr>
<tr>
<td>transverse wave</td>
<td>276</td>
</tr>
<tr>
<td>wave</td>
<td>274</td>
</tr>
</tbody>
</table>

**MAIN Idea**  Waves travel through matter as energy is transferred from particle to particle.
- A wave is a repeating disturbance that transfers energy through matter or space.
- Waves carry energy without transporting matter.
- In a transverse wave, matter in the medium moves at right angles to the direction that the wave travels.
- In a longitudinal wave, matter in the medium moves back and forth along the direction that the wave travels.

### Section 2 Wave Properties

<table>
<thead>
<tr>
<th>Term</th>
<th>p.</th>
</tr>
</thead>
<tbody>
<tr>
<td>amplitude</td>
<td>283</td>
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<tr>
<td>compression</td>
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</tr>
<tr>
<td>crest</td>
<td>279</td>
</tr>
<tr>
<td>frequency</td>
<td>280</td>
</tr>
<tr>
<td>period</td>
<td>280</td>
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<tr>
<td>rarefaction</td>
<td>279</td>
</tr>
<tr>
<td>trough</td>
<td>279</td>
</tr>
<tr>
<td>wavelength</td>
<td>280</td>
</tr>
</tbody>
</table>

**MAIN Idea**  Wave properties depend on the vibrations of the wave source and the material in which the wave travels.
- Wavelength is the distance between a point on a wave and the nearest point just like it.
- Wave frequency is the number of wavelengths passing a fixed point each second.
- Wave period is the amount of time it takes one wavelength to pass a fixed point.
- The speed of a wave is the product of its frequency and its wavelength.
- As the amplitude of a wave increases, the disturbance from that wave increases.

### Section 3 The Behavior of Waves

<table>
<thead>
<tr>
<th>Term</th>
<th>p.</th>
</tr>
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<tbody>
<tr>
<td>diffraction</td>
<td>290</td>
</tr>
<tr>
<td>interference</td>
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</tr>
<tr>
<td>node</td>
<td>294</td>
</tr>
<tr>
<td>refraction</td>
<td>288</td>
</tr>
<tr>
<td>resonance</td>
<td>295</td>
</tr>
<tr>
<td>standing wave</td>
<td>294</td>
</tr>
</tbody>
</table>

**MAIN Idea**  Waves interact with matter and with each other.
- 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 occurs when a wave changes direction by bending around an obstacle.
- Interference occurs when two or more waves overlap and form a new wave.
Use Vocabulary

Answer each question using the correct term from the Study Guide.

24. Which type of wave has points, called nodes, that do not move?
25. Which part of a longitudinal wave has the lowest density?
26. What can occur when a wave passes from one medium into another?
27. What occurs when waves overlap?
28. What is half the vertical distance from the crest to the trough of a transverse wave?
29. What can be measured in Hz?

Check Concepts

30. **THEME FOCUS** Which do waves transfer?
   A) matter  
   B) energy  
   C) matter and energy  
   D) the medium

31. What is the formula for calculating wave speed?
   A) \( v = f \lambda \)  
   C) \( v = \frac{f}{\lambda} \)
   B) \( v = f - \lambda \)  
   D) \( v = \lambda + f \)

32. When a longitudinal wave travels through a medium, in which direction does the matter in the medium move?
   A) in circles  
   B) perpendicular to the rest position  
   C) along the same direction the wave travels  
   D) in all directions

33. What is region X on the above wave called?
   A) crest  
   B) compression  
   C) rarefaction  
   D) trough

34. If the frequency of a vibrating object decreases, how does the wavelength of the resulting wave change?
   A) It stays the same.  
   B) It decreases.  
   C) It vibrates.  
   D) It increases.

35. If the amplitude of a wave changes, which also changes?
   A) disturbance from the wave  
   B) frequency  
   C) wave speed  
   D) refraction

36. Which term describes the bending of a wave around an object?
   A) refraction  
   B) interference  
   C) diffraction  
   D) reflection

37. Which is equal to the angle of reflection?
   A) angle of refraction  
   B) angle of diffraction  
   C) angle of bouncing  
   D) angle of incidence
Interpret Graphics

38. Copy and complete the following concept map.

Think Critically

39. **BIG IDEA** Explain An earthquake on the ocean floor produces a tsunami that reaches a remote island. Is the water that reaches the island the same water that was above the earthquake on the ocean floor? Explain.

40. Diagram a transverse wave. Label the crest, trough, wavelength, and amplitude. Identify the period and frequency for the wave.

41. Describe What happens to the frequency of a wave if the period of that wave is increased?

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

43. Describe the objects or materials that vibrated to produce three of the sounds that you have heard today.

44. Explain why it is easier to hear low-frequency sounds than high-frequency sounds when a large tree is between you and the sound source.

45. **Form a Hypothesis** In 1831, soldiers marching over the Broughton Suspension Bridge in England caused that bridge to collapse. Use what you have learned about wave behavior to form a hypothesis that explains why this happened.

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

Apply Math

47. **Calculate Wavelength** Calculate the wavelength of a wave traveling on a spring when the wave travels at 0.2 m/s and has a period of 0.5 s.

48. **Calculate Wavespeed** The microwaves produced inside a microwave oven have a wavelength of 12 cm and a frequency of 2,500,000,000 Hz. At what speed (in m/s) do the microwaves travel?

49. **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?
Multiple Choice

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

1. When a transverse wave travels through a medium, which way does matter in the medium move?
   A. in circles
   B. in all directions
   C. at right angles to the direction that the wave travels
   D. parallel to the direction the wave travels

Use the illustration below to answer questions 2 and 3.

2. What wave property is shown by G?
   A. amplitude
   B. wavelength
   C. crest
   D. trough

3. What part of the wave is shown at H?
   A. amplitude
   B. wavelength
   C. crest
   D. trough

4. What is the number of waves that passes a point in a certain time called?
   A. wavelength
   B. amplitude
   C. period
   D. frequency

5. The period of a wave can be directly calculated from which?
   A. angle of incidence
   B. amplitude
   C. frequency
   D. wavelength

6. To what is the size of the disturbance from a wave related?
   A. frequency
   B. wave speed
   C. amplitude
   D. refraction

7. What happens when two waves pass through each other?
   A. refraction
   B. diffraction
   C. reflection
   D. interference

8. When the crests of two identical waves meet, what is the amplitude of the resulting wave?
   A. half the amplitude of each wave
   B. twice the amplitude of each wave
   C. three times the amplitude of each wave
   D. four times the amplitude of each wave

Use the illustration below to answer questions 9 and 10.

9. What kind of wave is shown?
   A. electromagnetic
   B. longitudinal
   C. transverse
   D. sound

10. What happens to the yarn that is 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 forward along the coil along with the wave.
11. Explain why water waves traveling toward a swimmer on a float do not move the float forward along with the wave.

Use the illustration below to answer questions 12 and 13.

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

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

14. A tuning fork vibrates at a frequency of 440 Hz. The wavelength of the sound produced by the tuning fork is 0.75 m. What is the speed of the wave?

15. Describe how a standing wave forms and why it has nodes.

16. Explain why objects that are underwater seem to be closer to the surface than they actually are.

17. Compare and contrast refraction and diffraction of waves.

18. 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 illustration below to answer questions 19 and 20.

19. Describe how amplitude is related to the density of the coils in the bottom drawing.

20. Describe how you would change both drawings to show waves that cause a greater disturbance.