Chapter 20 Waves

Have you ever heard of the Bermuda Triangle? Many sailors know that the Bermuda Triangle is an area of the Caribbean Sea where many ships have been lost. For hundreds of years sailors believed the area was haunted. Today, we still worry about ships in the Bermuda Triangle but not because of ghosts. Some scientists believe the unusual shape of the sea floor and the ocean currents creates momentary "rogue" waves that can reach 100 feet above the sea surface. These waves often come and go in minutes, vanishing without a trace. An unlucky ship caught in one of those waves may not stand a chance!

Any coastal city has to worry about waves. Therefore, many harbors are designed to reduce the size of water waves. A quiet harbor allows for sailboats to sail, for goods to be brought in by big ships, and for coastal buildings to be safe. At beaches it is also important that waves not be too big so the water is safe for swimmers. Special computer programs allow designers of coastal areas to determine how to control waves. Usually, underwater structures are built to dampen waves. If you are a surfer, however, you want big waves. The same computer programs also predict the location of the biggest waves.

Water waves are useful for learning because they are easy to make and study. What you know about water waves applies to other waves too — including sound, light, and microwaves. The ideas even apply to gravity waves that occur when black holes crash into each other.

Key Questions

- ✓ How is your cell phone like a traffic light or a drum?
- ✓ Which wave interactions are involved in how sunglasses work?
- ✓ What is anti-noise?

20.1 Waves

A **wave** is an oscillation that travels from one place to another. A musician's instrument creates waves that carry sound to your ears. Dialing a cell phone to call a friend sends microwaves from the cell phone antenna; the microwaves carry the signal containing your voice to your friend. Similarly, when you throw a stone into a pond, the energy of the falling stone creates a waves in the water that carry the energy to the edge of the pond. In this section you will learn about waves.

Vocabulary

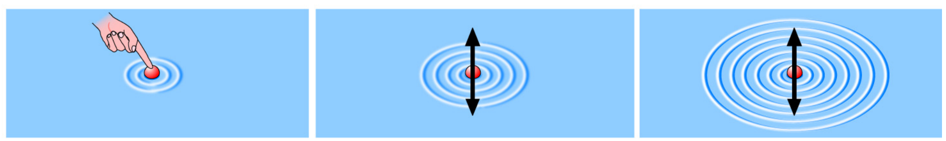
wave, transverse, longitudinal, crest, trough, wavelength, standing wave, fundamental, harmonics

Objectives

- ✓ Describe transverse and longitudinal waves.
- ✓ Learn the properties of waves.
- ✓ Calculate the speed of a wave.
- ✓ Identify the fundamental and harmonics of a standing wave.

Why learn about waves?

What is a wave? If you poke a ball floating on water it moves up and down in harmonic motion. But something else happens to the water as the ball oscillates. The surface of the water oscillates in response and the oscillation spreads outward from where it started. An oscillation that travels is a wave.



Energy and information Waves carry an oscillation from one place to another, causing oscillation in whatever they encounter. Because waves can change motion, we know that waves are a traveling form of energy. Waves also carry information, such as conversations, pictures, or music. Waves are used in many technologies because they can quickly carry information over great distances. The sound wave from a violin carries information about the vibration of the strings to your ear. Your ear hears the vibrations as music. In a similar way, a radio wave carries sounds from a transmitter to your car stereo. Another kind of radio wave carries television signals. All the information you receive in your eyes and ears comes from waves (Figure 20.1).

- The light from the traffic light is a wave.
- The ripples in the puddle of water are waves.
- The electricity flowing in the wires attached to the street lights is a wave.
- Waves carry radio, TV, and cell phone transmissions through the air all around you.

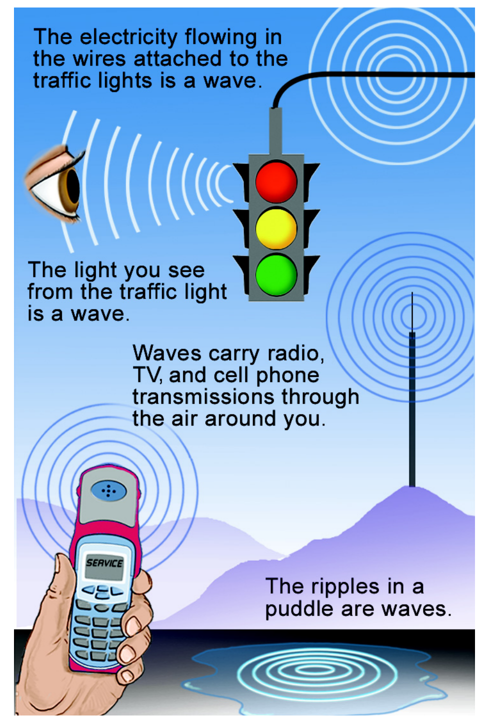


Figure 20.1: *Many examples of waves.*

Recognizing waves

How do you recognize a wave?

All waves are traveling oscillations that move energy from one place to another. The energy might be in actual motion, or it might be sound, light, or another form of energy. When you see the things in this list, you should suspect that there is some kind of wave involved.

Waves are present:

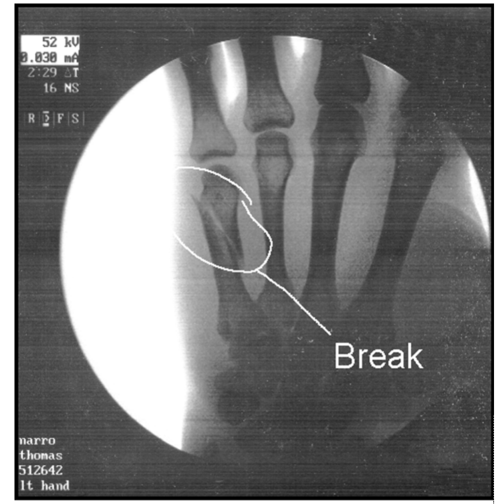
- when you see a vibration that moves.
  Example: A guitar string after it is plucked
- when something makes or responds to sound.
  Example: A drum or your ears
- when something makes or responds to light.
  Example: A light bulb or your eyes
- when technology allows us to "see through" objects.
  Examples: ultrasound, CAT scans, MRI scans, and X rays
- when information travels through the air (or space) without wires.
  Example: A satellite dish for receiving television signals

Waves transmit information

Waves are present whenever information, energy, or motion is transmitted over a distance without anything obviously moving. The remote control on a TV is an example. To change the channel you can use the remote or you can get up and push the buttons with your finger. Both actions provide the information needed to change the channel on the TV. One action uses physical motion and the other uses a wave that goes from the remote control to the television. Your knowledge of physics and waves tells you there must be some kind of wave coming from the remote control because information traveled from one place to another, and nothing appeared to move. The wave from the remote control is infrared light that is invisible to the eye.

All waves have common properties.

Like oscillations, waves have the properties of frequency, period, and amplitude. Information in waves is often transmitted in patterns of changing amplitude or frequency. For example, the number two might be represented by a wave whose amplitude was high for 2 seconds, then low again (Figure 20.3). Waves also have two new properties: *speed* and *wavelength*.



X ray

Figure 20.2: *An X ray is created by passing waves through the body. The calcium in bones absorbs X rays so bones show up as darker areas in an X ray photo. This photo clearly shows a broken finger.*

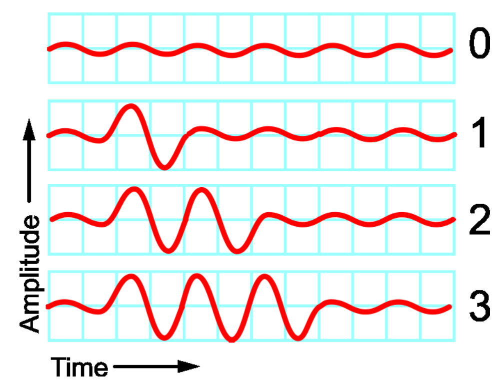


Figure 20.3: *One way to represent numbers using the amplitude of a wave.*

Transverse and longitudinal waves

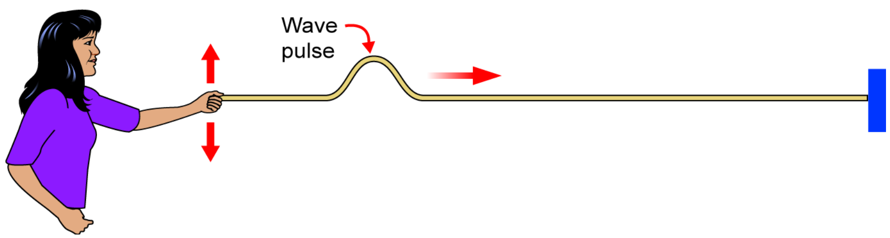
How waves travel

How do waves travel through the air or down a string? For a wave to travel, molecules need to be connected or in contact with each other. Because air molecules collide, waves can travel in the air. A wave can travel along a string because molecules are connected. If you cut a string, a wave would not spread across the break.

Transverse waves

A **transverse** wave has its oscillations perpendicular to the direction the wave moves. For example, the wave pulse in the diagram below moves from left to right. The oscillation (caused by the girl's hand) is up and down. Water waves are transverse waves because oscillation of the water's surface is perpendicular to the direction of the wave's motion (Figure 20.4 top).

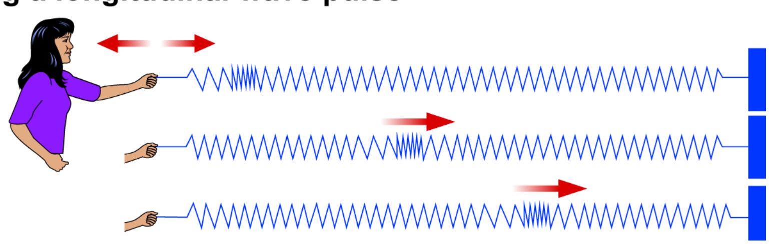
Making a transverse wave pulse

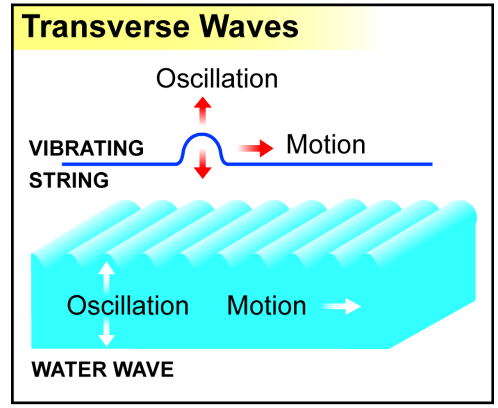


Longitudinal waves

A **longitudinal** wave has vibrations in the same direction as the wave moves (Figure 20.4 bottom). A large spring with one end fastened to a wall is a good way to demonstrate a longitudinal wave. A sharp push-pull on the end of the spring results in a traveling wave pulse as portions of the spring compress, then relax. The direction of the compressions are in the same direction that the wave moves. Sound waves are longitudinal waves. Like a wave pulse on a spring, air molecules oscillate back and forth as sound travels.

Making a longitudinal wave pulse





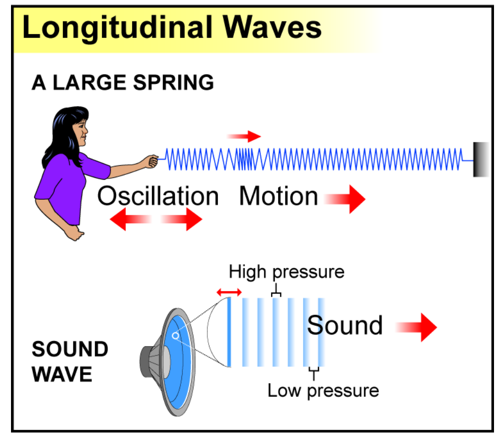


Figure 20.4: *(A) Transverse waves oscillate perpendicular to the direction the wave moves. A vibrating string and a water wave are transverse waves. (B) Longitudinal waves oscillate in the same direction the wave moves. A wave traveling along a large spring and a sound wave are longitudinal waves.*

Frequency, amplitude, and wavelength

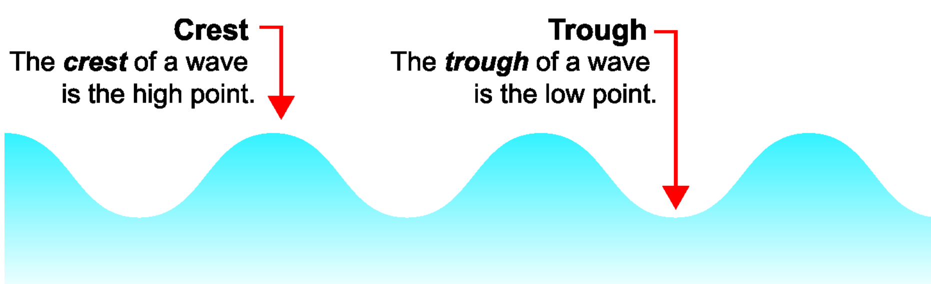
Waves are oscillators Waves have cycles, frequency, and amplitude. However, unlike other kinds of oscillators, waves travel and have speed. On this page, you will learn how frequency and amplitude are defined and measured for waves.

Frequency The frequency of a wave is a measure of how often it goes up and down (Figure 20.5). The frequency of the motion of one point on the wave is equal to the frequency of the whole wave. Distant points on the wave oscillate up and down *with the same frequency*. A wave carries its frequency to every place it reaches.

Frequency is measured in hertz Wave frequency is measured in *hertz* (Hz). A wave with a frequency of one hertz (1 Hz) causes everything it touches to oscillate at one cycle per second. Water waves made in a large pan of water typically have low frequencies, between 0.1 and 10 hertz. Sound waves that we hear have higher frequencies, between 20 Hz and 20,000 Hz.

Amplitude The amplitude of a wave is the maximum amount the wave causes anything to move away from equilibrium. Equilibrium is the average, or resting position (Figure 20.6) of the material the wave is moving through. You can measure amplitude as one-half the distance between the highest and lowest points.

Wavelength You can think of a wave as a series of high points and low points. A **crest** is a high point of the wave, a **trough** is the low point. **Wavelength** is the distance from any point on a wave to the same point on the next cycle of the wave (Figure 20.7). One wavelength is the length of one complete cycle of the wave. We use the Greek letter "lambda" to represent wavelength. A lambda (λ) looks like an upside down "y."



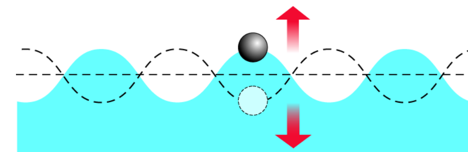


Figure 20.5: *The frequency of a wave is the rate at which every point on the wave moves up and down. The floating ball moves up and down at the frequency of the wave.*

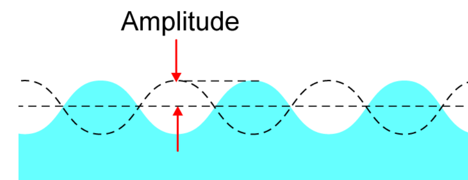


Figure 20.6: *The amplitude of a water wave is the maximum height the wave rises above the level surface. This is the same as half the distance between the lowest and highest places.*

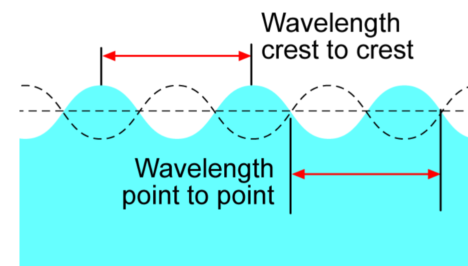
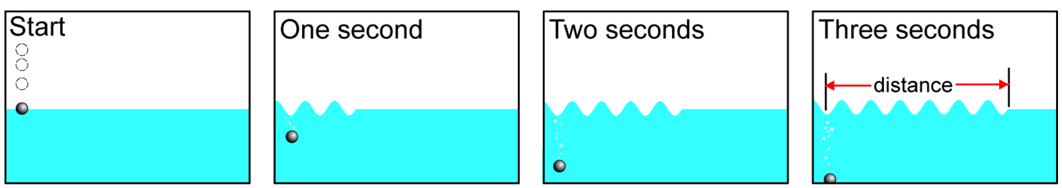


Figure 20.7: *The wavelength of a water wave can be measured from crest to crest. This is the same as the distance from one point on a wave to the same point on the next cycle of the wave.*

The speed of waves

What is moving? The speed of a wave is different from the speed of a moving object, like a ball. The speed of a ball is the speed at which the ball itself moves. The speed of a wave is the speed at which the wave's oscillations travel through a material. When a wave moves through water, *the water itself stays in the same average place*. The typical speed of a water wave is a few miles per hour. Light waves are extremely fast—186,000 miles per *second* (300,000 km/sec). Sound waves travel at about 660 miles per hour (about 1,000 km/h), faster than water waves and much slower than light waves.

What is the speed of a wave? The graphic below illustrates how to measure wave speed. You have to start a ripple in one place and measure how long it takes the ripple to affect a place some distance away. The speed of the wave is how fast the ripple gets from one place to the next, NOT how fast the wave surface moves up and down. As you learned on the previous page, the up-down speed of the water surface determines its frequency (Figure 20.8).



Speed is frequency times wavelength In one complete cycle, a wave moves forward one wavelength (Figure 20.8). The speed of a wave is the distance traveled (one wavelength) divided by the time it takes (one period). Since the frequency is the inverse of the period, it is easier to calculate the speed of the wave by multiplying wavelength and frequency. The result is true for all kinds of waves. Frequency times wavelength is the speed of the wave.

$$\textit{Speed} = \frac{\text{Distance traveled}}{\text{Time taken}} = \frac{\text{Wavelength}}{\text{Period}} = \left(\frac{1}{\text{Period}}\right) \times \text{Wavelength}$$

$$\textit{Speed} = \textit{Frequency} \times \textit{Wavelength}$$

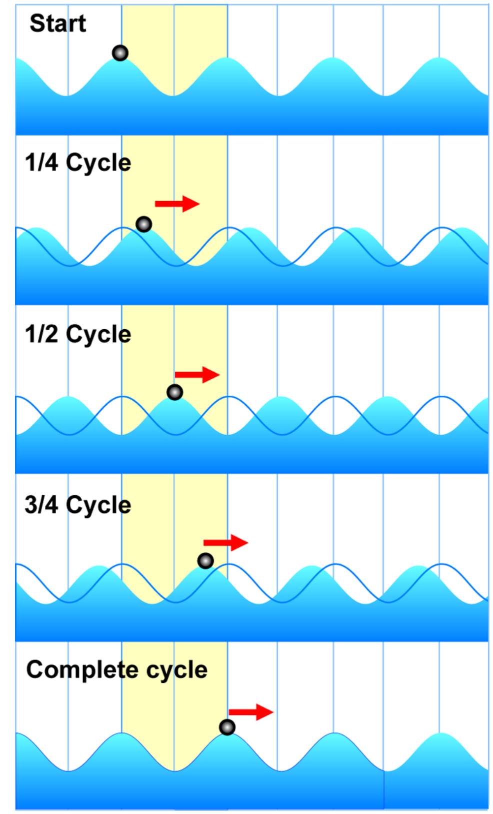


Figure 20.8: *A wave moves a distance equal to one wavelength in one cycle. Since a cycle takes one period, the speed of the wave is the wavelength divided by the period. The speed of a wave can also be calculated by multiplying frequency times wavelength.*

Calculating the speed of waves

Units You can calculate the speed of a wave if you know its frequency and wavelength. Recall that one hertz equals one cycle per second. The number of cycles is a pure number with no units. The *units* of Hz are 1 ÷ second. If wavelength is in meters, and frequency has units of 1 ÷ seconds, then the wave speed has units of meters per second (m/sec).

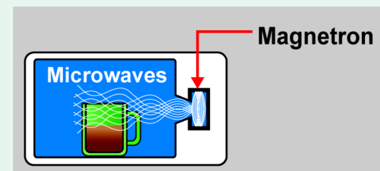
THE SPEED OF A WAVE

Speed (m/sec) → $v = f\lambda$ ← *Wavelength* (meters)

Frequency (hertz) → f

Cooking with waves

A magnetron is a device in a microwave oven that creates a wave driven by electricity. Some of the energy of this wave enters the inside of the microwave and cooks food. The shape of the magnetron forces the wave to vibrate at exactly 2.4 billion cycles per second (2.4 gigahertz), This frequency is a natural frequency of water molecules. A microwave heats food by transferring wave energy to water molecules.



Finding wave speed

The wavelength for a wave is 0.5 meter, and its frequency is 40 hertz. What is the speed of this wave?

1. Looking for: The speed of the wave in meters per second.

2. Given: Wavelength is 0.5 meter and frequency is 40 hertz.

3. Relationships: speed = frequency × wavelength

4. Solution: speed = 40 Hz × 0.5 m = 40 ($^{1}/_{sec}$) × 0.5 m
speed = 20 m/sec
The speed of the wave is 20 m/sec.

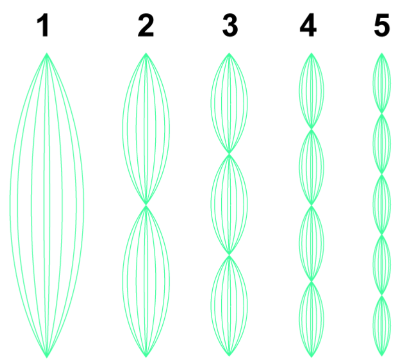
Your turn...

a. The frequency of a wave is 50 hertz and the wavelength is 0.001 meter. What is the wave speed? **Answer:** 0.05 m/sec
b. The period of a wave is 10 seconds and the wavelength is 2 meters. What is the wave speed? **Answer:** 0.2 m/sec

Standing waves on a string

What is a standing wave? A wave that is confined in a space is called a **standing wave**. It is possible to make standing waves of almost any kind, including sound, water, and even light. You can experiment with standing waves using a vibrating string. Vibrating strings are what make music on a guitar or piano.

Harmonics



The first five harmonics of the vibrating string

A string with a standing wave is a kind of oscillator. Like all oscillators, a string has natural frequencies. The lowest natural frequency is called the **fundamental**. A vibrating string also has other natural frequencies called **harmonics**. The diagram shows the first five harmonics. You can tell the harmonic number by counting the number of "bumps" on the string. The first harmonic has one bump, the second has two, the third has three, and so on. Another name for the "bump" on a wave is *antinode* (Figure 20.9).

Wavelength A vibrating string moves so fast that your eye sees a wave-shaped blur (Figure 20.10). At any one moment the string is in only one place within the blur. One complete "S" shape on the string is one wavelength. As frequency increases, wavelength decreases. Higher frequency waves have shorter wavelengths.

20.1 Section Review

1. Does a pair of walkie-talkies work using waves? Justify your answer.
2. Which is the fastest way to send information, using sound, light, or water?
3. Compare and contrast longitudinal and transverse waves in a short paragraph.
4. What is the speed of a wave that has a wavelength of 0.4 meter and a frequency of 10 Hz? Is this wave most likely to be a sound wave, light wave, or a water wave?
5. What is the period of a wave that has a wavelength of 1 meter and a speed of 20 Hz?

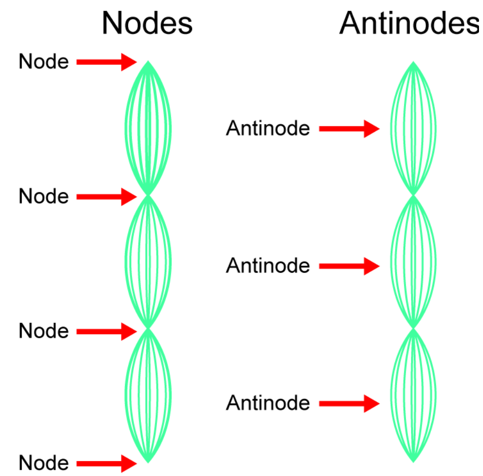


Figure 20.9: *Nodes and antinodes for the third harmonic of the vibrating string. Nodes are points where the string does not move. Antinodes are points of the greatest amplitude.*

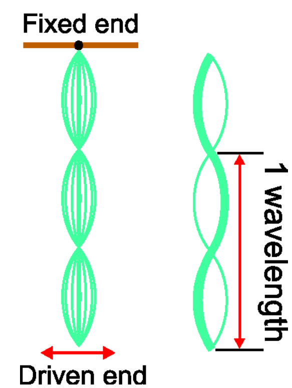


Figure 20.10: *A standing wave on a vibrating string. The wavelength is the length of one complete S shape of the wave.*

20.2 The Motion of Waves

Waves travel *through* substances, such as air or water. How do we know which direction a wave moves? What happens when a wave encounters an edge, or moves from one substance into another? We will find the answers by observing water waves because they are slow and easy to see. However, what we learn applies to all waves, including light and sound.

Vocabulary

propagate, plane wave, wave fronts, circular wave, boundaries, reflection, refraction, diffraction, absorption

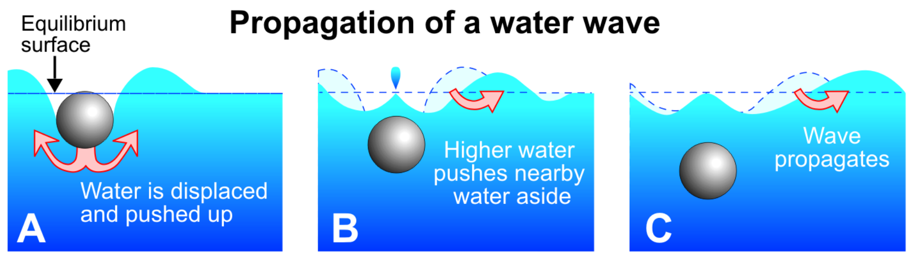
Objectives

- ✓ Learn how waves propagate.
- ✓ Describe the four wave interactions.

Wave patterns and directions

Why do waves travel?

Waves **propagate,** which means they spread out from where they begin. When you drop a ball into water, some of the water is pushed aside and raised by the ball (A). The higher water pushes the water next to it out of the way as it tries to return to equilibrium (B). The water that has been pushed then pushes on the water in front of *it*, and so on. The wave spreads through the interaction of each bit of water with the bit of water next to it (C).



Plane waves and circular waves

The easiest waves to make and study are plane waves and circular waves (Figure 20.11). The crests of a **plane wave** form a pattern of parallel straight lines called **wave fronts**. The crests of a **circular wave** form a pattern of circular wave fronts. A plane wave is started by disturbing water in a line. Pushing the water with a ruler makes a plane wave. A circular wave is started by disturbing water at a single point. A fingertip touched to the water's surface makes a circular wave.

The direction a wave moves

The direction a wave moves depends on the shape of the wave front. Plane waves are straight and move in a line perpendicular to the crest of the wave. Circular waves move outward in a circle from the center. Anything that changes the shape of the wave front changes the direction the wave moves.

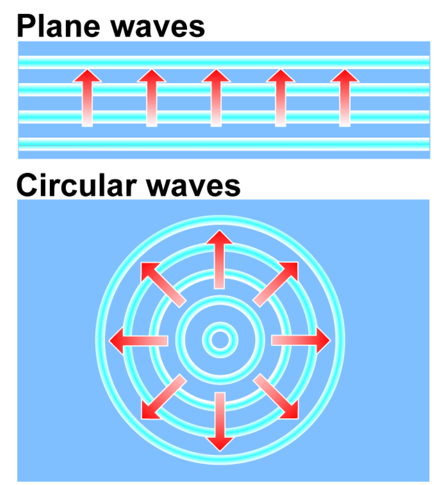


Figure 20.11: *Plane waves move perpendicular to the wave fronts. Circular waves radiate outward from the center.*

When a wave encounters objects

The four wave interactions

Have you ever heard a radio station fade out while driving into a tunnel or down into a valley? Radio signals are carried by radio waves. Like all waves, radio waves are affected by objects that get in their way. An FM radio wave can only propagate a short distance into a tunnel. Simple things like mirrors and complex things like X rays and ultrasound all depend on how waves behave when they encounter objects. When a wave hits an object or a surface, four things can happen. Sometimes all four happen at the same time, but to varying amounts. The four are listed below and illustrated in Figure 20.12.

Reflection	*The wave bounces and goes in a new direction.*
Refraction	*The wave bends as it passes into and through an object.*
Diffraction	*The wave bends around an object or through holes in the object.*
Absorption	*The wave is absorbed and disappears.*

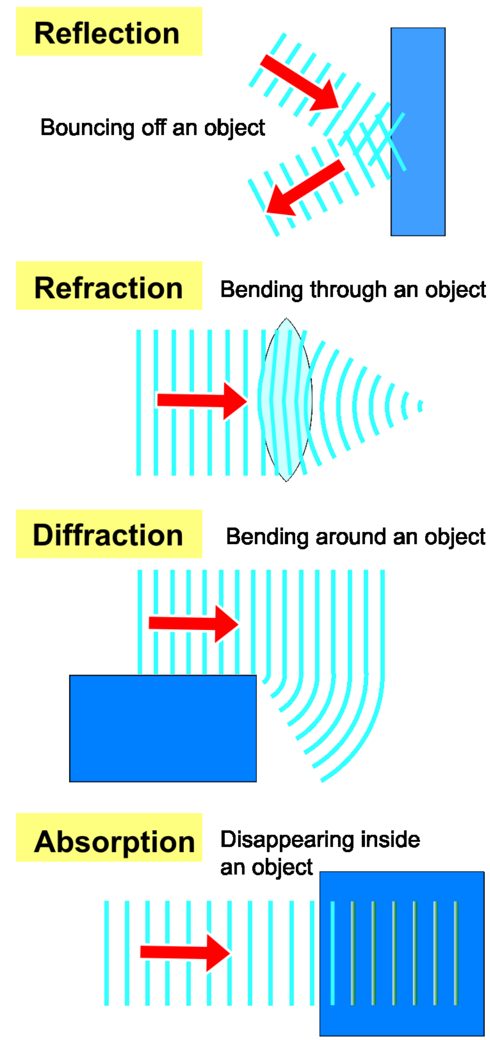


Figure 20.12: *The four basic interactions between waves and boundaries.*

Boundaries

Waves are affected by **boundaries** where conditions or materials change. A boundary is an edge or surface where things change suddenly. The surface of glass is a boundary. A wave traveling in the air sees a sudden change to a new material (glass) as it crosses the boundary. Reflection, refraction, and diffraction usually occur at boundaries. Absorption also occurs at a boundary, but usually happens more within the body of a material.

Reflection

When a wave bounces off an object we call it **reflection**. A reflected wave is like the original wave but moving in a new direction. The wavelength and frequency are usually unchanged. An echo is an example of a sound wave reflecting from a distant object or wall. People who design concert halls pay careful attention to the reflection of sound from the walls and ceiling.

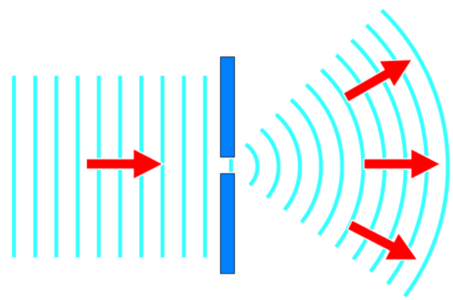
Refraction

Refraction occurs when a wave bends as it crosses a boundary. We say the wave is *refracted* as it passes through the boundary. Eyeglasses are a good example where refraction is used to bend light waves. People with poor eyesight have trouble focusing images. Glasses bend incoming light waves so that an image is correctly focused within the eye.

Diffraction and absorption

Diffraction The process of bending around corners or passing through openings is called **diffraction**. We say a wave is *diffracted* when it is changed by passing through a hole or around an edge. Diffraction usually changes the direction and shape of the wave. When a plane wave passes through a narrow opening diffraction turns it into a circular wave. Diffraction explains why you can hear someone even though a door is open only a tiny crack. Diffraction causes the sound wave to spread out from the crack.

Diffraction through a small opening turns plane waves into circular waves.



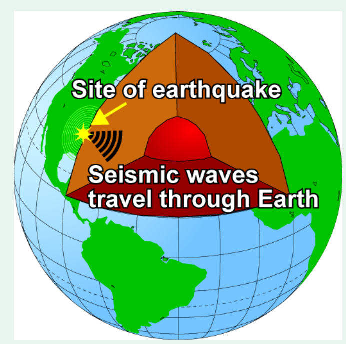
Absorption **Absorption** is what happens when the amplitude of a wave gets smaller and smaller as it passes through a material. The wave energy is transferred to the absorbing material. A sponge can absorb a water wave while letting the water pass. Theaters often use heavy curtains to absorb sound waves so the audience cannot hear backstage noise. The tinted glass or plastic in the lenses of your sunglasses absorbs some of the energy in light waves. Cutting down the energy makes vision more comfortable on a bright, sunny day.

20.2 Section Review

1. If you threw a small rock into a pond, would plane waves or circular waves be created?
2. Does a mirror work by reflection or refraction?
3. Why is refraction important in how eyeglasses work?
4. One of the four wave interactions is very important in how plants use light to grow. Guess which one and write a couple of sentences justifying your answer.

Waves and earthquakes

Earth's crust is not one shell, but is broken up into huge slabs called "plates". The plates float on top of a deep layer of softer, partly melted rock. Where the plates hit each other they sometimes slip very suddenly, resulting in earthquakes. An earthquake releases powerful seismic waves that travel along the surface and also through the planet. One kind of seismic wave is a longitudinal wave. Another kind of seismic wave is transverse. The transverse wave shakes the ground sideways and causes damage to buildings and bridges. Because seismic waves travel through the planet, they are used to study what Earth is like deep below the surface. The refraction and reflection of seismic waves are like an X ray of the Earth's internal structure.



20.3 Wave Interference and Energy

You almost never see (or hear) a single wave with only one frequency. That would be like seeing only one single color or hearing only one part of one note. Instead, you see (or hear) a complex mixture of waves of many different frequencies and amplitudes, all mixed together. **Interference** happens when two or more waves mix together. Interference mixes waves in ways that are very useful but can also be dangerous. For example, radio and television use the interference of two waves to carry music and video. In contrast, sometimes water waves add up to make a gigantic wave that may last only a few moments, but can sink even the largest ship.

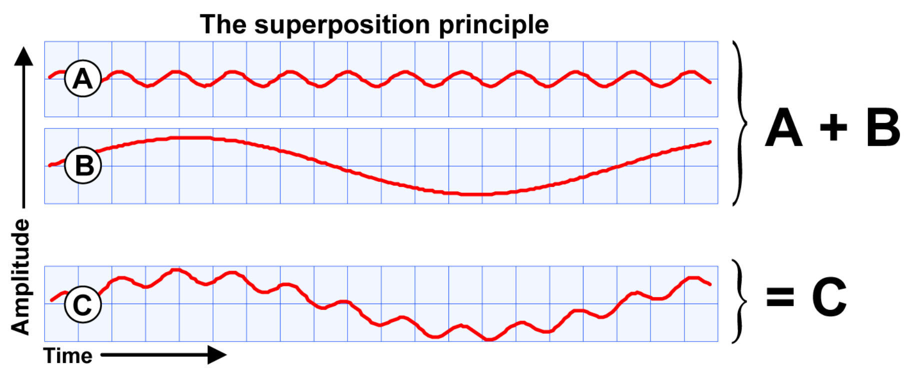
The superposition principle

The superposition principle

It is common for there to be many waves in the same system at the same time. For example, if you watch the ocean, you can see small waves on the surface of larger waves. When more than one wave is present, the **superposition principle** states that the total vibration at any point is the sum of the vibrations from each individual wave.

An example

The diagram below illustrates the superposition principle. If there are two waves present (A and B), the total vibration at any point in time (C) is the sum of the vibrations from wave (A) and wave (B). In reality, single waves are quite rare. The sound waves and light waves you experience are the superposition of thousands of waves with different frequencies and amplitudes. Your eyes, ears, and brain separate the waves in order to recognize individual sounds and colors.



Vocabulary

interference, superposition principle, wave pulse, constructive interference, destructive interference

Objectives

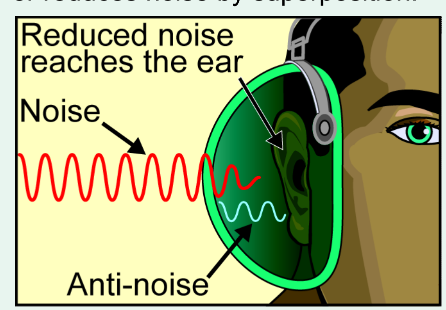
✓ Describe the superposition principle, and constructive and destructive interference.

✓ Review natural frequency and resonance.

✓ Learn about the relationship between wave energy and its properties.

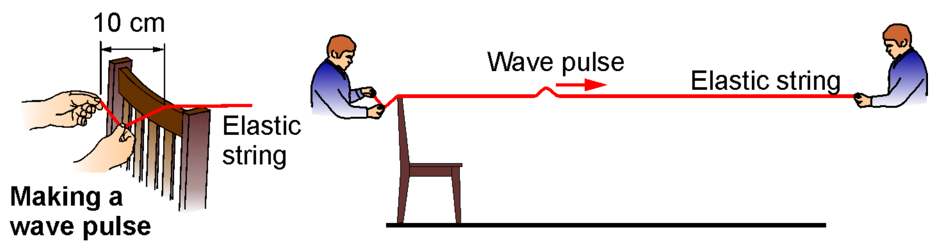
Active noise reduction

In some environments, people wear headphones to muffle noise and protect their hearing. Headphones can also create "anti-noise." A microphone in the headphone samples the noise and generates anti-noise, or sound that is 180 degrees out of phase with the noise. The anti-noise cancels out or reduces noise by superposition.



Constructive and destructive interference

Wave pulses A **wave pulse** is a short length of wave, maybe just a single oscillation. Imagine stretching an elastic string over the back of a chair (diagram below). To make a wave pulse, pull down a short length of the string behind the chair and let go. This creates a "bump" in the string that races away from the chair. The moving "bump" is a wave pulse. The wave pulse moves *on* the string, but each section of string returns to the same place after the wave moves past. The speed of the wave pulse is what we mean by the speed of a wave.



Constructive interference Suppose you make two wave pulses on a stretched string. One comes from the left and the other comes from the right. When the waves meet, they combine to make a single large pulse. **Constructive interference** occurs when waves add up to make a larger amplitude (Figure 20.13). Constructive interference is useful in working with light and sound. For example, when two sound waves constructively interfere, loudness increases.

Destructive interference There is another way to add two pulses. What happens when one pulse is on top of the string and the other is on the bottom? When the pulses meet in the middle, they cancel each other out (Figure 20.14). One pulse pulls the string up and the other pulls it down. The result is that the string flattens and both pulses vanish for a moment. In **destructive interference,** waves add up to make a wave with smaller or zero amplitude. After interfering both wave pulses separate again and travel on their own. This is surprising if you think about it. For a moment, the middle of the cord is flat, but a moment later, two wave pulses come out of the flat part and race away from each other. Waves still store energy, even when they interfere. Noise cancelling headphones are based on technology that uses destructive interference.

Constructive interference

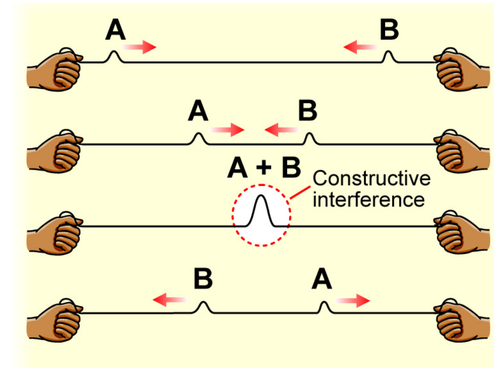


Figure 20.13: *Two wave pulses that are in phase can add up to make a single, bigger pulse when they meet. This is an example of constructive interference.*

Destructive interference

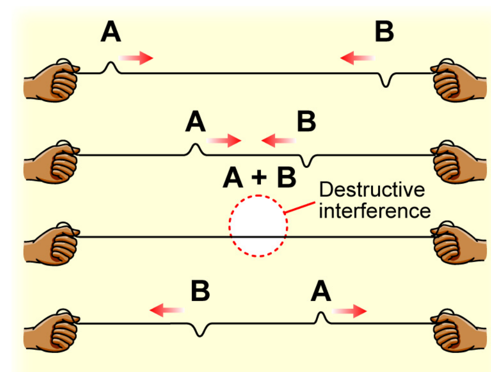
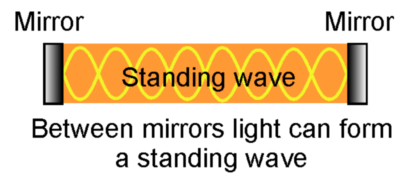


Figure 20.14: *Two equal wave pulses that are out of phase will subtract when they meet. The upward movement of one pulse exactly cancels with the downward movement of the other. For a moment there is no pulse at all. This is an example of destructive interference.*

Natural frequency and resonance

Natural frequency and resonance

As you learned in chapter 19, waves can have natural *frequency* and *resonance* just like oscillators. But first, a wave has to be caught in a system with boundaries. By itself, light keeps going in a straight line. There is no resonance. But catch the light between two perfect mirrors and you can get resonance of light waves, which is exactly how a *laser* works!



Resonance and reflections

Resonance in waves comes from the interference of a wave with its own reflections. To see how this works, think about making a pulse on an elastic string. One end of the string is tied to the wall, making a boundary. A pulse launched on the top reflects off the wall and comes back *on the bottom* of the string. When the pulse gets back to where it started, it reflects again, and is back on top of the string. After the second reflection, the pulse is traveling in the same direction, on the same side of the string as it started (Figure 20.15).

Resonance and constructive interference

To build up a large wave, you wait until a reflected pulse has returned to your hand before launching a new pulse. The new pulse adds to the reflected pulse to make a bigger pulse (constructive interference). The bigger pulse moves away and reflects again. You wait until the reflection gets back to your hand and then shake the string to add a third pulse. The total wave pulse is now three times as large as at the start. *Resonance is created by adding new pulses so that each adds to the reflected pulse in constructive interference.* After a dozen well-timed pulses, the string develops a single large wave motion, and you have resonance (Figure 20.16)! This is exactly how the standing waves on the vibrating string are formed.

Why resonance is important

The concepts of resonance and natural frequency apply to a huge range of natural and human-made systems. The tides of the oceans, musical instruments, the laser, the way our ears separate sound, and even a microwave oven are all examples of waves and resonance.

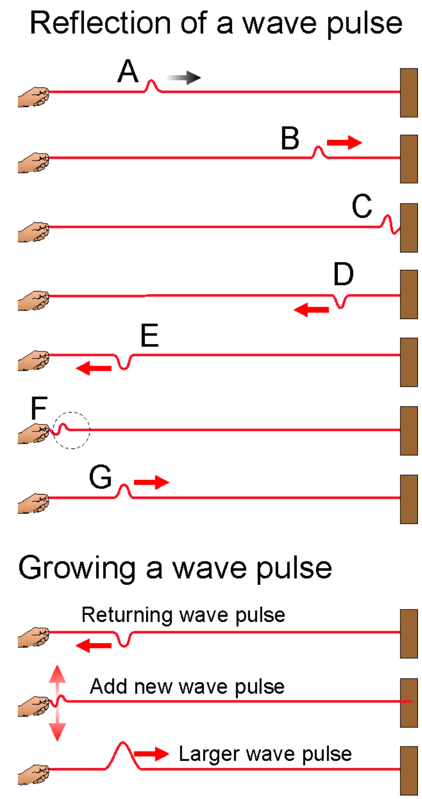


Figure 20.15: *Reflections of a wave pulse on an elastic string.*

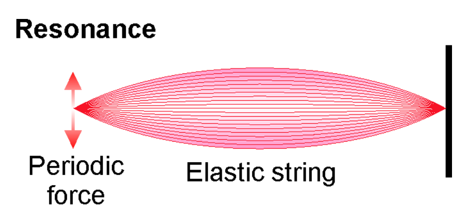


Figure 20.16: *A vibrating string in resonance has a single large wave pattern such as this.*

Waves and energy

A wave is a form of moving energy

What exactly moves in a wave? In a water wave, the water moves up and down, but stays, on average, in the same place. What moves is *energy*. A wave is an organized form of energy that travels. When you drop a stone into a pool, most of the stone's kinetic energy is converted into water waves. The waves spread out carrying the energy far from the place where the stone fell.

Frequency and energy

The energy of a wave is proportional to its frequency. Higher frequency means higher energy. This is obvious for a jump rope. You have to move the rope up and down twice, doing twice as much work, to make the rope swing at twice the frequency. Figure 20.17 shows three standing waves with the same amplitude and different frequencies. The wave with the higher frequency has more energy. The result is true for almost all waves. The energy of a wave is proportional to its frequency.

Amplitude and energy

The energy of a wave is also proportional to amplitude. Given two standing waves of the same frequency, the wave with the larger amplitude has more energy. With a vibrating string, the potential energy of the wave comes from the stretching of the string. Larger amplitude means the string has to stretch more and therefore stores more energy.

Why are standing waves useful?

Standing waves are used to store energy at specific frequencies. With the wave on the string you observed how a small input of energy at the natural frequency accumulated over time to build a wave with much more energy. Musical instruments use standing waves to create sound energy of exactly the right frequency. Radio transmitters and cell phones also use standing waves to create power at specific frequencies.

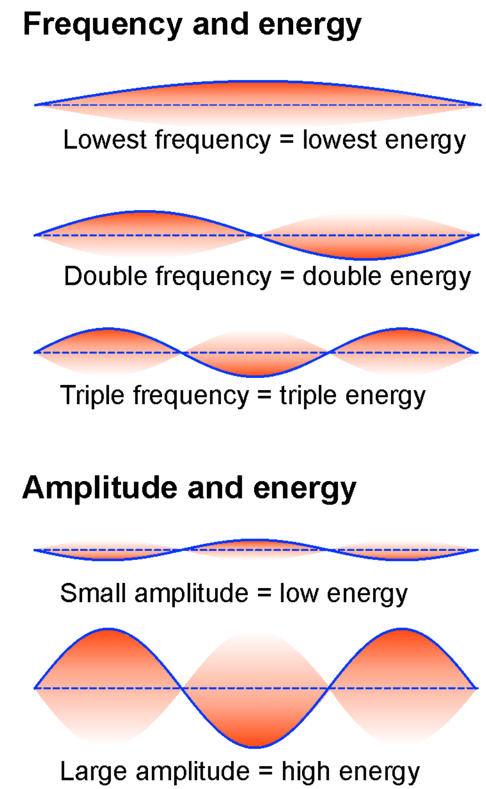
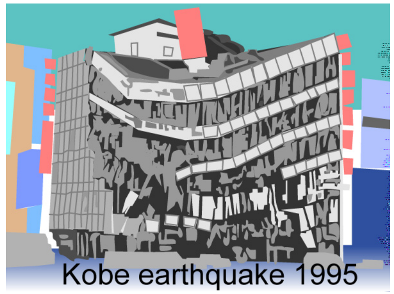


Figure 20.17: *The energy of a wave is proportional to its frequency and amplitude.*

20.3 Section Review

1. Explain the superposition principle in your own words.
2. Two waves combine to make a wave that is larger than either wave by itself. Is this constructive or destructive interference?
3. Can a wave have resonance when the wave is free to expand as far as it can go? Explain why or why not.
4. Which has more energy: a vibrating string at 30 Hz or the same vibrating string at 70 Hz?
5. If a wave is being absorbed, what would you expect to happen to the amplitude of the wave? Explain using the idea of energy.

Waves that Shake the Ground


Kobe earthquake 1995

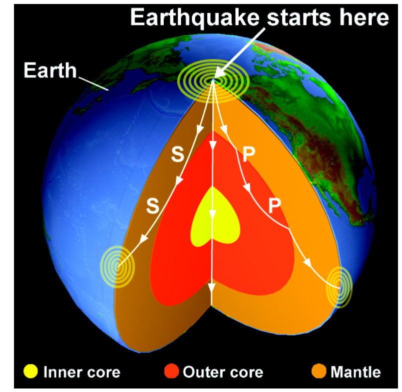
In 1995, a severe earthquake struck Kobe, Japan. During the quake, about 86,000 buildings—like the one at right—were damaged and about 82,000 collapsed even though it lasted only 20 seconds! So, much damage in so short a time all caused by waves traveling through Earth.

You know how to cause water waves and cause a wave to travel along a string or a Slinky™. How do waves get started in the ground? Earthquakes begin in Earth's rocky crust. Pressure can build up in underground rocks causing them to expand and contract. Like a stretched rubber band or a compressed spring, the rocks store energy. When the rocks break or change shape, stored energy is suddenly converted to ground-shaking energy. The result is that seismic waves radiate from the place where the rocks inside Earth release stored energy and an earthquake occurs. During a quake, there is a strong burst of shaking that lasts from seconds to minutes. The longest ever recorded earthquake occurred in 1964 in Alaska and lasted for four minutes.

Earthquake waves

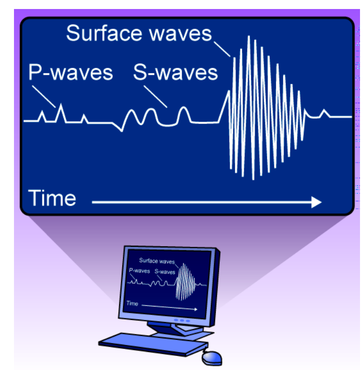
Seismic waves caused by an earthquake travel through the ground about 20 times faster than the speed of sound (about 5 kilometers per second). These waves can be slowed or bent depending on the properties of rock they encounter.

Two kinds of waves are released from the location that the earthquake starts. One kind of wave, called primary waves are faster and push and pull on rocks as they moves through Earth. The second kind of wave—secondary waves—move sideways and up and down, traveling a little slower than primary waves.



Because they are faster, primary waves reach Earth's surface first. When primary and secondary waves reach the surface they become surface waves. These waves move more slowly (about 10 percent slower than secondary waves), but can be very damaging. When these waves have a lot of energy, the ground rolls like the surface of the ocean. Surface waves can also move side to side and cause buildings to collapse.

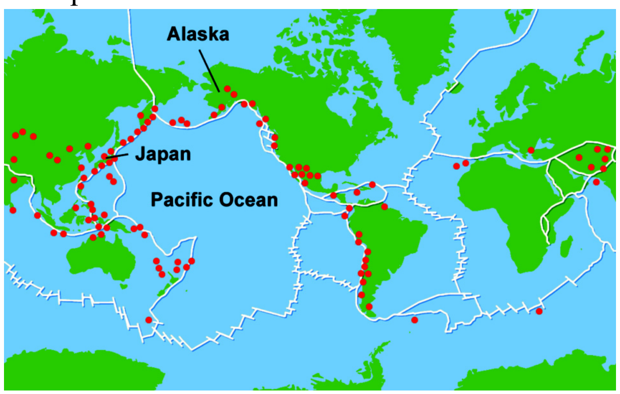
Seeing inside Earth



Seismic waves are recorded and measured by a seismograph. A worldwide network of seismographs at stations on land and in the oceans record earthquakes. The amplitudes of the recorded waves are related to the magnitude of the earthquake. People who record and interpret seismic waves are called seismologists. In addition to measuring earthquakes, seismologists use seismic waves to study Earth's internal structure. Primary and secondary waves travel through Earth and help identify the properties of the layers inside Earth. For example, primary waves but not secondary waves pass through the outer core of Earth. Secondary waves do not travel through liquids.Therefore, this observation indicates to seismologists that the outer core of Earth is liquid.

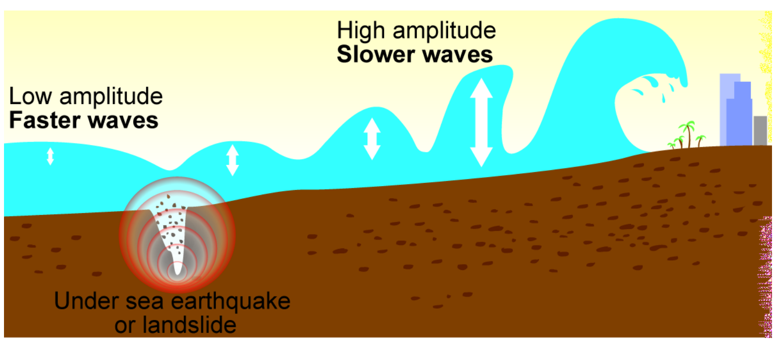
Where do earthquakes occur?

Earth is covered by a thin crust of rock. Rather than being continuous, the crust is broken into pieces called tectonic plates. These pieces constantly, although slowly, move. As edges of the plates move against each other, pressure builds up and an earthquake can occur. The graphic below shows the edges of Earth's "puzzle pieces" (white lines) and the red dots show common earthquake locations.



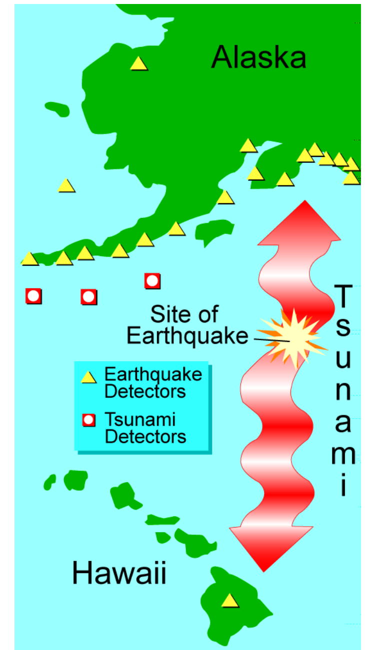
Dangerous underwater earthquakes

In the middle of the Pacific Ocean, earthquakes can occur on the ocean floor. When this happens, a huge and dangerous water wave called a tsunami can occur. The speed at which this wave travels can be about 700 kilometers per hour.



In the open ocean, you would not notice a tsunami because its amplitude is small. However, as the wave reaches a shallow area, the water piles up so that the wave amplitude greatly increases. The wave may get as high as 25 meters!

Tsunamis cause serious flooding and the power of their waves wrecks buildings and can cause loss of life. Tsunamis affect coastal areas and islands that experience earthquakes. To protect people from tsunamis, around the Pacific coastline of Alaska, Hawaii, and the west coast of the Lower 48 states, there are ocean-bound tsunami detectors and seismographs. Scientists use information from the detectors and seismographs to forecast tsunamis. Because scientists know how fast a tsunami can travel after it has been triggered by an earthquake, they can warn people in coastal places to evacuate to higher ground.



Questions:

1. List and describe the different types of seismic waves.
2. Research the Richter scale. What do the numbers on this scale represent?
3. Where are earthquakes most likely to occur on Earth?
4. If an earthquake occurs in the Pacific Ocean about 3,000 km from Hawaii and 1,900 km from Alaska, how much time do Hawaiians have to evacuate away from the coast? How much time do the Alaskans have? Use the speed for a tsunami from the reading.

Chapter 20 Review

Understanding Vocabulary

Select the correct term to complete the sentences.

harmonics	circular wave	absorption
reflection	waves	transverse waves
longitudinal waves	fundamental	trough
destructive interference	diffraction	constructive interference

Section 20.1

1. Waves on a string and water are examples of ____, and oscillate perpendicular to the direction the wave moves.
2. The low point of a wave is called its ____.
3. The lowest natural frequency of an object is known as the ____ frequency.
4. ____ carry energy and information from one place to another.
5. Sound waves are ____, and oscillate in the same direction as the wave motion.
6. Multiples of the natural frequency are called ____.

Section 20.2

7. By touching your finger at a single point of the surface of a smooth pond, you can create a(n) ____ pattern.
8. When waves bounce off an obstacle and change direction, it is known as ____.
9. A wave bending around obstacles and going through openings is called ____.
10. Using a heavy curtain in a theater to keep the audience from hearing backstage sound is an example of the ____ of sound waves.

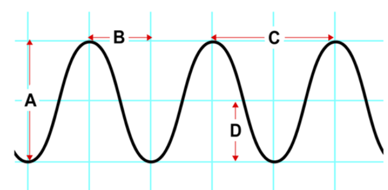
Section 20.3

11. Two waves meeting and adding up to a larger wave is called ____.
12. Two waves meeting and cancelling each other out is called ____.

Reviewing Concepts

Section 20.1

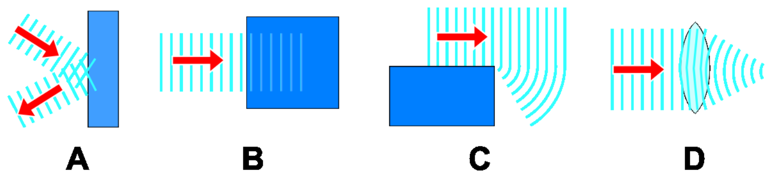
1. Identify how each of the following situations involves waves. Explain each of your answers.
   a. A person is talking to someone on a cell phone.
   b. An earthquake causes the floor of a house to shake.
   c. A person listens to her favorite radio station on the car stereo.
   d. A doctor makes an X ray to check for broken bones.
   e. You turn on a lamp when you come home in the evening.
2. Compare transverse waves and longitudinal waves. Give two examples of each type of wave.
3. Arrange the equation relating wave speed, frequency, and wavelength for each of the following scenarios. Let v = wave speed, f = frequency, and λ = wavelength:
   a. You know frequency and wavelength. Solve for v.
   b. You know frequency and wave speed. Solve for λ.
   c. You know wave speed and wavelength. Solve for f.
4. Write a formula relating the speed of a wave to its period and wavelength.
5. Give one example of a wave with a very short wavelength and one one with a very long wavelength.
6. For the wave in the diagram, which measurement shows the amplitude? Which measurement shows the wavelength?



7. What causes a standing wave?
8. How many nodes and antinodes are in a single wavelength of the second harmonic of a vibrating string?

Section 20.2

9. Sketch the wave crests, indicating the direction of motion, for:
   a. a circular wave
   b. a plane wave
10. Below are diagrams representing interactions between waves and boundaries. Identify each interaction by name.



11. What happens to the amplitude of a wave when the wave is absorbed?
12. Explain why you can hear a sound through a door that is only open a crack. Use the terms *wave* and *interaction* in your answer.
13. Read the descriptions below and indicate which of the four types of wave interactions (*absorption*, *reflection*, *refraction*, or *diffraction*) has occurred.
   a. The distortion of your partially submerged arm makes it look "broken" when viewed from the air.
   b. You hear the music even though you are seated behind an obstruction at a concert.
   c. You see yourself in a mirror.
   d. Water ripples passing through a sponge become smaller.
   e. Heavy curtains are used to help keep a room quiet.

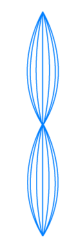
Section 20.3

14. What happens if two waves are in the same place at the same time? Use the term *superposition principle* in your answer.
15. Can two waves interfere with each other so that the new wave formed by their combination has *NO amplitude*? What type of interference is this?
16. What happens to the amplitude of two waves as the result of:
   a. constructive interference?
   b. destructive interference?

Solving Problems

Section 20.1

1. A wave has a frequency of 10 Hz and a wavelength of 2 meters. What is the speed of the wave?
2. A sound wave has a speed of 400 m/sec and a frequency of 200 Hz. What is its wavelength?
3. The wavelength of a wave on a string is 1 meter and its speed is 5 m/sec. Calculate the frequency and the period of the wave.
4. Draw at least one cycle of a transverse wave with an amplitude of 4 centimeters and a wavelength of 8 centimeters. If the frequency of this wave is 10 Hz, what is its speed?
5. The standing wave pattern in the graphic at right has a frequency of 30 Hz.
   a. What is the period?
   b. At what frequency will you find the fourth harmonic?
   c. At what frequency will you find the fifth harmonic?
   d. How many nodes are in this wave pattern?
   e. How many antinodes are in this wave pattern?



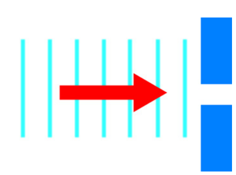
30 Hz

6. You are doing a vibrating string experiment and observe the sixth harmonic at 48 Hz. At what frequency do you find the third harmonic?
7. How many nodes and antinodes does this standing wave have?

8. An A note played on a piano vibrates at a frequency of 440 Hz. Find the frequency for its second harmonic.

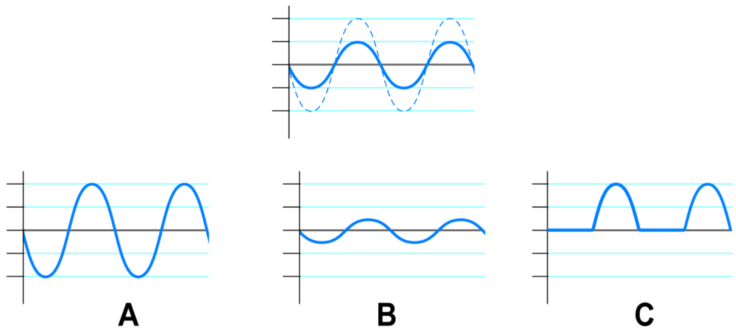
Section 20.2

9. The wave in the picture is about is about to pass through a small hole in a wall. Sketch what the wave front will look like after it passes through the hole.

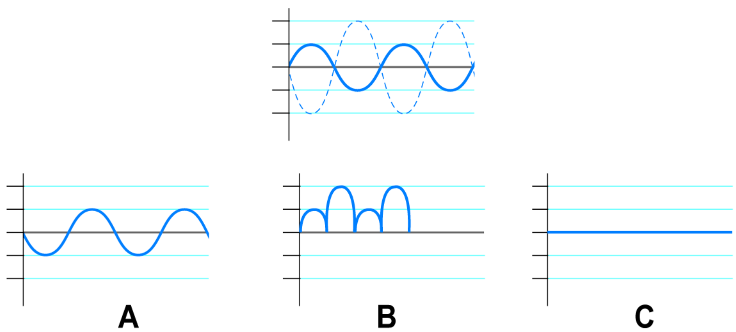


Section 20.3

10. Which graph shows the superposition of the two in-phase waves shown below?



11. Which graph shows the superposition of the two out-of-phase waves shown below?



Applying Your Knowledge

Section 20.1

1. Tsunami waves are large ocean waves generated by disturbances like underwater earthquakes or landslides. Tsunamis can travel on the open ocean at speeds of 200 m/s, which is comparable to the speed of a jet airplane.
    a. What type of wave is a tsunami, transverse or longitudinal?
    b. If the period of a tsunami is one hour (= 3,600 seconds), what is its frequency?
    c. If a tsunami's wave speed is 200 m/s and its period is 3,600 seconds, what is its wavelength?

2. The "sweet spot" on a baseball bat is related to how the bat vibrates when it hits a baseball. If a ball hits the sweet spot, your hands do not feel the vibrations of the bat. Whereas, if the ball hits a place on the bat that is *not* the sweet spot, the vibrations cause your hand to hurt after you hit the ball. Find out why this happens. Use your library or on the Internet to research this phenomenon. Write a short paragraph with a diagram to summarize your findings.

Section 20.2

3. Eye doctors use a refraction test to measure your eyesight for glasses. The test is performed by having you look through a refractor device at an eye chart. The refractor device has different types of lenses for you to look through. When a lens is found that gives you clear vision, the doctor can prescribe the correct set of eyeglasses for you.
    a. Why do you think this is called a refraction test?
    b. What kind of wave is being refracted by the refraction device?
    c. How do eyeglasses help you to see more clearly?

4. The reflection of sound waves leads to echoes, where the listener hears a delayed repeat of the original sound. If a canyon wall is 34 meters away and the speed of sound in air is 340 m/sec, what would be the time delay of an echo in the canyon?

Section 20.3

5. In 1933 the US Navy steamship *Ramapo* reported seeing a 64 meter wave in the open ocean where the sea is 4,000 to 6,000 meters deep. How might this wave have been formed? Is this just a sea tale or is a wave this size possible?

6. Have you ever been in a situation that was too noisy? Choose one of the following research topics on the subject of noise. Research your topic and present your findings in a one-two page essay. Include in your essay information about how noise is reduced using understanding of sound waves.
    a. Noise from airports
    b. Noise from highways
    c. Use of hearing protection by teenagers
    d. Health problems related to noise