CHAPTER 14 Waves and Energy Transfer

Surf's Up

Where does the surfer's kinetic energy come from? Try to trace the energy source back as far as you can.

Have you ever ridden a wave on a surf board, boogie board, or merely body surfed? Whether in ocean surf or in a wave pool, when you "catch the wave" you gain speed and stay just ahead of the breaking surf. Your body's kinetic energy increases. If you can, you do as this surfer does, and ride almost parallel to the wave at a very high speed. Surfing can be dangerous, however. Unless you are skilled, you can "wipe out" and be thrown down into the water or sand.

Does the water move with the wave? Leonardo da Vinci (1452–1519) answered this question five centuries ago.

> *The impetus is much quicker than the water, for it often happens that the wave flees the place of its creation, while the water does not...*

In other words, the wave moves on, the water does not. In this way, water waves are typical of the waves we will study in the next few chapters, those of sound and light.

✓ Concept Check

The following terms or concepts from earlier chapters are important for a good understanding of this chapter. If you are not familiar with them, you should review them before studying this chapter.
- velocity, Chapter 3
- period and frequency, Chapter 7
- potential energy and kinetic energy, Chapter 11

Objectives

- recognize that waves transfer energy without transferring matter.
- distinguish between longitudinal and transverse waves; between a wave pulse and a continuous wave.
- define amplitude, wavelength, frequency, and period; state the relationship between speed, wavelength, and frequency; solve problems using these quantities.

14.1 WAVE PROPERTIES

Both particles and waves transmit energy, but there is an important difference. If you throw a ball at a target, the target may gain some kinetic energy, but the ball will have moved from you to the target. If you tie a rope on the target and shake the rope, the target may also gain some kinetic energy. The rope, however, will remain in position, between you and the target. How do we describe waves, and how fast do they transmit the energy?

Types of Waves

Energy can be transferred by particles or by waves.

Water waves, sound waves, and the waves that travel along a spring or rope are mechanical waves. Mechanical wave motion requires a material medium. Water, air, and springs or ropes are the materials that carry the energy of these mechanical waves. Newton's laws govern the motion of mechanical waves.

Mechanical waves need a medium.

Light waves, radio waves, and X rays are examples of electromagnetic waves. No medium is needed for the motion of electromagnetic waves. They all travel through space at the speed of light, 299 792 458 m/s. The details of electromagnetic waves cannot be observed directly. Thus, we will use the easily observed mechanical waves as models for the behavior of electromagnetic waves that will be studied in later chapters.

There is a third type of wave, the matter wave. Electrons and other particles show wave-like behavior under certain conditions. Quantum mechanics is needed to describe the properties of matter waves. We will delay our study of matter waves until Chapter 27.

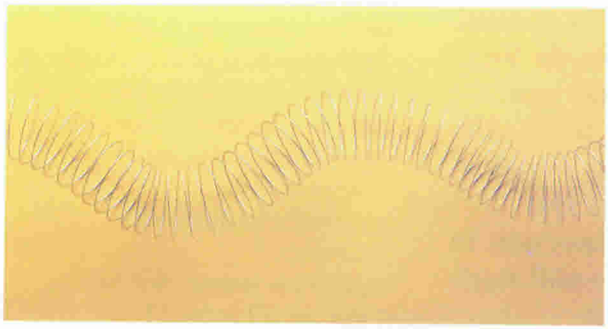
In a transverse wave, particles vibrate at right angles to the direction of the wave's velocity.

We can divide mechanical waves into three different types. Each type disturbs the medium in a different way. A **transverse wave** causes the particles of the medium to vibrate perpendicularly to the direction of motion of the wave. Figure 14–1a shows a transverse wave. The wave moves along the spring from left to right, but the spring is displaced up and down, at right angles to the motion of the wave. Waves in piano and guitar strings are examples of transverse waves.

A **longitudinal wave** causes the particles of a medium to move parallel to the direction of the wave. Figure 14–1b shows a longitudinal wave. The displacement of the spring is in the same direction as the motion of the wave. A sound wave is an example of a longitudinal

FIGURE 14–1. Two general types of waves are the transverse wave (a) and the longitudinal wave (b).

a



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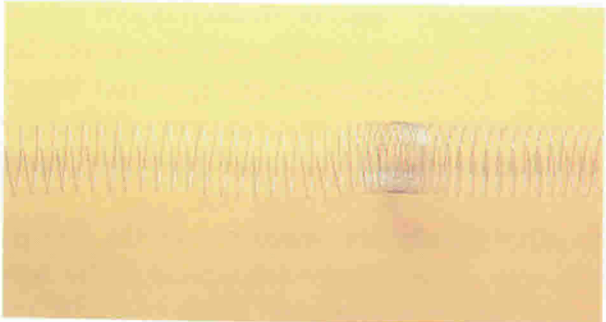


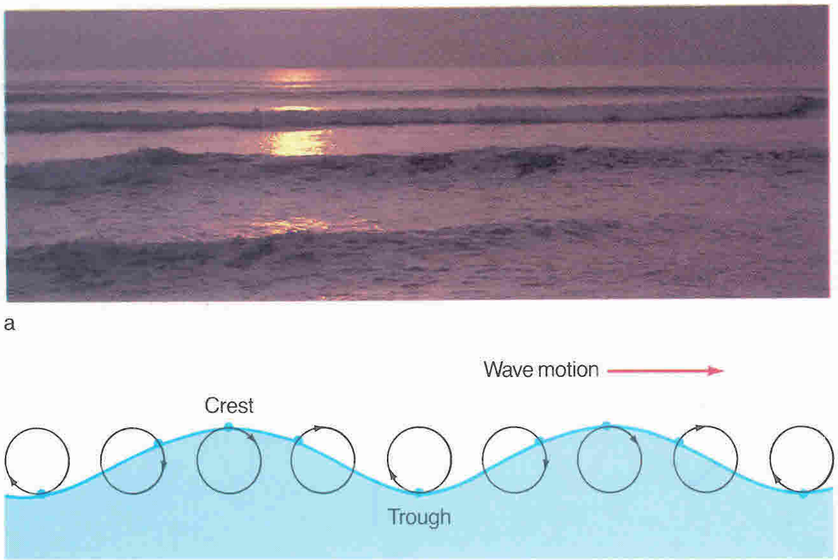


FIGURE 14–2. Surface waves show characteristics of both longitudinal and transverse waves. The paths of the particles are almost perfect circles.

A pulse is a single disturbance of a medium.

wave. Fluids, liquids, gases, or plasmas usually transmit only longitudinal waves.

Although waves deep in a lake or ocean are longitudinal, at the surface of the water, Figure 14–2, the particles move both parallel and perpendicular to the direction of the wave. These are **surface waves**, a mixture of transverse and longitudinal waves. The energy of water waves usually comes from storms far away. The energy of the storms initially came from the heating of Earth by solar energy. This energy, in turn, was carried to Earth by transverse electromagnetic waves.

Surf's Up

How are waves produced? Suppose you hold one end of a rope. If you suddenly jerk the rope to one side and quickly return it to the center, Figure 14–3, a wave pulse will travel down the rope. A **wave pulse** is a single disturbance that travels through a medium. A given point on the rope was at rest before the pulse reached it; it returned to rest after the pulse passed. If instead you move the rope from side to side in a regular manner, a **traveling wave** will move along the rope. A source that is vibrating with simple harmonic motion will produce a continuous traveling wave. Each point on the rope will vibrate regularly in response to the traveling wave.

A wave train, or traveling wave, is a series of pulses at regular intervals.

FIGURE 14–3. The two photographs were taken 1 s apart. During that time, the crest moved 0.8 m. The velocity of the wave is 0.8 m/s.

a b

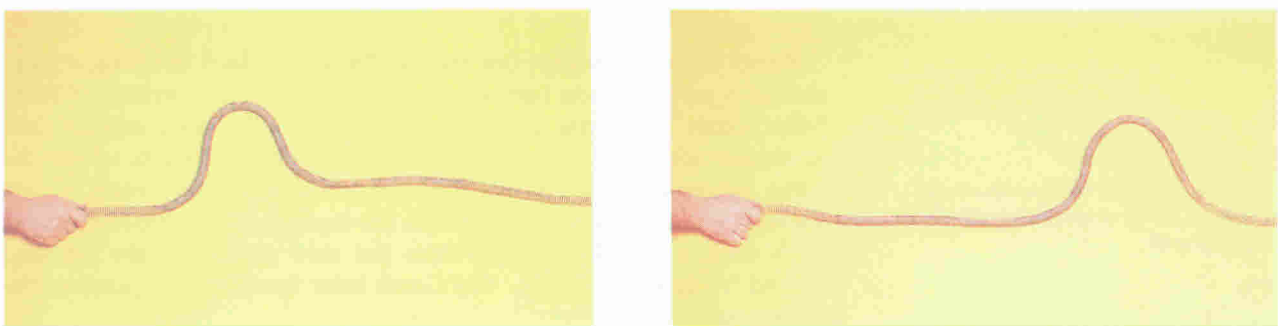
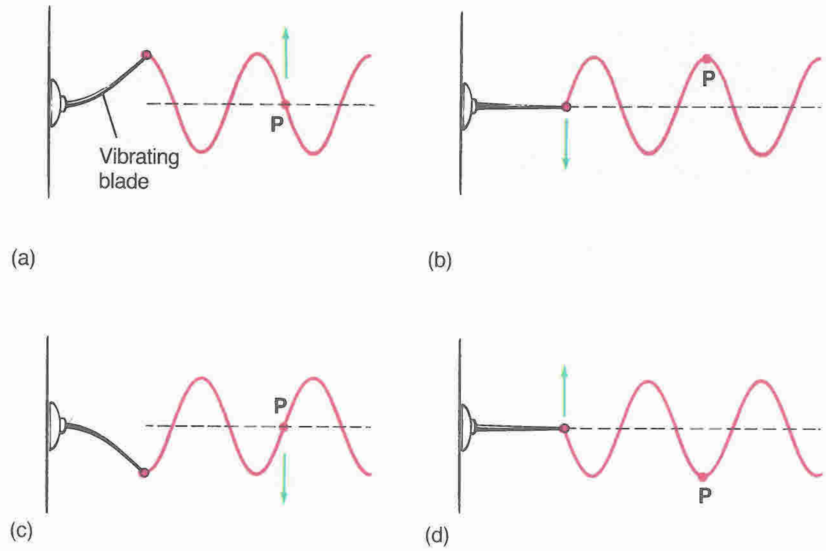


FIGURE 14–4. The left end of the string is attached to a vibrating blade. Note the change in position of the tape, P, over time.



F. Y. I.

The letter "M" may have originated as a hieroglyphic symbol representing the crests of waves and meaning "water."

The Measures of a Wave: Frequency, Wavelength, and Velocity

The period of a wave is the time needed for the motion to repeat itself.

Imagine putting a piece of tape at point **P** on the rope. How does that piece of tape move in time? Figure 14–4 shows that the **P** moves back and forth. The shortest time interval during which the motion repeats itself is called the **period**, T.

The **frequency** of a wave, f, is the number of complete vibrations per second measured at a fixed location. Frequency is measured in hertz. One hertz (Hz) is one vibration per second. The frequency and period of a wave are related by the equation

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

That is, they are reciprocals of each other.

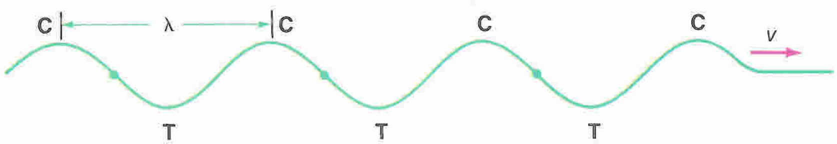


FIGURE 14–5. Points labeled C represent wave crests; points labeled T represent wave troughs.

Rather than focusing on one spot on the wave, think of taking a snapshot of a wave, so you can see the whole wave at one instant of time. From Figure 14–5, you can see that the form of the wave repeats itself at regular distances. The shortest distance between points where the wave pattern repeats itself is called the **wavelength**. The **crests**, C, are the high points of each wave motion; the **troughs,** T, are the low points. Each crest is one wavelength from the next crest. Troughs are also spaced by one wavelength. The Greek letter lambda, λ, represents the wavelength.

Wavelength is the shortest distance between points where the wave pattern repeats itself.

Example Problem

Period of a Wave

A sound wave has a frequency of 262 Hz. What is the time between successive wave crests?

Given: $f = 262$ Hz

Unknown: period, T

Basic equation: $f = \frac{1}{T}$

Solution: $f = \frac{1}{T}$, so $T = \frac{1}{f}$

$$T = \frac{1}{262\ \text{Hz}} = \frac{1}{262\ \text{s}^{-1}} = 3.82 \times 10^{-3}\ \text{s}$$

How fast does a traveling wave move? You could run alongside the wave just fast enough so that the wave appears to stand still. An easier way is to take two photographs at a known time interval apart. Figure 14–6 shows a drawing of two waves made one second apart. During the one-second time interval, the crests moved 0.8 m to the right. The velocity of any object is the distance moved divided y the time interval. Thus, the wave velocity is 0.8 m/s to the right.

In the special case that the time interval is exactly one period, the wave would move a distance of one wavelength. Thus, the velocity can be calculated from the equation

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

This is more conveniently written as

$$\boxed{v = \lambda f.}$$

Wave velocity is the product of the frequency and the wavelength.

POCKET LAB

THE SNAKEY

Tie a piece of ribbon or yarn to the middle of a long coil spring (snakey). With a lab partner, stretch the snakey to twice its original length. Quickly shake your hand sideways to put a pulse of energy into the snakey. Closely watch the ribbon. This type of wave motion is a transverse wave. Describe the motion of the ribbon. Does the ribbon move in the direction parallel to the length of the snakey?

Tightly grasp the snakey so that your hands are about 30 cm apart. Move your hands together so that the snakey coils are closer together. This is a higher pressure (compression) region. This high pressure region will move along the length of the snakey. This is a pressure (longitudinal) wave. Describe the motion of the ribbon.

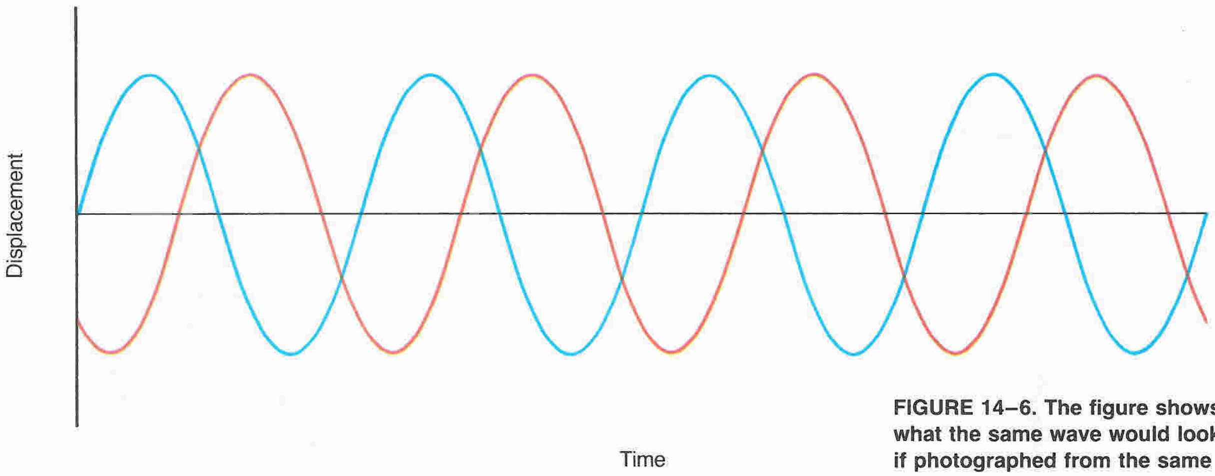


FIGURE 14–6. The figure shows what the same wave would look like if photographed from the same place at two different times.

PHYSICS LAB

Waves on a Snakey

Purpose

To investigate properties of waves using a snakey as a model.

Materials

- a long coil spring (snakey)
- stopwatch
- meter stick

Procedure

1. You will need a clear path of about 6 meters for this activity.
2. Slowly stretch the snakey to the length suggested by your instructor.
3. Grip the snakey firmly with one hand for the entire activity.
4. It is easier to see the motion of the snakey if you are near one end. Don't watch from the side.
5. As the pulses die out, they can still be felt. Trust your feelings!
6. This activity is a sensory experience. Each student in the group should take some time on the end of the snakey.
7. Make a quick sideways snap with your wrist to produce a transverse pulse in the snakey.
8. Notice how many times the pulse will move back and forth on the snakey.
9. Look closely at the questions in the observation section. Try to design and conduct an experiment to answer each question.

Observations and Data

1. What happens to
   a. the amplitude of a wave as it travels?
   b. the speed of a wave as it travels?
2. Does the speed depend on the amplitude?
3. Put 2 quick pulses into the snakey. The distance between pulses is called λ. Does λ change as the pulses move?
4. What can you do to decrease the value of λ?
5. Do pulses bounce off each other or pass through?

Analysis

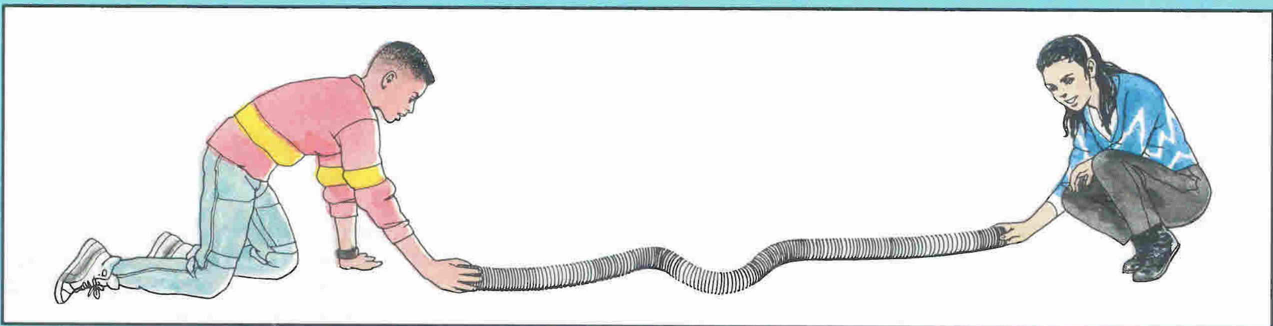
1. You probably used transverse waves for this activity. Should your answers be accurate for pressure (longitudinal) waves? Why?
2. Check your answers for steps 1-3 with *pressure* waves.
3. Use the snakey to find out if pressure waves go through each other. Describe your results.

Applications

Sound waves are pressure waves. Make your predictions consistent with your snakey results.

1. Does the speed of the sound depend on the loudness? (Do louder sounds travel *faster* than quiet sounds?)
2. Compare the speed of high frequency (short wavelength) sounds to low frequency (long wavelength) sounds.

* NOTE * Snakeys are *NOT SOCIAL*. Do not allow the snakeys to get tangled together! Each snakey should be stored in its own personal container!



Example Problem

Velocity of a Traveling Wave

A sound wave with frequency 262 Hz has a wavelength of 1.29 m. What is the velocity of the sound wave?

Given: frequency, $f = 262$ Hz, wavelength, $\lambda = 1.29$ m

Unknown: velocity, v

Basic equation: $v = \lambda f$

Solution: $v = \lambda f = (1.29\text{ m})(262\text{ Hz}) = 338\text{ m/s}$

Practice Problems

1. A sound wave produced by a clock chime 515 m away is heard 1.50 s later.
   a. What is the speed of sound in air?
   b. The sound wave has a frequency of 436 Hz. What is its period?
   c. What is its wavelength?
2. A hiker shouts toward a vertical cliff 685 m away. The echo is heard 4.00 s later.
   a. What is the speed of sound in air?
   b. The wavelength of the sound is 0.750 m. What is its frequency?
   c. What is the period of the wave?
3. A radio wave, a form of electromagnetic wave, has a frequency of 99.5 MHz (99.5×10^6 Hz). What is its wavelength?
4. A typical light wave has a wavelength of 580 nm.
   a. What is the wavelength of the light in meters?
   b. What is the frequency of the wave?

GEOLOGY CONNECTION

Waves through a solid can be either transverse or longitudinal. An earthquake produces both transverse and longitudinal waves that travel through Earth. Geologists studying the waves with seismographs found that longitudinal waves could pass through Earth's core, transverse waves could not. From this evidence, they concluded that Earth's core is liquid. From its density, it is most likely molten iron.

When a wave passes through a medium, the particles move, but they are not carried along with the wave. For example, as a transverse wave passes through a spring, Figure 14–2a, each coil is in the same position as before the wave arrived. Even though huge waves may crash on a beach as the result of a distant storm, the water in the waves remains near the beach.

Amplitude of a Wave

Two waves with the same frequency can have different wavelengths. Waves can differ from one another in another way. A rope can be shaken violently or gently; a sound can be loud or soft. A water wave can be a giant tidal wave or a gentle ripple. The **amplitude** of a wave is its maximum displacement from the rest or equilibrium position. The two waves in Figure 14–7 have the same frequency, velocity, and wavelength, but their amplitudes differ.

In order to produce a wave with larger amplitude, more work has to be done. For example, strong winds produce larger water waves than

The speed of sound in air depends on temperature; it may not be the same in all problems.

The amplitude of a wave is its maximum displacement from the rest position.

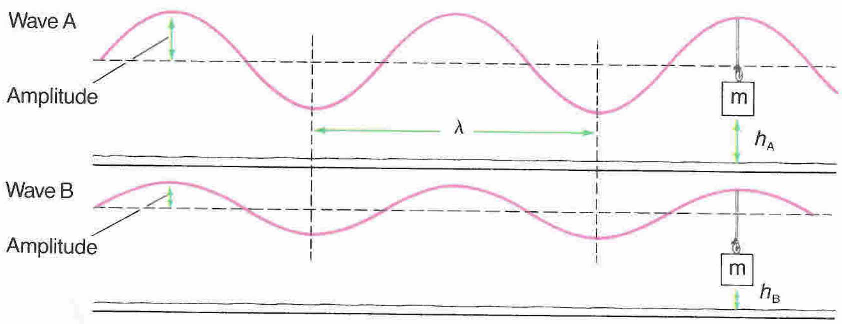


FIGURE 14–7. The relationship of the amplitude of a wave to the work it can perform is shown here. The greater the work done to create the wave, the greater the amplitude of the wave. The greater the amplitude of the wave, the more work it can do.

POCKET LAB

FEEL THE PULSE

Does the speed of a pulse depend on its amplitude? Without a stopwatch, design an experiment using a snakey to find out. Make a record of your procedures and observations.

gentle breezes. A wave with larger amplitude transfers more energy. A small wave might move sand on a beach back and forth. When a giant wave crashes on a beach, however, it can uproot trees or move heavy boulders. The larger the amplitude, the greater the energy transferred. In fact, for waves that travel at the same velocity, the rate at which energy is carried is proportional to the square of the amplitude of the wave. Thus, if you double the amplitude of the wave, you increase the energy it transfers every second by a factor of four.

The energy transferred by a wave depends on the square of its amplitude.

CONCEPT REVIEW

1.1 Suppose you and your lab partner were asked to measure the speed of a transverse wave in a giant Slinky. How could you do it? List the equipment you would need.

1.2 You are creating waves in a rope by shaking your hand back and forth. Without changing the distance your hand moves, you begin to shake it faster and faster. What happens to the amplitude, frequency, period, and velocity of the wave?

1.3 If you pull on one end of a Slinky, does the pulse reach the other end instantaneously? What if you pull on a rope? Hit the end of a metal rod? Discuss any differences.

1.4 **Critical Thinking:** If a rain drop falls into a pool, small-amplitude waves result. If a swimmer jumps into a pool, a very large-amplitude wave is produced. Why doesn't the heavy rain in a thunderstorm produce large waves?

Objectives

- understand that wave speed depends on the medium.
- understand what occurs when a wave crosses the boundary between two media with different wave speeds.
- be able to solve problems involving waves crossing boundaries.
- state the principle of superposition and understand how constructive and destructive interference result.
- state the law of reflection.
- describe refraction in terms of behavior of a transmitted wave.
- define diffraction of a wave around a barrier.

14.2 WAVE INTERFERENCE

Two particles cannot be in the same place at the same time. Matter, after all, takes up space. This is not true for waves. The properties that are characteristic of wave behavior are the result of two or more waves existing in the same area at the same time.

Waves at Boundaries Between Media

The speed of a mechanical wave does not depend on the amplitude or the frequency of the wave. It depends only on the properties of the

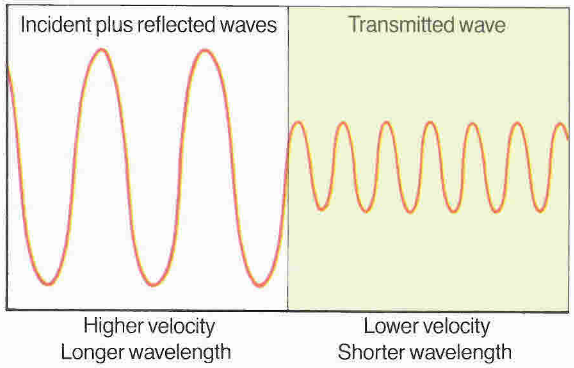
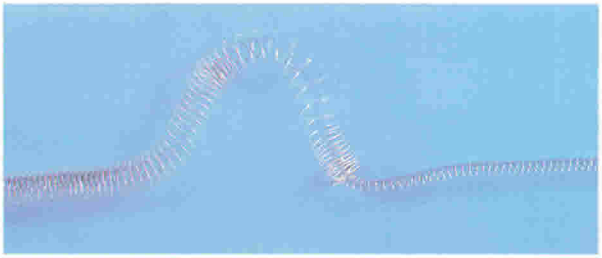


FIGURE 14–8. The speed and wavelength of a wave change when the wave enters a new medium. The left half of the figure shows the sum of the incident and reflected waves. The transmitted wave is on the right.



a

b

FIGURE 14–9. The junction of the two springs is a boundary between two media. A pulse reaching the boundary (a) is partially reflected and partially transmitted.

medium. The speed of water waves depends on the depth of the water. The speed of waves in a rope depends on the force exerted on the rope and its mass per unit length. The speed of sound in air depends on the temperature of the air. Although a wave with larger amplitude transfers more energy, it moves at the same speed as a smaller amplitude wave through a given medium. A wave with a higher frequency has a shorter wavelength, as given by the equation $v = \lambda f$. As long as the material is the same, the speed of high and low frequency waves is the same.

Often a wave moves from one medium to another. Light might move from air into water, Figure 14–8. In Figure 14–9, waves move from large to small springs. The spring can end by being fastened to a rigid wall, as in Figure 14–10, or by being allowed to move freely, Figure 14–11. What happens to a wave when the medium changes?

Suppose a wave, called the incident wave, reaches the boundary of a medium. Part of the energy carried by the incident wave continues on in the new medium as a wave with the same frequency. This wave is called the transmitted wave. In addition, part of the energy moves backward from the boundary as a wave in the old medium. This wave is called the reflected wave.

If the difference in the media is small, then the amplitude of the transmitted wave will be almost as large as that of the incident wave, and the amplitude of the reflected wave will be small. Most of the energy of the incident wave will be transmitted. If the two materials are very different, however, most of the wave energy will be reflected.

Figure 14–10 shows a wave on a spring approaching a rigid wall. The spring and wall are very different, so most of the wave energy is reflected. The figure also shows that the reflected wave is inverted. The incident wave pulse is in the upward direction, the reflected pulse is in the downward direction. Whenever a wave passes from a less dense to a more dense medium, the reflected wave is inverted.

F.Y.I.

Because radio waves travel at 3.0×10^8 m/s and sound waves are slower, 3.4×10^2 m/s, a broadcast voice can be heard sooner 13 000 miles away than it can be heard at the back of the room in which it originated.

FIGURE 14–10. A pulse is shown as it approaches a rigid wall (a) and as it is reflected from the wall (b). Notice that the amplitude of the reflected pulse is nearly equal to the amplitude of the incident pulse but that the reflected pulse is inverted.

a

b

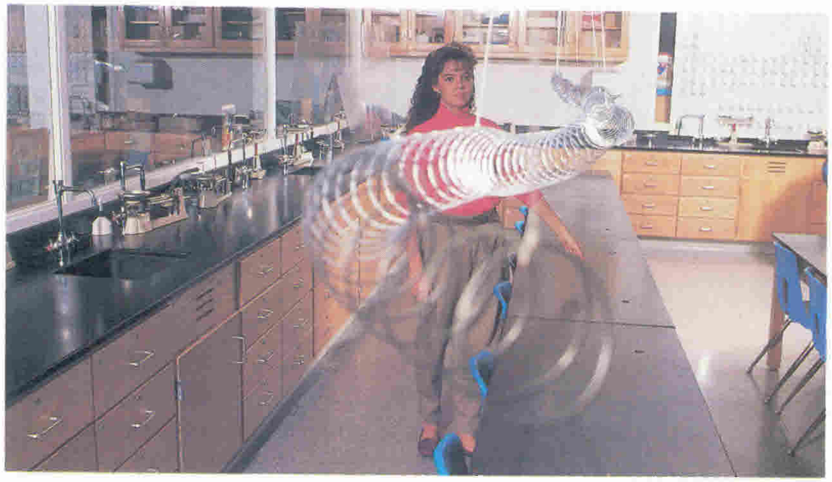


FIGURE 14–11. A pulse reflected from an open-ended boundary returns erect.

In Figure 14–11, the spring is supported by light threads. When a pulse reaches the end of the spring, the pulse is transmitted into another medium, air. Because the two media are very different, most of the energy of the wave is reflected. In this case, however, the reflected wave is not inverted. When a wave passes from a more dense to a less dense medium, the reflected pulse is erect, not inverted.

When the medium changes, wave energy is both reflected and transmitted.

Suppose a wave on a light spring is transmitted to a heavy spring. The wave in the light spring generated the wave in the heavy spring, so the frequencies of the two waves are the same. The speed of the wave in the heavier spring is slower. The speed, frequency, and wavelength of a wave are related by the equation $v = \lambda f$. Because the speed of the transmitted wave is different, but the frequency remains the same, the wavelength of the transmitted wave must also be different. The speed in the heavier spring is less, so the wavelength is smaller. On the other hand, if the speed of a wave increases when it passes into a new medium, then its wavelength also increases.

Although the waves in the examples are transverse waves, longitudinal waves behave in exactly the same way. Whenever a wave reaches a boundary, some of the wave energy is transmitted, some is reflected. The amount of reflected energy is larger if the two media have vastly different properties.

Waves passing from one medium to another have the same frequency. The wavelength change depends on velocity change so that $f = v/\lambda$ is constant.

Practice Problems

5. A pulse is sent along a spring. The spring is attached to a light thread that is tied to the wall, Figure 14–12.
   a. What happens when the pulse reaches point **A**?
   b. Is the pulse reflected from **A** erect or inverted?
   c. What happens when the transmitted pulse reaches **B**?
   d. Is the pulse reflected from **B** erect or inverted?

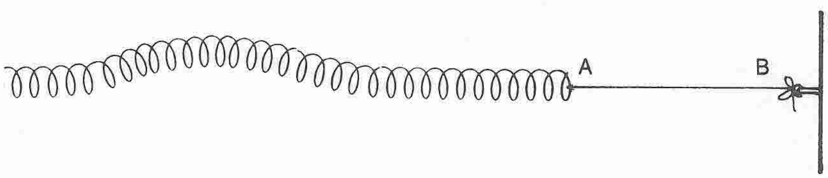


FIGURE 14–12. Use with Practice Problem 5.

6. A long spring runs across the floor of a room and out the door. A pulse is sent along the spring. After a few seconds, an inverted pulse returns. Is the spring attached to the wall in the next room or is it lying loose on the floor?
7. If you want to increase the wavelength of waves in a rope, should you shake it at a higher or lower frequency?

Constructive interference occurs when two waves combine to produce a wave with larger amplitude.

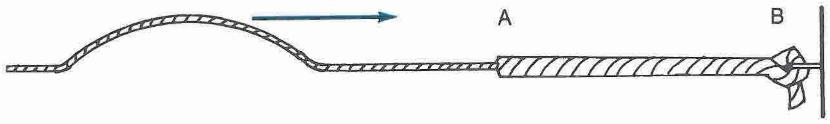


FIGURE 14–13. Use with Practice Problem 8.

8. A pulse is sent along a thin rope that is attached to a thick rope. The thick rope is itself tied to a wall, Figure 14–13.
   a. What happens when the pulse reaches point **A**?
   b. Is the pulse reflected from **A** erect or inverted?
   c. What happens when the transmitted pulse reaches **B**?
   d. Is the pulse reflected from **B** erect or inverted?

Destructive interference occurs when two waves combine to produce a wave with a smaller amplitude.

Superposition of Waves

What happens when two or more waves travel through a medium at the same time? Each wave affects the medium independently. As a result, we can analyze the effects of these waves using the principle of superposition. The **principle of superposition** states that *the displacement of a medium caused by two or more waves is the algebraic sum of the displacements caused by the individual waves.* The result of the superposition of two or more waves is called **interference.**

Interference can be either constructive or destructive. **Constructive interference** occurs when the wave displacements are in the same direction. The result is a wave with larger amplitude than any of the individual waves. Figure 14–14 shows the constructive interference of two equal pulses. When the two pulses meet, a larger pulse is formed. The amplitude of the larger pulse is the algebraic sum of the amplitudes of the two pulses. After the two pulses have passed through each other, they regain their original shape and size. The pulses are not changed by their interaction.

Figure 14–15 shows the **destructive interference** of two pulses with equal but opposite amplitudes. As the two pulses overlap, the displacement of the medium at each point in the overlap is reduced. When the pulses are at the same location, the displacement is zero. The pulses keep moving and resume their original form. An important characteristic of waves is the ability to pass through one another unchanged.

If the pulses have unequal amplitudes, the destructive interference is not complete. The pulse at overlap is the algebraic sum of the two pulses. Some wave amplitude always remains.

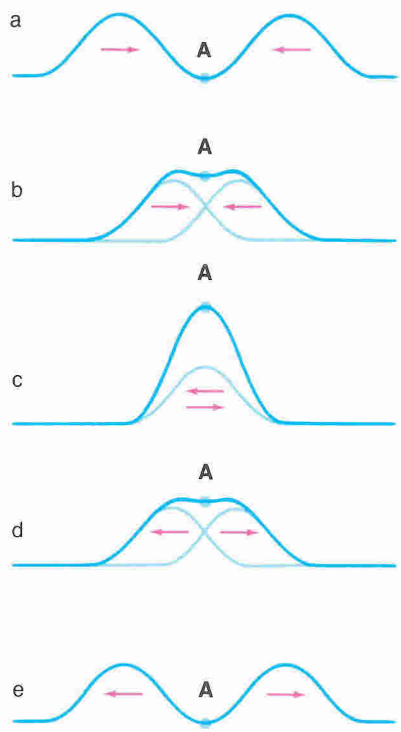


FIGURE 14–14. Constructive interference of two equal pulses. An antinode is a point of maximum displacement.

Standing Waves

Look again at Figure 14–15. Two pulses with equal but opposite amplitudes meet. You can find one point in the medium that is completely undisturbed at all times. This point is called a **node**. At a node, the medium is never displaced. If you put your finger on the rope at the node, you will feel no motion. A node is produced by the destructive interference of waves.

In Figure 14–14, two pulses with equal amplitudes in the same direction meet. There is one point that undergoes the greatest displacement. Its maximum amplitude is equal to the sum of the amplitudes of the two pulses. This point of maximum displacement is called an **antinode.** Constructive interference of waves produces antinodes.

Imagine one end of a rope attached to a fixed point. You continuously vibrate the other end up and down. A traveling wave will leave your hand, move to the other end, be inverted and reflected, and return toward your hand. At your hand, the wave will be inverted and reflected again. At each reflection, the displacement direction will change. If the original displacement was upward, it will be downward when moving back to your hand, but be upward again after reflection from your hand.

Now, suppose you adjust the motion of your hand so that the period of the rope's vibration equals the time required for the wave to travel to the fixed point and back. The displacement your hand gives to the rope each time will add to the displacement of the reflected wave. The result is a very large amplitude oscillation in the rope, much larger than the motion of your hand. This large amplitude oscillation is an example of resonance. There are nodes at the ends of the rope and an antinode in the middle. The nodes and antinodes are stationary. The wave appears to be standing still. It is called a **standing wave**. If you double the frequency of vibration, you can produce additional nodes in the rope. It appears to vibrate in two segments. Further increases in frequency produce even more nodes, Figure 14–16.

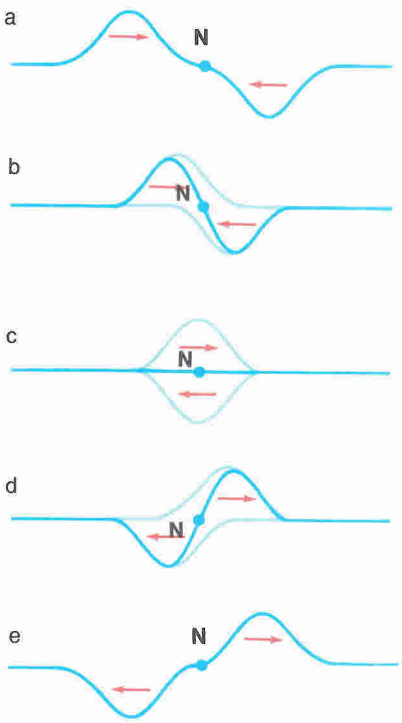


FIGURE 14–15. Destructive interference of two equal pulses. A node is a point of the medium that remains undisturbed.

At a node, the medium is not displaced as the waves pass through each other.

At an antinode, the displacement caused by interfering waves is largest.

A standing wave has stationary nodes and antinodes. It is the result of identical waves traveling in opposite directions.

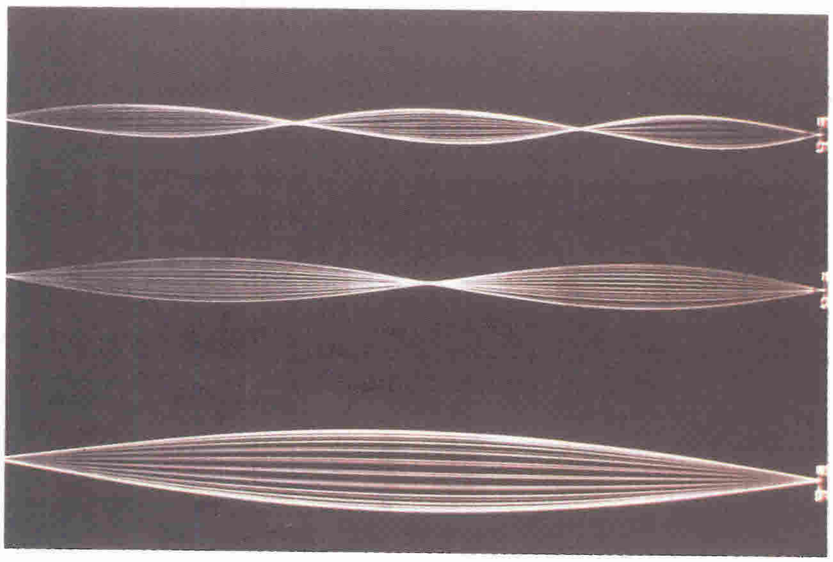


FIGURE 14–16. Interference produces standing waves in a rope.

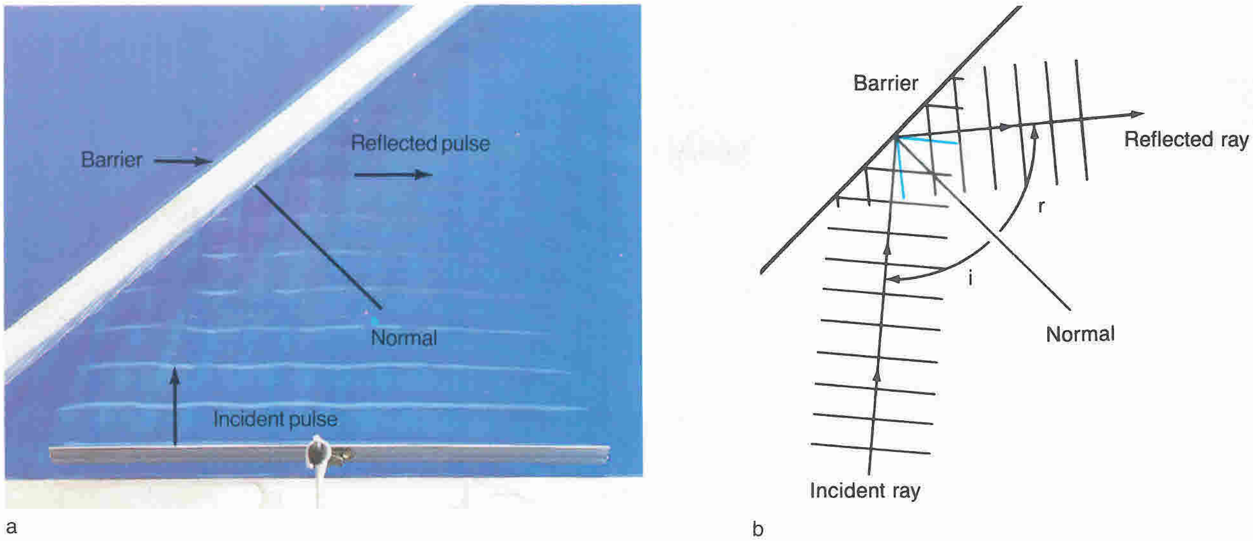


FIGURE 14–17. Reflection of a plane wave pulse by a barrier (a). In (b), part of the pulse front is shown in time sequence as it approaches, and then is reflected from the barrier.

Reflection of Waves

We have studied waves reflecting from a rigid support, where the amplitude of the wave was forced to be zero. These waves move in only one dimension. Waves on the surface of water move in two dimensions, while sound and electromagnetic waves move in three dimensions. A ripple tank can be used to show the properties of two-dimensional waves. A ripple tank contains a thin layer of water. Vibrating boards produce wave pulses or traveling waves with constant frequency. A lamp above the tank produces shadows below the tank that show the locations of the crests of the waves. Figure 14–17 shows a wave pulse traveling toward a straight rigid wall, a barrier that will reflect the wave. The incident pulse moves upward. The reflected pulse moves toward the right.

The angle at which a wave approaches a barrier is equal to the angle at which it is reflected.

The direction of waves moving in two or three dimensions is often shown by ray diagrams. A ray is a line drawn at a right angle to the crest of the wave. A ray diagram shows only the direction of the waves, it does not show the actual waves. In Figure 14–17, the ray representing the incident ray is the arrow pointing upward. The ray representing the reflected ray points to the right.

The direction of the barrier is also shown by a line drawn at a right angle to it. This line is called the **normal**. The angle between the incident ray and the normal is called the **angle of incidence**. The angle between the normal and the reflected ray is called the **angle of reflection**. The **law of reflection** states that *the angle of incidence is equal to the angle of reflection.*

Refraction of Waves

A ripple tank can also be used to study the behavior of waves as they move from one medium into another. Figure 14–18a shows a glass plate placed in a ripple tank. The water above the plate is shallower than in the rest of the tank. The velocity of water waves depends on the water depth, so the water above the plate acts like a different medium.

HELP WANTED

AUDIOLOGIST

A private practice seeks a certified audiologist to provide in-office services, as well as to deliver contract services to outside businesses and agencies.

Patience, compassion, excellent communicative skills, thorough knowledge of current equipment, strong concentration skills, and attention to detail are required for success in this career field. Only candidates with a master's degree need apply. For information contact:

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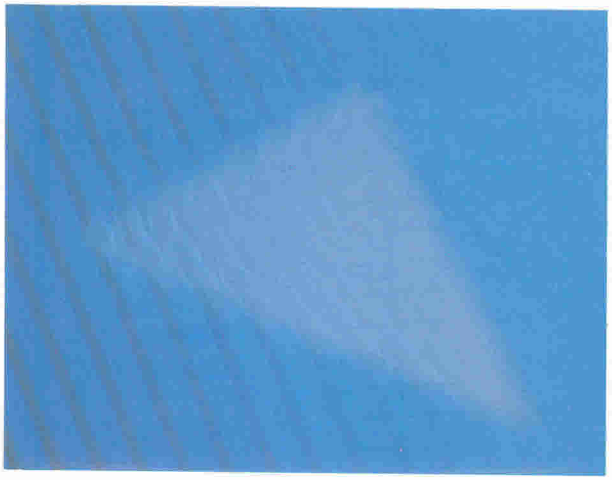


a

b

FIGURE 14–18. Notice the change in wavelength, as the water waves enter a more shallow region (a). When waves enter at an angle they change direction, demonstrating refraction (b).

Refraction is the change of wave direction at the boundary between two media.

How does the velocity of waves depend on water depth? In Figure 14–18a, a wave train passes over a glass plate, changing the depth of the water. As the waves move from deep to shallow water, their wavelength decreases and the direction of the waves changes. Because the waves in the shallow water are generated by the waves in deep water, their frequency is not changed. From the equation $v = \lambda f$, the decrease in the wavelength of the waves means that the velocity is lower in the shallower water.

In Figure 14–18b, the waves approach the shore at an angle. The ray direction is not parallel to the normal. Not only does the wavelength decrease over the shallower bottom, but the direction of the waves changes. The change in the direction of waves at the boundary between two different media is known as **refraction**.

POCKET LAB

WAVE INTERACTION

What happens to the waves coming from different directions when they meet? Do they bounce off or go through each other? Do they slow down? Use the snakey to find out by devising a way to test these questions. Record your procedures and results.

Diffraction and Interference of Waves

If particles are thrown at a barrier with holes in it, the particles will either reflect off the barrier or pass straight through the holes. When waves encounter a small hole in a barrier, however, they do not pass straight through. Rather, they bend around the edges of the barrier, forming circular waves that spread out, Figure 14–19. The spreading of

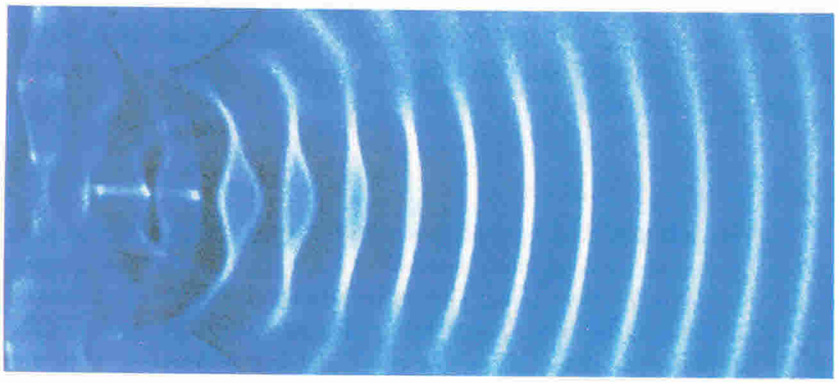
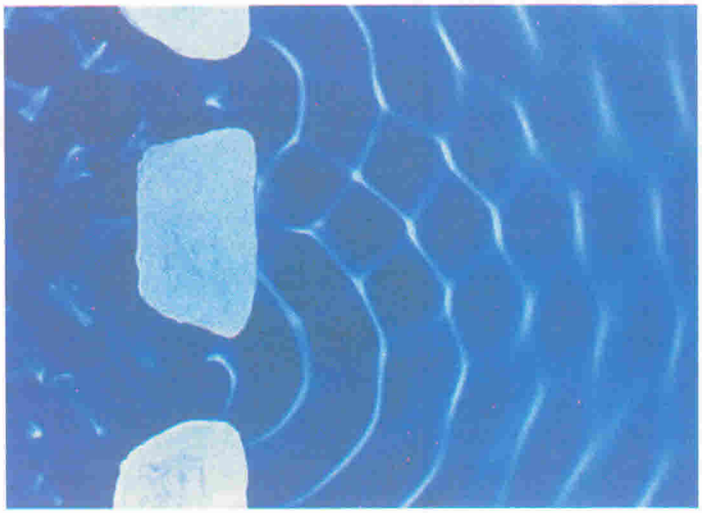
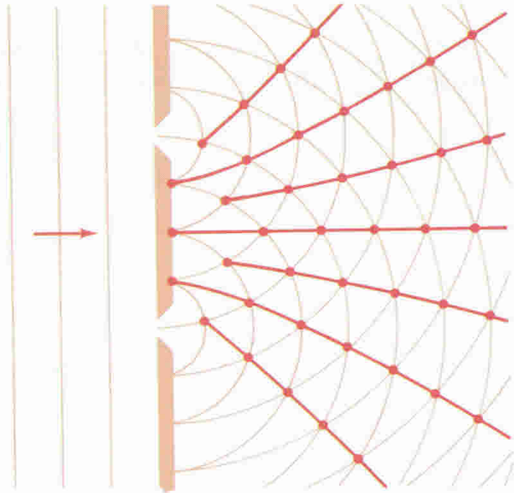


FIGURE 14–19. Waves bending around barriers demonstrate diffraction.



a



b

FIGURE 14–20. Waves are diffracted at two openings in the barrier. At each opening, circular waves are formed. The circular waves interfere with each other, with points of constructive interference appearing as bright spots in the photograph (a). Lines of constructive interference (antinodal lines) occur where crest meets crest (b).

waves around the edge of a barrier is called **diffraction**. Diffraction also occurs when waves meet a small obstacle. They can bend around the obstacle, producing waves behind it. The smaller the wavelength in comparison to the size of the obstacle, the less the diffraction.

Figure 14–20a shows the result of waves striking a barrier having two closely-spaced holes. The waves are diffracted by each hole, forming circular waves. But the circular waves interfere with each other. There are regions of constructive interference where the resulting waves are large, and bands of destructive interference where the water remains almost undisturbed. Constructive interference occurs where two crests or two troughs from the two circular waves meet. The antinodes lie on lines called antinodal lines. These lines radiate from the barrier, Figure 14–20b. Between the antinodal lines are areas where a crest from one circular wave and a trough from the other meet. Destructive interference produces nodes where the water is undisturbed. The lines of nodes, or nodal lines, lie between adjacent antinodal lines.

Diffraction is the spreading of waves around the edge of a barrier.

CONCEPT REVIEW

2.1 If a wave moves from a medium with a high wave velocity to one with a low wave velocity, which of the following CANNOT change: frequency, amplitude, wavelength, velocity, direction?

2.2 A rope vibrates with the two waves at once, Figure 14–21. Sketch the resulting wave.

2.3 Would you expect high frequency or low frequency sound waves to be more diffracted when they pass through an open door?

2.4 Critical Thinking: For another way to understand wave reflection, return to Figure 14–15. Cover the right-hand side of each drawing with a piece of paper. The edge of the paper should be at the point **N**, the node. Now, concentrate on the sum wave, shown in blue. Note that it acts like a wave reflected from a boundary. Is the boundary a rigid wall or open ended? Repeat for Figure 14–14.

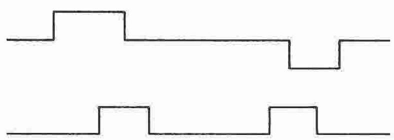


FIGURE 14–21. Use with Concept Review 2.2.

Physics and technology

MICROWAVE-POWERED AIRCRAFT

Imagine an aircraft that does not carry on-board fuel and can stay in flight for half a year. Or imagine a spacecraft whose orbits could be adjusted using engines powered by microwave-energy beams transmitted from Earth. With less rocket fuel to carry, larger payloads could be lifted into space. Advances in microwave technology could bring both of these dreams to life.

Microwave-energy beaming is much like radio-wave transmission, except that it works with higher power levels. A transmitter sends out microwave energy, and a distant antenna and receiver pick it up and convert it to another form of energy, usually electricity. The waves transfer energy without moving matter.

Research on the potential of microwave power is underway at NASA's Lewis Research Center in Cleveland, Ohio. Scientists are working on a Mars mission in which a mother ship orbiting the planet would transmit microwave beams to power a remote-controlled drone. The drone would fly down, land, and unload a rover vehicle that would explore the planet's surface and collect samples. It is estimated that the drone could cover about 40% of Mars' surface without refueling.

· What advantages could microwave power have when compared to other power sources such as jet propulsion, chemical, rocket power, and nuclear power?

CHAPTER 14 REVIEW

SUMMARY

14.1 Wave Properties

- Waves transfer energy without the transfer of matter.
- Mechanical waves, such as sound waves and the waves on a rope, require a medium. Electromagnetic waves, such as light and radio waves, do not need a medium.
- In transverse waves, the particles of the medium move perpendicularly to the direction of the wave. In longitudinal waves, the particles move parallel to the wave direction. In surface waves, the particles move both perpendicularly and parallel to the direction of the wave's motion.
- The frequency of a wave, f, is the number of vibrations per second of any one point on a wave. The period of a wave is the time interval between successive wave crests or troughs.
- The shortest distance between points where the wave pattern repeats itself is called the wavelength, λ.
- The velocity of a wave, the distance a point on the wave moves in a unit time interval, can be calculated from the equation $v = \lambda f$.
- The amplitude of a wave is its maximum displacement from the rest or equilibrium position. Energy transferred by a wave is proportional to the square of the amplitude.

14.2 Wave Interference

- The speed of a wave depends on the properties of the medium through which the wave moves.
- When waves reach the boundary between two media, they are partially transmitted and partially reflected. The amount reflected depends on how much the two media differ.

- When a wave moves from a less dense to a more dense medium, the reflected wave is inverted. When it moves from a more dense to a less dense medium, the reflected wave is erect.
- The principle of superposition states that the displacement of a medium due to two or more waves is the algebraic sum of the displacements caused by the individual waves.
- The result of the superposition of two or more waves on a medium is called interference. Interference does not affect the individual waves.
- Maximum destructive interference produces a node where there is no displacement. Maximum constructive interference results in an antinode, a location of the largest displacement.
- The nodes and antinodes of a standing wave are stationary.
- The law of reflection states that the angle of incidence is equal to the angle of reflection. Waves are reflected from a barrier at the same angle at which they approach it.
- The change in the direction of waves at the boundary between two different media is known as refraction.
- The spreading of waves around the edge of a barrier is called diffraction.

KEY TERMS

transverse wave
longitudinal wave
surface waves
wave pulse
traveling wave
period
frequency
wavelength
crests
troughs
amplitude
principle of superposition
interference
constructive interference
destructive interference
node
antinode
standing wave
normal
angle of incidence
angle of reflection
law of reflection
refraction
diffraction

REVIEWING CONCEPTS

1. How many general methods of energy transfer are there? Give two examples of each.
2. What is the primary difference between a mechanical wave and an electromagnetic wave?
3. What is the difference among transverse, longitudinal, and surface waves?
4. Rhonda sends a pulse along a rope. How does the position of a point on the rope, before the pulse comes, compare to the position after the pulse has passed?
5. What is the difference between a pulse and a wave?
6. What is the difference between wave frequency and wave velocity?
7. Suppose you produce a transverse wave by shaking one end of a spring back and forth. How does the frequency of your hand compare with the frequency of the wave?
8. Waves are sent along a spring of fixed length.
   a. Can the speed of the waves in the spring be changed? Explain.
   b. Can the frequency of a wave in the spring be changed? Explain.
9. What is the difference between the speed of a transverse wave pulse down a spring and the motion of a point on the spring?
10. Sharon is lying on a raft in the wave pool. Describe to Sharon, in terms of the waves she is riding, each of the following: amplitude, period, wavelength, speed, frequency.
11. What is the amplitude of a wave and what does it represent?
12. What is the relationship between the amplitude of a wave and the energy carried?
13. When a wave reaches the boundary of a new medium, part of the wave is reflected and part is transmitted. What determines the amount of reflection?
14. A pulse reaches the boundary of a medium more dense than the one from which it came. Is the reflected pulse erect or inverted?
15. A pulse reaches the boundary of a medium less dense than the one from which it came. Is the reflected pulse erect or inverted?
16. When a wave crosses a boundary between thin and thick rope, its wavelength and velocity change, but its frequency does not. Explain why the frequency is constant.
17. When two waves interfere, is there a loss of energy in the system? Explain.
18. What happens to the spring at nodes of a standing wave?
19. A metal plate is held fixed in the center and sprinkled with sugar. Using a violin bow, the plate is stroked along one edge and made to vibrate. The sugar begins to collect in certain areas and move away from others. Describe these regions in terms of standing waves.

20. If a string is vibrating in four parts, there are points it can be touched without disturbing its motion. Explain. How many points exist?
21. How does the pulse reflected from a rigid wall differ from the incident pulse?
22. Is interference a property of only some types of waves or all types of waves?

APPLYING CONCEPTS

1. George holds a 1-m metal bar in his hand and hits its end with a hammer; first, in a direction parallel to its length; second, in a direction at right angles to its length. Describe the waves George produces in the two cases.
2. You repeatedly dip your finger into a sink full of water to make circular waves. What happens to the wavelength as you move your finger faster?
3. What happens to the period of a wave as the frequency increases?
4. What happens to the wavelength of a wave as the frequency increases?
5. Joe makes a single pulse on a stretched spring. How much energy is required to make a pulse with twice the amplitude?
6. In each of the four waves in Figure 14–22, the pulse on the left is the original pulse moving toward the right. The center pulse is a reflected pulse; the pulse on the right is a transmitted pulse. Describe the boundaries at **A, B, C,** and **D.**

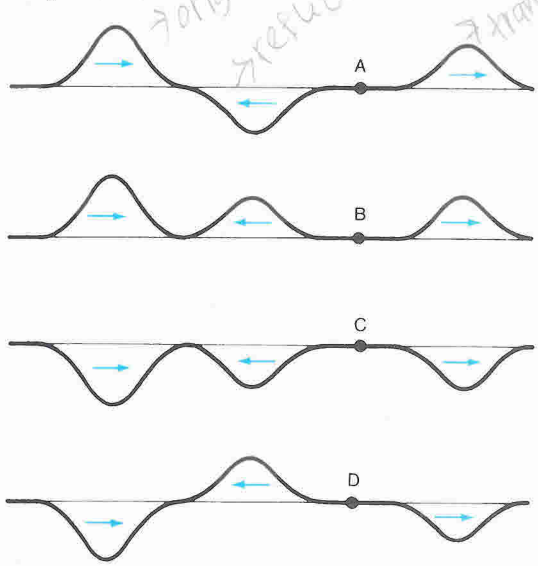


FIGURE 14-22. Use with Applying Concepts 6.

7. Sonar is the detection of sound waves reflected off boundaries in water. A region of warm water in a cold lake can produce a reflection, as can the bottom of the lake. Which would you expect to produce the stronger echo? Explain.
8. You can make water slosh back and forth in a shallow pan only if you shake the pan with the correct frequency. Explain.
9. AM radio signals have wavelengths between 600 m and 200 m, while FM signals have wavelengths about 3 m. Explain why AM signals can often be heard behind hills while FM signals cannot.

PROBLEMS

14.1 Wave Properties

1. The Sears Building in Chicago sways back and forth with a frequency of about 0.10 Hz. What is its period of vibration?
2. An ocean wave has a length of 10.0 m. A wave passes a fixed location every 2.0 s. What is the speed of the wave?
3. Water waves in a shallow dish are 6.0 cm long. At one point, the water oscillates up and down at a rate of 4.8 oscillations per second.
   a. What is the speed of the water waves?
   b. What is the period of the water waves?
4. Water waves in a lake travel 4.4 m in 1.8 s. The period of oscillation is 1.2 s.
   a. What is the speed of the water waves?
   b. What is their wavelength?
5. The frequency of yellow light is 5.0×10^{14} Hz. Find its wavelength.
6. ▶ A group of swimmers is resting in the sun on an off-shore raft. They estimate that 3.0 m separates a trough and an adjacent crest of surface waves on the lake. They count 14 crests that pass by the raft in 20 s. How fast are the waves moving?
7. AM radio signals are broadcast at frequencies between 550 kHz and 1600 kHz (kilohertz) and travel 3.0×10^{8} m/s.
   a. What is the range of wavelengths for these signals?
   b. FM frequencies range between 88 MHz and 108 MHz (megahertz) and travel at the same speed. What is the range of FM wavelengths?

8. A sonar signal of frequency 1.00×10^6 Hz has a wavelength of 1.50 mm in water.
   a. What is the speed of the signal in water?
   b. What is its period in water?
   c. What is its period in air?
9. A sound wave of wavelength 0.70 m and velocity 330 m/s is produced for 0.50 s.
   a. What is the frequency of the wave?
   b. How many complete waves are emitted in this time interval?
   c. After 0.50 s, how far is the front wave from the source of the sound?
10. The speed of sound in water is 1498 m/s. A sonar signal is sent from a ship at a point just below the water surface and 1.80 s later the reflected signal is detected. How deep is the ocean beneath the ship?

▶ 11. The velocity of the transverse waves produced by an earthquake is 8.9 km/s, while that of the longitudinal waves is 5.1 km/s. A seismograph records the arrival of the transverse waves 73 s before that of the longitudinal waves. How far away was the earthquake?

▶ 12. The velocity of a wave on a string depends on how hard the string is stretched, and on the mass per unit length of the string. If T is the force exerted on the string, and μ is the mass/unit length, then the velocity, v, is

$$v = \sqrt{\frac{T}{\mu}}.$$

A piece of string 5.30 m long has a mass of 15.0 g. What must the force on the string be to make the wavelength of a 125 Hz wave 120.0 cm?

13. The time needed for a water wave to change from the equilibrium level to the crest is 0.18 s.
    a. What fraction of a wavelength is this?
    b. What is the period of the wave?
    c. What is the frequency of the wave?

14.2 Wave Interference

▶ 14. The wave speed in a guitar string is 265 m/s. The length of the string is 63 cm. You pluck the center of the string by pulling it up and letting go. Pulses move in both directions and are reflected off the ends of the string.
    a. How long does it take for the pulse to move to the string end and return to the center?
    b. When the pulses return, is the string above or below its resting location?
    c. If you plucked the string 15 cm from one end of the string, where would the two pulses meet?

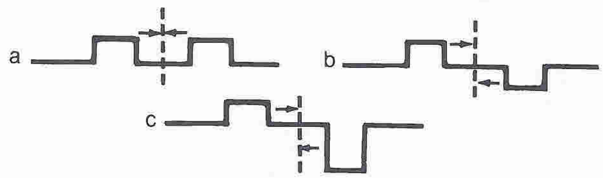


FIGURE 14-23. Use with Problem 15.

15. Sketch what happens, for each of the three cases shown in Figure 14–23, when centers of the two wave pulses lie on the dashed line so the pulses exactly overlap.
16. If you slosh the water back and forth in a bathtub at the correct frequency, the water rises first at one end and then at the other. Suppose you can make a standing wave in a 150-cm long tub with a frequency of 0.30 Hz. What is the velocity of the water wave?

USING LAB SKILLS

1. After doing the Pocket Lab on page 294, design an experiment using a stopwatch to show whether the amplitude of a wave pulse affects its speed.

THINKING PHYSIC-LY

1. Why can animals such as bats, that have tiny, light-weight ear parts, hear sounds with much higher frequencies than humans can hear?
2. If you put one ear under water in a bath tub, you can hear sounds from other parts of the house or apartment building where you live. Why is this true?