CHAPTER

8

Mechanical waves transmit energy in a variety of ways.

Key Concepts

In this chapter you will learn about:

- mechanical waves — longitudinal and transverse
- universal wave equation
- reflection
- interference
- acoustical resonance
- Doppler effect

Learning Outcomes

When you have finished this chapter, you will be able to:

Knowledge

- describe how transverse and longitudinal waves move through a medium
- explain how the speed, wavelength, frequency, and amplitude of a wave are related
- describe how interference patterns can be used to determine the properties of the waves
- explain the Doppler effect
- describe the difference between transverse and longitudinal waves
- describe how waves are reflected
- explain the relationship between rays and waves
- apply the universal wave equation to explain how frequency, wavelength, and wave velocity are related
- explain the effects of constructive and destructive interference

Science, Technology, and Society

- explain that the goal of technology is to provide solutions to practical problems

▲ **Figure 8.1**

What do bats and dolphins have in common? The phrase "blind as a bat" states a common fallacy. Bats have some vision using light, but when placed in pitch-black rooms crisscrossed with fine wires, they can easily fly around and unerringly locate tiny flying insects for food. Dolphins have shown that they can quickly locate and retrieve objects even when they are blindfolded. We usually assume that vision requires light but both bats and dolphins have evolved the ability to "see" using sound waves.

Research in science and technology has developed "eyes" that enable humans also to see using sound waves, that is, navigate with senses other than sight. Medicine uses ultrasound (frequencies above the audible range) to look at objects such as a fetus or a tumour inside the body. Submarines can circumnavigate the globe without surfacing by using sound waves to explore their underwater environment.

In Chapter 6, you studied how mass transfers energy when it moves through space. Waves, on the other hand, are able to transmit vast quantities of energy between two places without moving any mass from one location to another. Radio waves carry information, sound waves carry conversations, and light waves provide the stimulus for the cells that enable vision. This chapter introduces you to the nature and properties of waves. By experimenting with various forms of wave motion, you will learn about this common, but often misunderstood method of energy transmission.

8-1 QuickLab

Fundamental Properties of Wave Motion

Problem

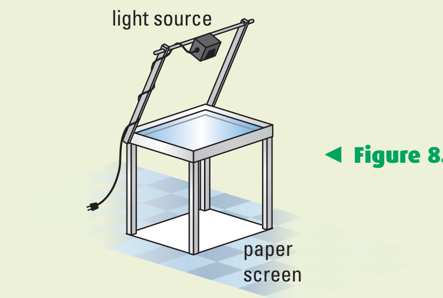
To determine properties of waves in a ripple tank.

Materials

ripple tank and apparatus for its operation
dowel (~ 1.5 cm in diameter)
2 stopwatches
ruler, two paper clips
light and stand to project waves onto screen
screen (a large sheet of newsprint works well)

Procedure

1 Set up the ripple tank as shown in Figure 8.2. The water should be about 1 cm deep. Make sure that energy-absorbing buffers are placed around the edge of the tank to prevent unwanted reflections. Check your assembly with your instructor.



◀ **Figure 8.2**

2 (a) Place a tiny spot of paper in the middle of the ripple tank.

(b) Dip the end of your finger once into the water about the middle of the ripple tank to create a single, circular, wave front. Observe the speck of paper as the wave front passes it.

Sketch what you observe. Describe the motion.

3 (a) On the screen, place the two paper clips at a measured distance apart, ~ 30–40 cm.

(b) Position your finger so that its shadow is over one of the paper clips and generate another single wave front.

(c) Using a stopwatch, measure the time for the wave to travel from one paper clip to the other. Record the distance and time. Calculate the speed of the wave. Do a few trials for accuracy.

4 (a) Place the dowel horizontally in the water near one edge of the tank. Tap the dowel gently and observe the wave front. Sketch and describe the motion.

(b) Position the paper clips in the wave's path and measure the speed of the straight wave front.

CAUTION: Use care with ripple tanks. It is easy to break the glass bottom or to spill water. This is a serious hazard in an area where electricity is being used. Vibrating the tank will generate unwanted waves.

Questions

1. When a wave front passes the speck of paper, what motion does the paper make? Does it move in the same or the opposite direction to the motion of the wave front? What does that tell you about the motion of the water as the wave moves through it?
2. On your sketches, draw several vector arrows along the fronts to indicate the direction in which they are moving. What is the angle between the line of the wave front and its motion? In Procedure 4(a), what is the angle between the edge of the dowel and the direction of the motion of the wave front?
3. Which wave front moves faster, the circular wave front or the straight wave front?

Think About It

1. What differences and similarities are there between the ways energy is transmitted by waves and by matter?
2. What assumptions must be made to use water waves as a model for sound waves?

Discuss your answers in a small group and record them. As you complete each section of this chapter, review your answers to these questions. Note any changes in your ideas.

eSIM

Find out more about waves in ripple tanks. Go to www.pearsoned.ca/school/physicssource.

8.1 The Properties of Waves

***info* BIT**

In December of 2004, an earthquake near the island of Sumatra set off a tsunami that is estimated to have had more than 2 petajoules (10^{15} J) of energy. This tsunami, the most powerful in recorded history, took over 225 000 lives and did untold billions of dollars in damage to the economies and the environments of the countries that border on the Indian Ocean.

***info* BIT**

On the day of the tsunami of 2004 that devastated Phuket, Thailand, people travelling in a ferry in deep water offshore from Phuket felt only a greater than usual swell as the wave passed them by.

▲ **Figure 8.3** Surfers use a wave's energy to speed their boards across the water.

medium: material, for example, air or water through which waves travel; the medium does not travel with the wave

wave: disturbance that moves outward from its point of origin, transferring energy through a medium by means of vibrations

equilibrium position: rest position or position of a medium from which the amplitude of a wave can be measured

crest: region where the medium rises above the equilibrium position

trough: region where the medium is lower than the equilibrium position

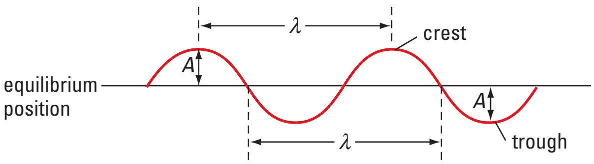
When a surfer catches a wave, many people assume that the forward motion of the surfer is the result of the forward motion of the water in the wave. However, experimental evidence indicates that in a deep-water wave the water does not, in general, move in the direction of the wave motion. In fact, the surfer glides down the surface of the wave just as a skier glides down the surface of a ski hill. Like the skier, the surfer can traverse across the face of the hill as well as slide down the hill. But, unlike the ski hill, the water in the wave front is constantly rising. So, even though the surfer is sliding down the front of the wave he never seems to get much closer to the bottom of the wave.

It is a common misconception that the water in a wave moves in the direction in which the waves are travelling. This may be because waves arriving at the shoreline move water to and fro across the sand. As you will see, this movement is a feature of the interaction of the wave with the sloping shoreline rather than the actual motion of the wave itself. In deep water, there is only very limited lateral motion of water when a wave moves past a particular point.

Waves and Wave Trains

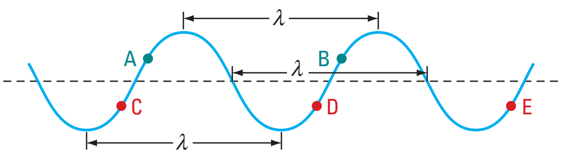
When a stone is thrown into a still pond or lake, a ripple moves outward in ever-enlarging concentric circles (Figure 8.4). The water is the transporting **medium** of the **wave** and the undisturbed surface of the water is known as the wave's **equilibrium position**. Regions where the water rises above the equilibrium position are called **crests** and regions where the water is lower than its equilibrium position are called **troughs**. In the crest or trough, the magnitude of greatest displacement from the equilibrium is defined as the waves' **amplitude** (A)**.** A complete cycle of a crest followed by a trough is called a **wavelength**; its symbol is the Greek letter lambda, λ (Figure 8.5).

▲ **Figure 8.4** Many of the terms used to describe wave motions come from the observation of waves on the surface of water.



▲ **Figure 8.5** Properties of a wave

A **wave front** moving out from the point of origin toward a barrier is called an **incident wave**. A wave front moving away from the barrier is called a **reflected wave,** while a series of waves linked together is a **wave train**. The concept of a wave train implies a regular repetition of the motion of the medium through which the wave travels. As a result, many parts of the medium are moving in a motion that is identical to the motion of other points on the wave train. At these points, the waves are said to be **in phase** (Figure 8.6).



▲ **Figure 8.6** In-phase points along a wave train have identical status relative to the medium and are separated by one wavelength, λ.

Instead of creating individual pulses by hand in a ripple tank, you may use a wave generator to create a continuous series of crests and troughs forming a wave train. Wave generators can act as a **point source** similar to the tip of a finger, or as a straight line source, similar to a dowel. In 8-1 QuickLab you measured the speed of a single pulse by observing its motion. However, because it is impossible to keep track of a single wave in a wave train, to measure the speed of a wave train requires a greater understanding of the properties of waves.

e WEB

To learn more about experiments using ripple tanks, follow the links at www.pearsoned.ca/school/physicssource.

amplitude: the distance from the equilibrium position to the top of a crest or the bottom of a trough

wavelength: the distance between two points on a wave that have identical status. It is usually measured from crest to crest or from trough to trough.

wave front: an imaginary line that joins all points reached by the wave at the same instant

incident wave: a wave front moving from the point of origin toward a barrier

reflected wave: a wave front moving away from a barrier

wave train: a series of waves forming a continuous series of crests and troughs

point source: a single point of disturbance that generates a circular wave

8-2 Inquiry Lab

Wave Trains in a Ripple Tank, Part 1: Reflecting Waves

Required Skills
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

In this ripple tank experiment, the properties of a two-dimensional wave train are analyzed.

Question

How do the incident and reflected wave trains interact when wave trains reflect from a straight barrier?

Materials and Equipment

ripple tank, including the apparatus for its operation
straight barrier
wave generators (point-source and straight-line)
light and stand to project waves onto screen
screen (a large sheet of newsprint works well)

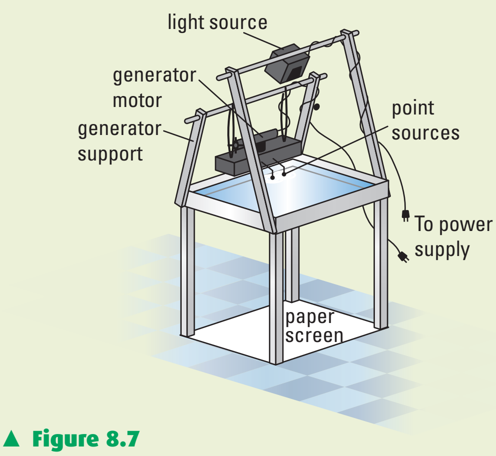
Variables

In this experiment you are to observe the directions of motion of the incident waves and reflected waves and how these directions are related to each other. Other variables to be observed are the interactions that occur when the incident and reflected wave trains move in different directions through the same point in the ripple tank. As you observe the wave motions you should identify which are the controlled variables, manipulated variables, and responding variables.

General Procedure

1 (a) Set up the ripple tank as shown in Figure 8.7.
(b) When using motorized wave generators, it is important that the generator just barely contacts the surface of the water. It should never touch the tank during operation. Check with your instructor to make sure that your apparatus is properly assembled.

CAUTION: Use care with ripple tanks. It is easy to break the glass bottom or to spill water. This is a serious hazard in an area where electricity is being used. Vibrating the tank will generate unwanted waves that interfere with the desired observations. The wave generator should never touch the tank during operation.



▲ **Figure 8.7**

Procedure

1 (a) Place the point-source wave generator at one edge of the ripple tank and the straight barrier at the other edge. The shadow of both the barrier and the source should be visible on the screen.
(b) Use the point-source wave generator to create a continuous wave train in the ripple tank. Observe what happens to the incident wave train when it meets the reflected wave train.
(c) Make a sketch of your observations. Wave trains are a bit tricky to observe at first. Discuss what you see with your team members. When you have reached a consensus, write a brief description of your observations. On your sketch, place vector arrows along an incident and a reflected wave front to indicate the direction and speed of their motions.

2 (a) Set up the straight-line wave generator at one edge of the ripple tank. Place the barrier at the other edge parallel to the generator. The shadows of both the generator and the barrier should be visible on the screen.
(b) Start the generator to create a continuous wave train. Observe what happens when the reflected wave train moves back through the incident wave train. Draw diagrams and write a description of the observations. Again, draw vector arrows along incident and reflected wave fronts to indicate their relative velocities.

3 Move the barrier so that it is at an angle of about 30° to the generator and repeat step 2 (b).

4 Set the barrier so that the angle between it and the generator is about 60° and repeat step 2 (b).

Analysis

1. (a) When the incident wave train created by the point-source generator is passing through the reflected wave train, what happens to the waves in the region where they overlap?
   (b) Can you see the direction of the motion for both the incident and reflected wave trains?

2. (a) When the barrier is parallel to the straight wave generator, what pattern do you observe when the reflected waves are moving back through the incident waves?
   (b) In which direction does the pattern seem to be moving? Can you see the direction of the motion for both the incident and reflected wave trains?

3. Answer question 2 for the set-up when the barrier is at an angle to the straight wave generator.

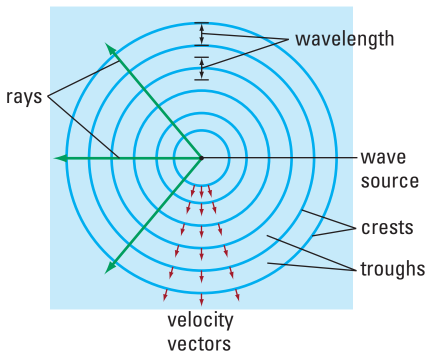
4. In all cases above, how does the spacing of the waves in the reflected wave train compare to the spacing of the waves in the incident wave train?

Waves and Rays

When waves in a ripple tank are viewed from above (Figure 8.8) the wave fronts appear as a set of bright and dark bands (crests and troughs). When we draw wave trains as seen from above, we use a line to represent a wave front along the top of a crest. The point halfway between two lines is the bottom of a trough. A series of concentric circles represents the wave train generated by a point source.

ray: a line that indicates only the direction of motion of the wave front at any point where the ray and the wave intersect

▲ **Figure 8.8** View of a ripple tank from above

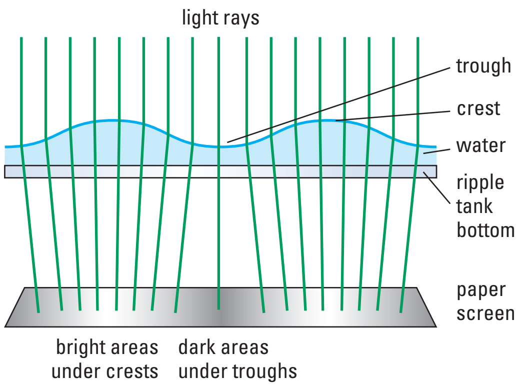


▲ **Figure 8.9** A point source generates waves that move outward as concentric circles with the source at their centre

Waves are in constant motion. At all points on a wave front, the wave is moving at right angles to the line of the crest. There are two ways to indicate this (Figure 8.9). You could draw a series of vector arrows at right angles to the wave front with their length indicating the speed of the wave. Or, you could draw **rays**, lines indicating only the direction of motion of the wave front at any point where the ray and the wave front intersect. The rays in Figure 8.9 are called **diverging** rays since they spread out as they move away from the origin. When rays diverge, it indicates that the energy given to the wave at its source is being spread over a larger and larger area. This is why, as sound moves away from a point source such as a bell, the volume decreases with the square of the distance.

e WEB

To learn more about the mathematical relationship between the volume of sound and the distance from the source, follow the links at www.pearsoned.ca/school/physicssource.



▲ **Figure 8.10** Sketch of a wave showing light refracting through a crest and a trough

When waves in a ripple tank are projected onto a screen below, the wave fronts appear as a set of bright and dark bands. It may seem logical that the light and dark bands seen on the screen below the ripple tank result from the differences in water depth between the crests and the troughs. But that difference is only about a millimetre and cannot account for the high contrast in light seen on the screen. In fact, a crest acts like a converging lens to concentrate the light, creating a bright bar. A trough acts like a diverging lens to spread the light out, making the area under the trough darker (Figure 8.10). You will learn more about light refraction in Unit VII of this course.

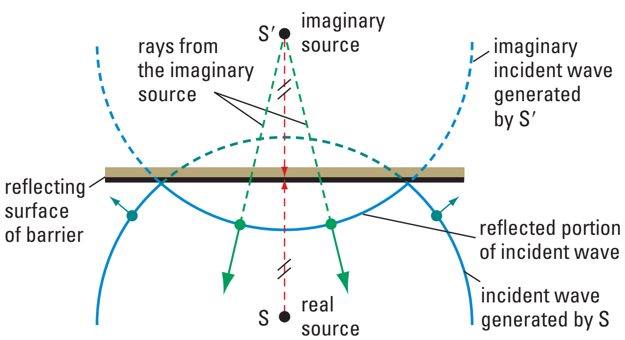
Reflection of a Wave Front

When a wave front is incident on a straight barrier, it reflects. The direction the wave travels after reflection depends on the angle between the incident wave front and the barrier. A circular wave front, as generated by a point source, S, produces the simplest reflection pattern to explain. In this case, the reflected wave follows a path as if it had been generated by an imaginary point source S′, at a position behind the barrier identical to that of the actual point source in front of the barrier (Figure 8.11).

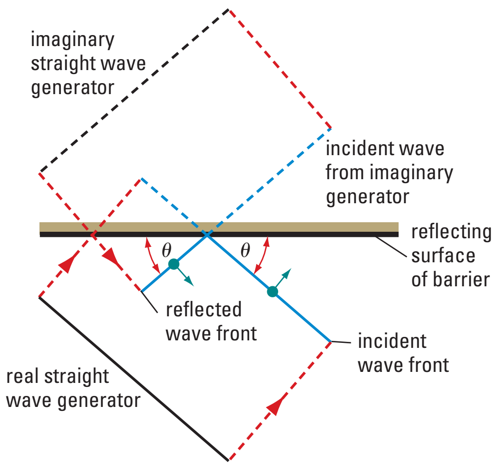
Now consider an incident wave front created by a straight wave generator (Figure 8.12). The straight wave front also reflects as if the reflected wave had been generated by an imaginary generator located behind the barrier. The position of the imaginary generator behind the barrier is equivalent to the position of the real generator in front of the barrier. The incident wave front and the reflected wave front are travelling in different directions, but the angle θ between the incident wave front and the barrier must be identical to the angle θ between the reflected wave front and the barrier.

eSIM

Find out more about the ways waves reflect. Go to www.pearsoned.ca/school/physicssource.



▲ **Figure 8.11** When circular waves reflect from a straight barrier, the reflected waves seem to be moving away from an imaginary source.



▲ **Figure 8.12** When straight waves reflect from a straight barrier, the angle between the reflected wave front and the barrier must be equal to the angle between the incident wave front and the barrier.

MINDS ON Waves Can Have Curls Too

When waves travel in deep water, their shape is similar to the waves in a ripple tank. But as waves near the shoreline they change shape and develop what is known as a curl in which the top of the wave falls in front of the wave. Recall Figure 8.3 on page 394. Explain the causes of a wave's curl in terms of its motion.

8-3 Inquiry Lab

Required Skills
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Wave Trains in a Ripple Tank, Part 2: Wave Speed and Wavelength

In this ripple tank experiment, the properties of a two-dimensional wave train are further analyzed.

Question

What effect does a change in speed have on wave trains?

Materials and Equipment

ripple tank, including the apparatus for its operation
wave generators (point-source and straight-line)
light and stand to project waves onto screen
screen (a large sheet of newsprint works well)
two small blocks of wood about 8 mm thick

Variables

In this lab you will be observing how water depth affects the properties of waves. The variables that might be affected by changes in the depth are speed, frequency, wavelength, and direction. As you make your observations, consider which of the variables are controlled variables, manipulated variables, and responding variables.

General Procedure

1. (a) Set up the ripple tank as shown in Figure 8.7 (page 396).
   (b) When using motorized wave generators, it is important that the generator just barely contacts the surface of the water. It should never touch the tank during operation. Check with your instructor to make sure that your apparatus is properly assembled.

CAUTION: Use care with ripple tanks. It is easy to break the glass bottom or to spill water. This is a serious hazard in an area where electricity is being used. Vibrating the tank will generate unwanted waves that interfere with the desired observations. The wave generator should never touch the tank during operation.

Procedure

1. Place small pads (about 8 mm thick) under the legs along one edge of the ripple tank so that the water gets shallower toward that edge. The water should be less than 1 mm deep at the shallow edge.
2. (a) Near the deep edge, create a wave train using the point-source generator.
   (b) Observe what happens to the wave fronts as the wave train moves toward the shallow edge. Discuss your observations with your team members. Sketch and briefly describe your observations.
   (c) Place vector arrows along several of the wave fronts to indicate the direction and speed of the wave fronts as they move into shallow water.
3. (a) Set up the straight-line wave generator at the deep edge of the tank.
   (b) Turn on the generator and observe the wave train as it moves into the shallow water.
   (c) Sketch your observations and describe the motion of the wave train as it moves into shallow water. Use vector arrows along the wave fronts to assist you in your descriptions.
4. (a) Now place the pads under the legs of the ripple tank on an edge that is at a right angle to the position of the straight-line wave generator.
   (b) Use the straight-line wave generator to create a wave train.
   (c) Observe the wave train as it travels across the tank. Discuss your observations with your team members. Sketch and write a brief description of what you saw to accompany your sketch. Use vector arrows drawn along several of the wave fronts to indicate their relative velocity as they move into the shallow water.

Analysis

1. For each of the trials, when the waves moved from deep to shallow edge (or vice versa), comment on the kinds of changes you observed.
   (a) Were the wavelengths of the incident waves affected as they moved into shallow water?
   (b) Was the shape of the wave fronts affected as they entered shallow water?
   (c) If so, how did the shape of the wave fronts change as they changed speed?
2. What do you think causes the observed changes?
3. When the straight wave fronts moved across the tank at right angles to the change in the depth of the water, was the shape of the wave front affected?
4. What properties of waves are affected as the waves move from deep to shallow water?
5. When a water wave moves toward a beach, how would the change in the depth of the water affect the motion of the wave?

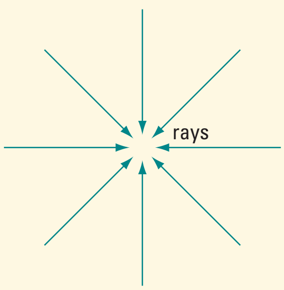
8.1 Check and Reflect

Knowledge

1. If a wave pattern is created by a point source, what is the nature of the ray diagram that would represent the wave fronts?
2. When a wave front reflects from a barrier, what is the relationship between the direction of the motions of the incident and reflected wave fronts?

Applications

3. The sketch shows a ray diagram that represents the motion of a set of wave fronts. If you were observing these wave fronts in a ripple tank, describe what you would see.



4. Draw a diagram of a set of straight wave fronts that are incident on a straight barrier such that the angle between the wave fronts and the barrier is 40°. Draw the reflected wave fronts resulting from this interaction. How do the properties (speed, wavelength, and amplitude) of the reflected wave compare with the properties of the incident wave? Use a wavelength of about 1 cm in your diagram.

Extensions

5. Reflection of light is the essence of how we use mirrors to see images. What does the reflection of waves in a ripple tank tell you about the formation of images? Hint: Think of where the reflected waves in the ripple tank seem to originate.
6. When a sound travels in water, the speed of the sound depends on the temperature of the water. If the sonar ping emitted by a submarine has a wavelength of 2.50 m, what happens to that wavelength when it enters a region where sound travels faster?

eTEST

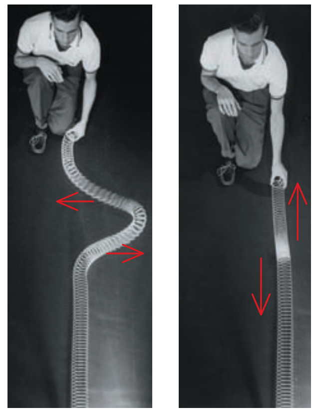
To check your understanding of the properties of waves, follow the eTest links at www.pearsoned.ca/school/physicssource.

8.2 Transverse and Longitudinal Waves

Did you ever have a Slinky™ toy when you were a child? When a Slinky™ is stretched out along the floor and oscillated from side to side across its axis (centre line), or forward and back along its axis, mechanical waves are transmitted along its length. The sideways oscillations set up a **transverse wave** while those along the axis set up a **longitudinal wave** as shown in Figure 8.13. In this section we will consider the characteristics of such waves.

info BIT

The ever-popular Slinky™ was invented in 1945 by Richard James, a naval engineer working on tension springs. The name comes from the Swedish for "sleek" or "sinuous." Each Slinky™ is made from 80 feet (24.384 m) of wire.



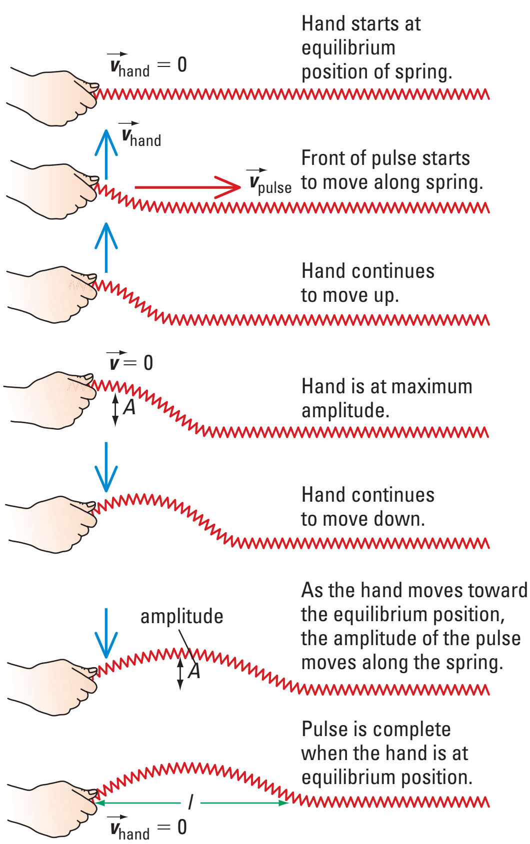
▲ **Figure 8.13**
(a) A transverse pulse
(b) A longitudinal pulse
Arrows indicate the direction of the medium. The pulses are moving through the springs toward the bottom of the page.

Transverse Pulses

A pulse moving through a spring is a good introduction to the way a wave moves through a medium. An ideal spring is one that allows a pulse to travel through it without loss of energy. By definition, a **pulse** is just the crest or the trough of a wave; its length is one-half a wavelength. The spring provides a medium in which the motion of a pulse can be observed from the side. Initially, the spring is in its equilibrium position. When you flip the spring sharply to the side and back, the motion of your hand sets up a series of sequential motions in the coils of the spring. Each coil imitates, in turn, the motion of the hand. This results in a **transverse** pulse (Figure 8.14) that moves along the spring.

pulse: a disturbance of short duration in a medium; usually seen as the crest or trough of a wave

As a pulse moves along a spring, the coils of the spring move at right angles to the direction of the pulse's motion. Compare $\vec{v}_{\text{hand}}$ and $\vec{v}_{\text{pulse}}$ in Figure 8.14. At the front of the pulse, the coils are moving away from the spring's equilibrium position toward the point of maximum displacement from the equilibrium. In the trailing edge of the pulse, the coils are moving back toward the equilibrium position.



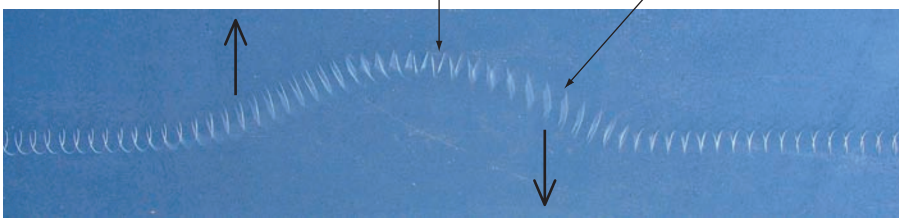
◀ **Figure 8.14** When you move your hand you set up a sequence in which the coils of the spring imitate the motion of your hand. This creates a moving pulse.

e WEB

To learn more about the forces operating in an oscillating spring, follow the links at www.pearsoned.ca/school/physicssource.

Energy Changes During the Movement of a Pulse

Along the pulse, energy is stored in the form of both elastic potential energy and kinetic energy. As a section of the spring moves from the equilibrium position to the top of the pulse, that section has both kinetic energy (it is moving sideways relative to the direction of the pulse) and elastic potential energy (it is stretched sideways). At the point on the pulse where the displacement is greatest the coils are, for an instant, motionless. Then, the tension in the spring returns the coils to their equilibrium position.



▲ **Figure 8.15** A transverse pulse is generated when a spring is given a sharp flip to the side. Arrows indicate the direction of motion of the coils. Can you determine which way the pulse is moving?

In Figure 8.15 the blurring on the front and back segments of the pulse indicates the transverse motion and the presence of kinetic energy as well as elastic potential energy. At the top, there is no blurring as the coils are temporarily motionless. At that instant that segment of the spring has only elastic potential energy. As it returns to its equilibrium position, the segment has, again, both kinetic and potential energies. The energy in a pulse moves along the spring by the sequential transverse motions of the coils.

Recall from section 6.3 that a pendulum, along the arc of its path, has both kinetic and potential energy, but at the point where the pendulum's displacement is greatest, all the energy is in the form of potential energy. Thus, the energy of an oscillating pendulum is equivalent to its potential energy at the point where its displacement is greatest. Similarly, the amplitude of the wave in an experimental spring can be used to determine the quantity of energy that is stored in the pulse.

info **BIT**

When considering sound, amplitude determines loudness.

Concept Check

You generate a pulse in a Slinky™ stretched out on the floor. If you wish to, you could give the next pulse more energy. How would you do that?

8-4 Inquiry Lab

Required Skills

- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Pulses in a Spring, Part 1: Pulses in an Elastic Medium

In this experiment, you will study how a pulse moves through a medium.

Question

What are the mechanics by which pulses move through a medium?

Variables

The measured properties of a pulse include its amplitude (A), pulse length (l), period (Δt), and speed (v).

Materials and Equipment

light spring	stopwatch
metre-stick or measuring tape	masking tape

CAUTION: A stretched spring stores considerable amounts of elastic potential energy. Be careful not to release the end of a spring while it is stretched. When collapsing a spring, have the person holding one end walk the spring slowly toward the other end. If you allow the spring to gently unwind as you are walking you will prevent the spring from tying itself into a knot.

Procedure

1. Have one team member hold the end of the spring while another stretches it until it is moderately stretched (about 5–6 m).

2. Place strips of masking tape on the floor at either end of the spring to mark this length. Near the middle of the spring, attach a strip of tape about 5 cm long to one of the coils.

3. Have one of the people holding the spring generate a transverse pulse. Generate the pulse by moving your hand sharply to one side (about 60–75 cm) and back to its original position. This is a **transverse pulse** since its amplitude is perpendicular to the direction of its motion.

4. Sketch the pulse. Indicate the motions of the pulse and the coils using vector arrows. Observe the motion of the tape at the middle of the spring to assist in these observations. Generate more pulses until you understand the nature of the motion of the pulse in the spring.

5. On your sketch of the pulse, label the following parts:
   - The amplitude (A) is the perpendicular distance from the equilibrium position of the spring to the top of the pulse.
   - The pulse length (l) is the distance over which the spring is distorted from its equilibrium position.

   NOTE: When you stand at the side of the spring, the pulse seems to move past you very quickly, almost as a blur. Watching from the end of the spring may make it easier to observe the details of the motion.

6. Make a **longitudinal pulse** by moving your hand sharply toward the person holding the spring at the other end, and then back to its original position. This pulse is called a longitudinal pulse, because its amplitude is along the direction of its motion. Repeat the pulse a few times to determine the nature of the motion of the spring as the pulse moves through it. Sketch and describe the motion of the coils as the pulse moves along the spring.

Analysis

1. What determines the amplitude of the transverse pulse? The longitudinal pulse?

2. Does the pulse change shape as it moves along the spring? If so, what causes the change in shape of the pulse? Would you expect the pulse shape to change if this were an isolated system?

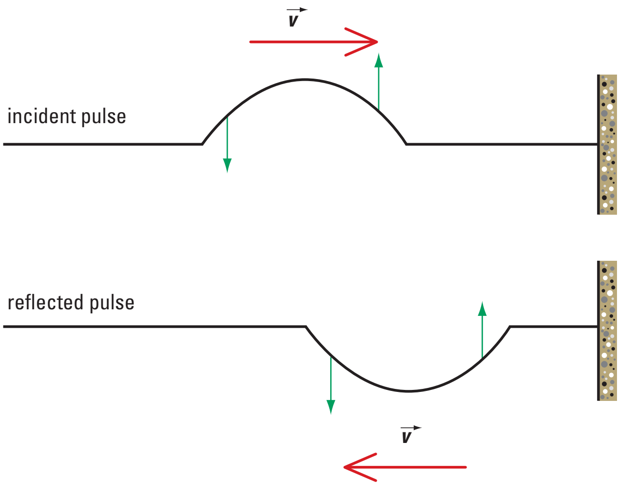
3. How is the reflected pulse different from the incident pulse? If this were an isolated system, how would the reflected pulse differ from the incident pulse?

4. Describe the motion of the strip of tape at the middle of the spring as the pulse passes it. Does the tape move in the direction of the pulse?

5. How does the motion of the medium relate to the motion of the pulse?

6. How does the pulse transfer energy from one end of the spring to the other?

7. The motion of a pulse in the spring requires you to make assumptions about the motion of an ideal pulse. What assumptions must you make to create a model of how a transverse pulse moves through an elastic medium?



▲ **Figure 8.16** Reflection from the fixed end of a spring causes the pulse to be inverted.

Reflection of Pulses from a Fixed Point

When a pulse (or wave) is generated in a spring it soon arrives at the other end of the spring. If that end is held in place, the total pulse reflects from the end and travels back toward the source. The reflected pulse is always inverted relative to the incident pulse (Figure 8.16).

In an ideal medium, the other properties of the pulse (amplitude, length, and speed) are unaffected by reflection. These properties of the reflected pulse are identical to those of the incident pulse.

When a wave train is generated in the spring, the crests of the incident wave are reflected as troughs while the troughs of the incident wave are reflected as crests.

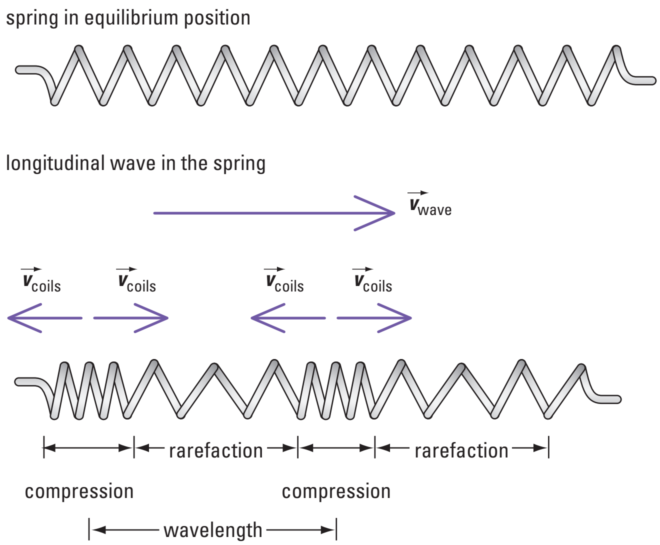
Longitudinal Waves

eSIM

Find out about similarities and differences between transverse and longitudinal waves. Go to www.pearsoned.ca/school/physicssource.

If, instead of moving your hand across the line of the spring, you give the spring a sharp push along its length, you will observe that a pulse moves along the spring. This pulse is evidence of a **longitudinal wave**. The pulse is seen as a region where the coils are more tightly compressed followed by a region where the coils are more widely spaced. These two regions are called, respectively, a **compression** and a **rarefaction** and correspond to the crest and trough in a transverse wave. In the case of a longitudinal wave, the coils of the spring oscillate back and forth parallel to the direction of the motion of the wave through the medium (Figure 8.17). But, as with transverse waves, once the wave has passed through, the medium returns to its original position. Once again, energy is transmitted through the medium without the transmission of matter.

► **Figure 8.17** Longitudinal waves are formed when the source oscillates parallel to the direction of the wave motion.



Project LINK

What aspect of your seismograph will relate to the ideas of compression and rarefaction in a longitudinal wave?

8-5 Inquiry Lab

Required Skills
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Pulses in a Spring, Part 2: Speed, Amplitude, and Length

In this experiment, you will study the speed, amplitude, and length of pulses. You will set up the experiment similarly to 8-4 Inquiry Lab on page 403.

Question

What is the relationship between the amplitude, length, and speed of a pulse?

Variables

The measured properties of a pulse include its amplitude (A), pulse length (l), period (Δt), and speed (v).

Materials and Equipment

light spring
stopwatch
metre-stick or measuring tape
masking tape

Procedure

1. (a) Measure the speed of a transverse pulse as it moves along the spring. Have the person creating the pulse "count down" so that team members with stopwatches can time the pulse as it moves toward the other end. Measure the time from the instant the front edge of the pulse leaves the hand of the person generating it until the front edge arrives at the hand at the other end. Do this a few times to establish a consistent value. Record your results. Use the time and the distance between the hands to calculate the speed of the pulse.

   (b) Generate pulses by moving your hand to the side and back at different speeds (more quickly or more slowly). Measure the speed of each of these pulses.

2. Have the person holding one end of the spring move so that the spring is stretched about 1 m farther. (Do not overstretch the spring.) Generate a pulse and measure the speed of the pulse in the spring at this higher tension. Carefully walk the spring back to the length used initially.

3. Make a transverse pulse by moving your hand a different distance sideways. Try to keep the time used to make the pulse the same as before. Repeat this a few times to observe changes in the pulse. Record your observations.

4. Now make several transverse pulses by moving your hand to a given amplitude but change the speed at which you move. Repeat a few times and record your observations.

Analysis

1. Does the speed at which you moved your hand to generate a pulse affect the speed of the pulse?
2. When the spring was stretched to a greater length, what happened to the speed of the pulse?
3. What controls the amplitude (A) of the pulse? Can you create pulses with equal lengths but different amplitudes?
4. What controls the length (l) of the pulse? Can pulses of equal amplitudes have different lengths?
5. What is the relationship between the length of the pulse and the speed (v) of the pulse in the medium?
6. Does the length of a pulse affect its larger amplitude or vice versa? Explain why or why not.
7. Does the energy in a pulse seem to depend on its amplitude or its length? Give reasons for your decision. Consider what changes occur as the pulse moves through the spring.
8. What determines the speed, the length, and the amplitude of the pulse?
9. What aspect of wave motion in water can you simulate by changing the tension in a spring?
10. What do your findings for the relationship of the amplitudes and lengths of pulses in springs tell you about the relationship between the amplitudes and wavelengths of waves in water?
11. Sound is often referred to as a wave. What aspect of a sound would relate to (a) the amplitude and (b) the wavelength of its waves?

Pulse Length and Speed

The speed of the pulse depends on the medium. If you stretch the spring so that the tension increases, then the speed of the pulse increases. Relaxing the tension causes the speed to decrease. The speed of the pulse in the spring also determines the length of the pulse.

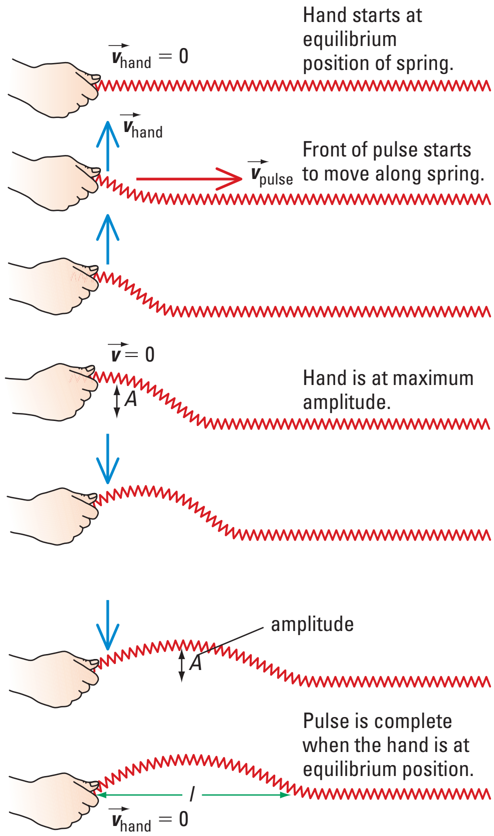
The instant you start to move your hand to generate a pulse, the disturbance begins to move along the spring at a constant speed, v. Assume that the time it takes to move your hand to create the complete pulse is Δt. By the time your hand returns the spring to its equilibrium position, the front of the pulse will have travelled a distance Δd, which can be defined as the length l of the pulse (Figure 8.18).

Remember

$$v = \frac{\Delta d}{\Delta t} \quad \text{and, therefore}$$

$$\Delta d = v\Delta t$$

$$\therefore l = v\Delta t$$



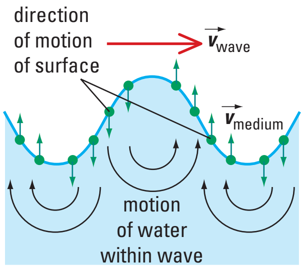
▶ **Figure 8.18** The length (l) of the pulse depends on the speed (v) of the pulse and the time (Δt) taken to complete the pulse.

e WEB

To learn more about the way the structures of the human ear transfer sound waves, follow the links at www.pearsoned.ca/school/physicssource.

info BIT

When a wave moves across the surface of water, the water moves between crests and troughs by localized circular motions. This local circular motion moves water back and forth between a trough and the adjacent crest.



◀ **Figure 8.19**

Waves and the Medium

A solid such as a spring is an elastic medium and can store elastic potential energy by stretching longitudinally or transversely. Typically, the way that fluids (liquids and gases) store elastic potential energy is by being compressed. Therefore, waves within fluids are typically longitudinal waves, known as pressure waves. This is the principle used in engines and aerosol sprays. As compressions and rarefactions move through a fluid, the motion of the molecules in the fluid is very similar to the motion of the coils when a longitudinal wave moves through a spring.

For water to transmit energy as a transverse wave, the waves must be displaced vertically, but in liquids the vertical displacement cannot be a form of elastic potential energy. Thus, transverse waves can be transmitted only at the surface of water, or other liquids, where the waves are the result of gravitational potential energy rather than elastic potential energy.

MINDS ON Wave Motion in Fluids

Water can transmit both transverse (surface) waves and longitudinal (internal) waves such as sound. We know that sound waves in gases are longitudinal waves.

Is it possible to create a transverse wave in a gas? Why or why not? Consider how transverse waves are created in liquids.

Example 8.1

To create a pulse in a fixed ideal spring, you move your hand sideways a distance of 45 cm from the equilibrium position. It takes 0.80 s from the time you begin to move your hand until it returns the spring to its equilibrium position. If the pulse moves at a speed of 2.5 m/s, calculate the length of the pulse and describe the incident pulse and reflected pulse that pass through the midpoint of the spring.

Given

$A = 45 \text{ cm} = 0.45 \text{ m}$

$\Delta t = 0.80 \text{ s}$

$v = 2.5 \text{ m/s}$

Required

(a) length of the pulse

(b) description of incident pulse passing the midpoint of the spring

(c) description of reflected pulse passing the midpoint of the spring

Analysis and Solution

(a) The length of the pulse can be found using $l = v\Delta t$.

$$\begin{aligned} l &= v\Delta t \\ &= \left(2.5 \frac{\text{m}}{\cancel{\text{s}}}\right)(0.80 \cancel{\text{s}}) \\ &= 2.0 \text{ m} \end{aligned}$$

(b) The spring is defined as an ideal spring, so the amplitude of the pulse is constant. The amplitude at all points on the spring will be the same as at the source. Therefore,

$A = 0.45 \text{ m}$

At the midpoint of the spring, the amplitude of the incident pulse is 0.45 m, its length is 2.0 m, and its speed is 2.5 m/s.

(c) Reflection inverts the pulse but does not change any of its properties. The reflected pulse is identical to the incident pulse except that it is inverted relative to the incident pulse.

Paraphrase and Verify

(a) The length of the pulse is equal to 2.0 m.

(b) In an ideal spring the amplitude of the pulse is constant.

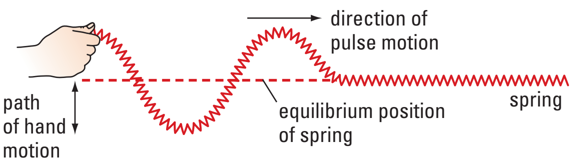
(c) When pulses are reflected from a fixed end of a spring they are inverted.

Practice Problems

1. A pulse is generated in a spring where it travels at 5.30 m/s.
   (a) If the time to generate the pulse is 0.640 s, what will be its length?
   (b) How does the speed of the pulse affect its amplitude?
2. A pulse moves along a spring at a speed of 3.60 m/s. If the length of the pulse is 2.50 m, how long did it take to generate the pulse?
3. A pulse that is 1.80 m long with an amplitude of 0.50 m is generated in 0.50 s. If the spring, in which this pulse is travelling, is 5.0 m long, how long does it take the pulse to return to its point of origin?
4. A spring is stretched to a length of 6.0 m. A pulse 1.50 m long travels down the spring and back to its point of origin in 3.6 s. How long did it take to generate the pulse?

Answers

1. (a) 3.39 m (b) It does not; they are independent.
2. 0.694 s
3. 2.8 s
4. 0.45 s



▲ **Figure 8.20** Simple harmonic motion generates a wave train in the form of a sine curve.

Waves Are a Form of Simple Harmonic Motion

If you move your hand from side to side in simple harmonic motion, as indicated in Figure 8.20, transverse waves are generated in the spring. When a transverse wave moves through a medium, the motion of the medium may seem, at first, quite complex. In a transverse wave, each segment of the medium simply oscillates in simple harmonic motion about its equilibrium position in the direction perpendicular to the direction of the wave motion. This simple harmonic motion is transferred sequentially from one segment of the medium to the next to produce the motion of a continuous wave.

Universal Wave Equation

Pulses provide a useful tool to introduce the nature of waves. However, in nature, sound and light are wave phenomena rather than pulses. In this section, we will begin to shift the emphasis to the properties of waves. Whereas the letter l is used to indicate the length of a pulse, the Greek letter lambda, λ, is used to indicate wavelength. The terms **crest** and **trough** come from the description of water waves but are used throughout wave studies. For a water wave, the crest occurs where the medium is displaced above the equilibrium position, while a trough is the region displaced below the equilibrium position. However, for media such as springs, the terms crest and trough merely refer to two regions in the medium that are displaced to opposite sides of the equilibrium position (Figure 8.20).

Other variables used in wave studies (**frequency**–f, **period**–T, **amplitude**–A) come from and have the same meanings as in your study of simple harmonic motion in section 7.2. The period (T) is the time taken to generate one complete wavelength. Since two pulses join to create one wave, the period for a wave is twice the time required to generate a pulse. Therefore, the wavelength of a wave is twice the length of a pulse.

With this in mind, the relationship between wavelength, speed, and period is the same for waves as it is for pulses. That is,

$$\lambda = vT$$

rather than

$$l = v\Delta t.$$

For periodic motion,

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

The equation for wavelength now can be written as

$$\lambda = \frac{v}{f}$$

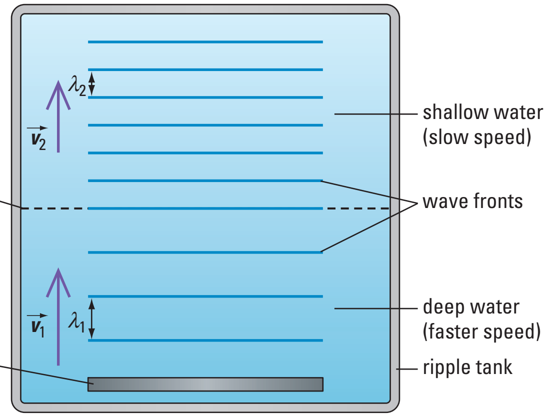
or

$v = f\lambda$. The latter form is known as the **universal wave equation**.

Constant Frequency, Speed, and Wavelength

In 8-3 Inquiry Lab, you investigated what happened to a wave train as it moved from deep to shallow water. Changes occurred because the speed in shallow water was slower than it was in deep water. Since the frequency of the waves as they moved from deep to shallow water was unchanged, the reduction in speed was, as predicted by the universal wave equation, accompanied by a reduction in wavelength (Figure 8.21). For a constant frequency, the ratio of the velocities is the same as the ratio of the wavelengths.

$$\frac{v_1}{v_2} = \frac{\lambda_1 \cancel{f}}{\lambda_2 \cancel{f}} = \frac{\lambda_1}{\lambda_2}$$



▲ **Figure 8.21** When the frequency is constant, a change in speed results in a change in wavelength.

When waves change speed, they often change direction as well. You will study this phenomenon further in Unit VII.

Example 8.2

To generate waves in a stretched spring, you oscillate your hand back and forth at a frequency of 2.00 Hz. If the speed of the waves in the spring is 5.40 m/s, what is the wavelength?

Given

$v = 5.40$ m/s

$f = 2.00$ Hz

Required

wavelength

Analysis and Solution

The variables (v, f, λ) are related by the universal wave equation.

$$v = f\lambda$$

$$\lambda = \frac{v}{f} = \frac{5.40\ \frac{\text{m}}{\text{s}}}{2.00\ \text{Hz}} = \frac{5.40\ \frac{\text{m}}{\cancel{\text{s}}}}{2.00\ \frac{1}{\cancel{\text{s}}}} = 2.70\ \text{m}$$

Paraphrase and Verify

The wavelength is 2.70 m.

Practice Problems

1. Orchestras use the note with a frequency of 440 Hz ("A" above middle "C") for tuning their instruments. If the speed of sound in an auditorium is 350 m/s, what is the length of the sound wave generated by this frequency?
2. A submarine sonar system sends a burst of sound with a frequency of 325 Hz. The sound wave bounces off an underwater rock face and returns to the submarine in 8.50 s. If the wavelength of the sound is 4.71 m, how far away is the rock face?
3. A fisherman anchors his dinghy in a lake 250 m from shore. The dinghy rises and falls 8.0 times per minute. He finds that it takes a wave 3.00 min to reach the shore. How far apart are the wave crests?

Answers

1. 0.795 m
2. 6.51 km
3. 10 m

MINDS ON Wavelength, Frequency, and Speed

- Walk side by side with a partner at the same speed. One student should take long steps while the other takes very short steps.

  1. If the two students maintain their pace, what is the relationship between the frequency and the length of their steps?

- With both students keeping their steps the same length as in the first trial, walk so that your steps are in phase (take steps at the same time).

  2. When the two students walk in phase, what is the effect of taking shorter steps? What is the relationship between speed and step length?

8.2 Check and Reflect

Knowledge

1. Explain the relationship between the motion of a transverse wave and the motion of the medium through which it moves.

2. Explain how the medium moves when a longitudinal wave passes through it.

3. What is the difference between a transverse and a longitudinal wave?

4. What determines the amount of energy stored in a wave?

Applications

5. Sound waves travel through seawater at about 1500 m/s. What frequency would generate a wavelength of 1.25 m in seawater?

6. Temperature changes in seawater affect the speed at which sound moves through it. A wave with a length of 2.00 m, travelling at a speed of 1500 m/s, reaches a section of warm water where the speed is 1550 m/s. What would you expect the wavelength in the warmer water to be?

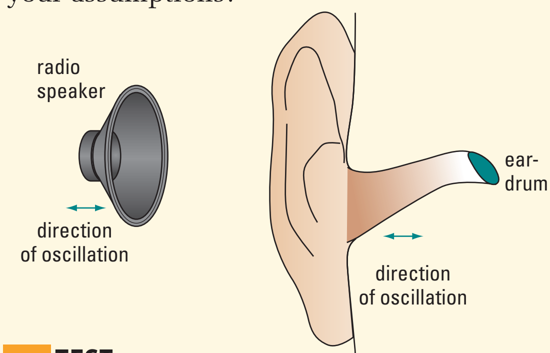
7. A speaker system generates sound waves at a frequency of 2400 Hz. If the wave speed in air is 325 m/s, what is the wavelength?

8. When you generate a wave in a spring, what is the relationship between the frequency, wavelength, and amplitude?

9. Two tuning forks are generating sound waves with a frequency of 384 Hz. The waves from one tuning fork are generated in air where the speed of sound is 350 m/s. The other tuning fork is generating sound under water where the speed of sound is 1500 m/s. Calculate the wavelength for the sound (a) in air, and (b) in water. (c) Would you hear the same musical note under water as you did in air?

Extensions

10. A radio speaker generates sounds that your eardrum can detect. What does the operation of the speaker and your eardrum suggest about the nature of sound waves? How does the nature of the medium (air) through which sound travels support your assumptions?



eTEST

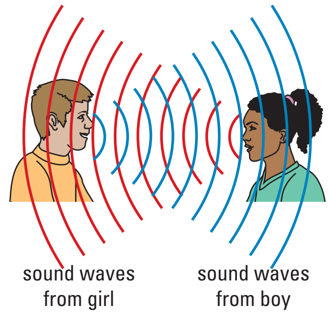
To check your understanding of transverse and longitudinal waves, follow the eTest links at www.pearsoned.ca/school/physicssource.

8.3 Superposition and Interference

Superposition of Pulses and Interference

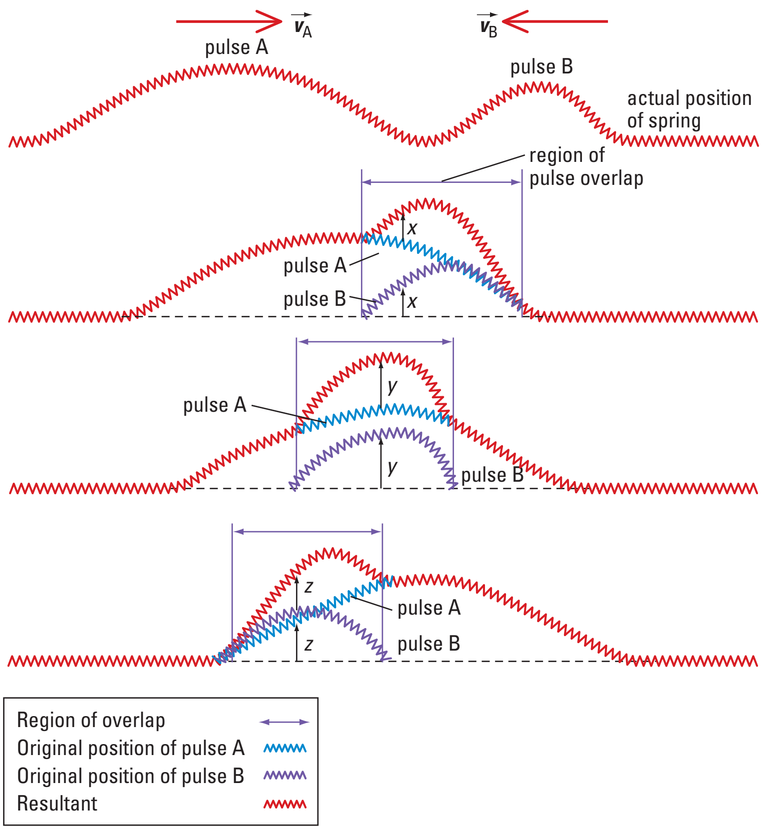
When waves travel through space it is inevitable that they will cross paths with other waves. In nature, this occurs all the time. Imagine two people who sit facing each other and are speaking at the same time. As each person's sound waves travel toward the other person they must meet and pass simultaneously through the same point in space (Figure 8.22). Still, both people are able to hear quite plainly what the other person is saying. The waves obviously were able to pass through each other so that they reached the other person's ears unchanged.

How waves interact when they cross paths is well understood. When you observe two waves crossing in the ripple tank, things happen so quickly that it is difficult to see what is happening. Still, it is plain that the waves do pass through each other. By sending two pulses toward each other in a spring, it is easier to analyze the events. It is helpful to imagine that the spring in which the pulses are travelling is an ideal, isolated system. The pulses then travel without loss of energy. First, consider two upright pulses moving through each other. When two pulses pass through the same place in the spring at the same time, they are said to **interfere** with each other. In the section of the spring where **interference** occurs, the spring takes on a shape that is different from the shape of either of the pulses individually (Figure 8.23).



▲ **Figure 8.22** When two people talk simultaneously, each person's sound waves reach the other person's ears in their original form.

interference: the effect of two pulses (or two waves) crossing within a medium; the medium takes on a shape that is different from the shape of either pulse alone



◀ **Figure 8.23** When two upright pulses move through each other, the displacement of the resultant pulse is the sum of the displacements of pulse A and pulse B. If at any point in the region of overlap, the displacement of one pulse, shown here as *x*, *y*, and *z*, is added to the displacement of the other, the displacement of the resultant pulse is increased. This is called constructive interference.

principle of superposition: the displacement of the combined pulse at each point of interference is the sum of the displacements of the individual pulses

constructive interference: the overlap of pulses to create a pulse of greater amplitude

destructive interference: the overlap of pulses to create a pulse of lesser amplitude

e **WEB**

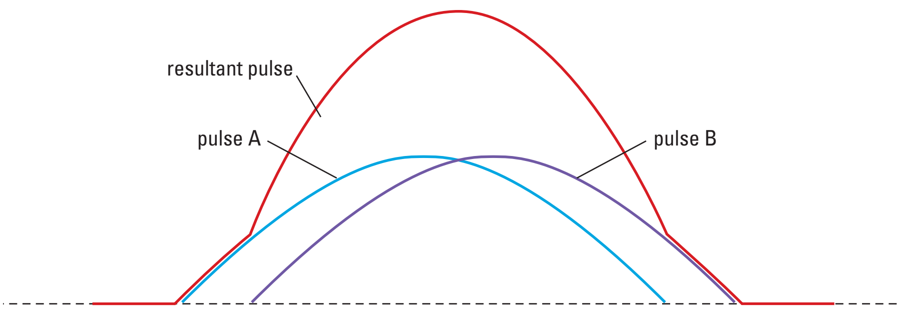
Find out more about superposition of pulses. Follow the links at www.pearsoned.ca/school/physicssource.

The new shape that the spring takes on is predicted by the **principle of superposition**. This principle, based on the conservation of energy, makes it quite easy to predict the shape of the spring at any instant during which the pulses overlap.

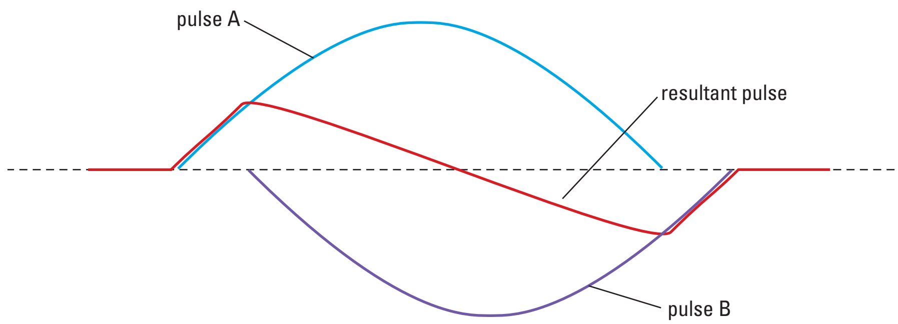
The displacement of the combined pulse at each point of interference is the algebraic sum of the displacements of the individual pulses.

In Figure 8.23 the two pulses have different sizes and shapes and are moving in opposite directions. The displacement of a pulse is positive for crests and negative for troughs. Since in Figure 8.23 both displacements are positive, at any point where the two pulses overlap, the displacement of the resultant pulse is greater than the displacements of the individual pulses. When pulses overlap to create a pulse of greater amplitude, the result is **constructive interference** (Figure 8.24).

Now consider the case when an inverted pulse meets an upright pulse. The displacement of the inverted pulse is a negative value. When the displacements of these pulses are added together, the displacement of the resultant pulse is smaller than the displacement of either pulse. When pulses that are inverted with respect to each other overlap to create a pulse of lesser amplitude, the result is **destructive interference** (Figure 8.25).



▲ **Figure 8.24** Constructive interference



▲ **Figure 8.25** Destructive interference

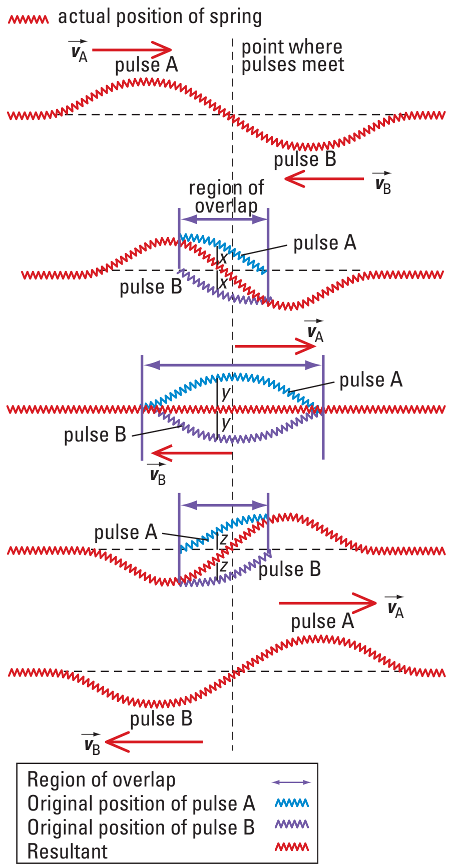
Figure 8.26 shows a special case of destructive interference. Two pulses that have the same shape and size are shown passing through each other. Because the pulses are identical in shape and size, their displacements at any position equidistant from the front of each pulse are equal in magnitude but opposite in sign. At the point where the two pulses meet, the sum of their displacements will always be zero. At the instant when these two pulses exactly overlap, the displacement at all points is zero and the pulses disappear. The resultant is a flat line. Immediately following this instant, the pulses reappear as they move on their way.

The Inversion of Reflected Pulses in a Fixed Spring

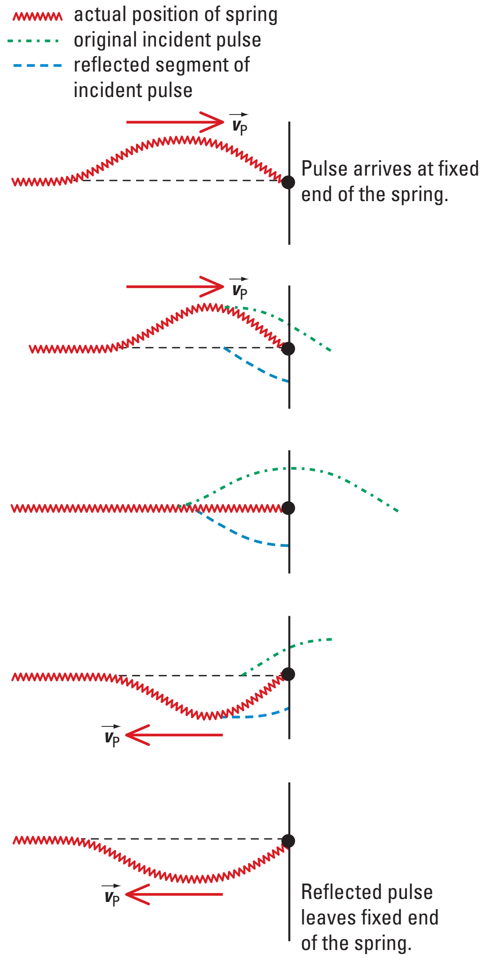
The principle of superposition explains why pulses are inverted when they reflect from the fixed end of a spring (Figure 8.27). Because the end of the spring is fixed in place, at that point the sum of the displacements of the incident pulse and the reflected pulse must always be zero. Thus, at the point of reflection, the displacement of the reflected pulse must be the negative of the incident pulse. Hence, the reflected pulse must be inverted relative to the incident pulse.

info BIT

Since, at the point of reflection in the spring the system is basically an isolated system, all the energy in the incident pulse must be carried away by the reflected pulse.



▲ **Figure 8.26** When pulses that are inverted with respect to each other overlap, the displacement of one pulse is reduced by the displacement of the other pulse. At any point in the region of overlap, the displacement of Pulse B, shown here as *x*, *y*, and *z*, reduces the displacement of Pulse A to produce the resultant. This is called destructive interference.



▲ **Figure 8.27** If the end of the spring is fixed, the reflected pulse must be inverted relative to the incident pulse.

8-6 Inquiry Lab

Interference of Waves

Required Skills
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Questions

1. What happens when two pulses pass through the same point in a medium?
2. How can two waves, moving in opposite directions, exist simultaneously in the same space?
3. What causes a standing wave?

Materials

light spring
heavy spring
masking tape
stopwatch
tape measure or metre-stick

CAUTION: A stretched spring stores considerable amounts of elastic energy. Be careful not to release the end of a spring while it is stretched. When collapsing a spring, have the person holding one end walk the spring slowly toward the other end. Allow the spring to gently unwind as you are walking to prevent the spring from tying itself into a knot.

Variables

Part 1: In this part you are concerned with the amplitudes and lengths of the pulses. Observe these variables before, during, and after the period in which they interfere with each other.

Part 2: In this part you will explore the relationship between the frequency and the standing wave pattern generated in a spring. From the structure of the standing wave pattern and the length of the spring, the wavelength and the speed of the standing wave are easily calculated.

For both parts, identify which are the controlled variables, manipulated variables, and responding variables.

Part 1: Superposition and Interference of Pulses

1. (a) Place two parallel strips of tape on the floor about 5 m apart. Measure and record the distance between them. Use these tapes to maintain a constant length for the spring while it is stretched. Attach a third strip of tape about 5 cm long to one of the coils near the middle of the spring as a marker.

   (b) Have the team member holding one end of the spring generate a transverse pulse. When this pulse reaches the fixed end of the spring, have the same team member generate a second similar pulse. Try to generate the second incident pulse so that it meets the reflection of the first pulse at the strip of tape near the middle of the spring. Focus on the nature of the spring's motion while the pulses interact. This complex interaction occurs quite quickly and may need to be repeated a few times until you are confident that you can see what is happening. Discuss the observations with your team members.

   (c) Record your observations in sketches and writing.

2. (a) Again, have one team member generate two pulses. This time, however, generate the second pulse so that it is on the opposite side of the spring (i.e., inverted) to the first pulse. The second pulse will now be on the same side of the spring as the reflected pulse. Again, time the pulses so that they meet near the centre of the spring.

   (b) Observe how these pulses interact when they meet at the centre of the spring. Discuss what you think is happening with the other members of your team.

Analysis

1. When pulses on opposite sides of the spring meet, does the amplitude increase or decrease in the region of overlap?
2. When pulses on the same side of the spring meet, does the amplitude increase or decrease in the overlap region?

Part 2: Standing Waves

Procedure

1. (a) Have a team member at one end of the spring create a double wave (a series of four pulses) by oscillating his or her hand back and forth twice across the spring's equilibrium position.

   (b) Observe what happens as this wave travels back and forth along the spring. Pay particular attention to what happens when the reflected portion of the wave is passing through the incident wave. Discuss your observations with your lab team to come to a consensus on what is occurring.

(c) Record your observations. Keep in mind what you observed when the pulses crossed in Part 1 of the lab.

2 (a) Now create a steady wave train by moving your hand back and forth. Try to find the frequency such that the spring oscillates in two segments about its midpoint. If, at first, there are more than two segments, then reduce the frequency slightly. If, at first, the spring is oscillating as only one segment, then increase the frequency until the second segment appears. Once the spring begins to oscillate as two segments, maintain that frequency.

(b) Measure and record the frequency of oscillation by timing ten oscillations. Since you know the length of the spring (the distance between the tapes you placed on the floor), record the length of a wave for this frequency. Each half of the spring is a pulse so that, in this mode, the wavelength is equal to the length of the spring.

(c) Record the data obtained in step 2(b) in a table. Use column headings: trial number, number of segments, frequency, wavelength, and speed.

3 (a) Begin with the frequency at which the spring oscillates in two halves and gradually increase the frequency.

(b) Describe what happens when you try to maintain a slight increase in the frequency. Keep increasing the frequency until a new oscillation pattern is established. Measure the frequency for this pattern. Record your results in your table of data.

(c) Starting from this frequency, gradually increase the frequency until a new pattern of oscillation is found. Once the new wave pattern is established, measure its frequency and record your measurements in your data table.

4 If time permits, change to the heavier spring and repeat steps 2 and 3.

CAUTION: Be very careful not to accidentally release the heavy spring while it is stretched. It will contain a large quantity of elastic potential energy and may seriously injure someone. To relax the tension in the spring, walk one end of the spring slowly toward the other end.

Analysis

1. When you created a sustained wave so that the spring oscillated as a stable pattern, in which direction did the waves move? Why do you think that is the case? Does this tell you why this pattern is known as a **standing wave**?

2. (a) Two segments of a standing wave are equal to one wavelength. For each trial recorded in the table of data, calculate the wavelength of the standing wave.

(b) For each trial, use the universal wave equation to calculate the speed of the waves in the spring.

3. To what does the speed of a standing wave refer?

4. Express the frequencies, for the different trials recorded in your data table, as ratios using simple whole numbers. Compare these ratios to the number of segments in which the spring oscillates for each trial. **NOTE:** The parts of a standing wave that remain motionless are called **nodes** or **nodal points**. The midpoints of the parts that oscillate back and forth are called **antinodes**. Each segment that contains an antinode is simply a pulse or one-half a wavelength. In a standing wave two adjacent segments are required to complete one wavelength.

5. Once a standing wave is established in the spring, what do you notice about the amplitude of the oscillations you use to sustain the wave compared with the amplitude of the antinodes? What explanation might exist for the difference in these two amplitudes?

6. Beginning at the fixed end of the spring, describe the locations of the nodes (points that remain motionless) and antinodes (midpoints of the parts that oscillate back and forth) along the spring in terms of wavelength.

7. How does the principle of superposition explain what must be happening at the antinodes of a standing wave?

8. What relationship exists between the wavelength of a standing wave and the frequency creating the wavelength?

9. Go back to your observations in Part 1 of 8-2 Inquiry Lab. When a train of straight waves parallel to the barrier was reflected back through the incident wave train, did you observe a standing wave?

10. If you could generate a standing wave for sound, what do you think would be the nature of the sound at the location of an antinode? a node?

***e*LAB**

For a probeware activity, go to www.pearsoned.ca/school/physicssource.

MINDS ON Total Destruction?

At the instant when two pulses "completely destroy" each other, the spring is in its equilibrium position. How is it possible for the two pulses to reappear as if from nothing?

Where does the energy in the pulses go when the sum of the amplitudes is zero? **Hint:** It might help to think of the spring in terms of a system.

Standing Waves and Resonance

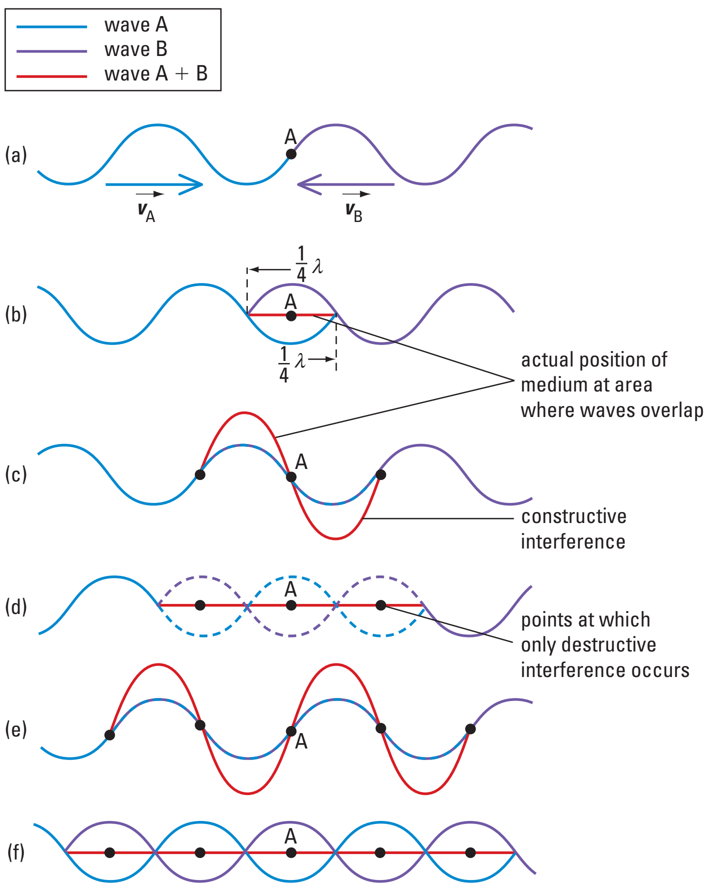
When two wave trains with identical wavelengths and amplitudes move through each other (Figure 8.28), the resulting interference pattern can be explained by using the principle of superposition. When crests from the two waves or troughs from the two waves occupy the same point in the medium, the waves are **in phase.** Waves that are in phase produce constructive interference. When a crest from one wave occupies the same point in the medium as a trough from a second wave, we say that these waves are **out of phase**. Out-of-phase waves produce destructive interference. As the two wave trains pass through each other in opposite directions, they continually shift in and out of phase to produce a wave that seems to oscillate between fixed nodes, rather than move through the medium.

e MATH

To graphically analyze the superposition of waves that are in or out of phase, visit www.pearsoned.ca/school/physicssource.

e WEB

Find out more about the superposition of waves. Follow the links at www.pearsoned.ca/school/physicssource.



▶ **Figure 8.28** The diagrams show how waves travelling in opposite directions interfere as they move through each other.

- (a) Point A is the initial point of contact between the two wave trains shown in blue and purple. The crest from the purple wave train and the trough from the blue wave train arrive at point A at the same instant.
- (b) The two identical waves have moved a distance of $\frac{1}{4}\lambda$ in opposite directions. This overlap results in destructive interference and the spring is flat in the region of overlap. The position of the spring where the two waves overlap, the resultant, is shown in red.
- (c) Each wave has moved a further $\frac{1}{4}\lambda$ along the spring. Now the waves are exactly in phase and constructive interference occurs. The regions to the left and right of point A show a crest and a trough, respectively, with displacement of the resultant being twice that of the blue or purple waves.
- Every time the wave trains move a further $\frac{1}{4}\lambda$ along the spring, the interference changes from constructive to destructive and vice versa.

At point A, only destructive interference occurs. The magnitudes of the displacements of the waves arriving at point A are always equal but opposite in sign. As the waves continue to move in opposite directions, the nature of the interference continually changes. However, at point A and every $\frac{1}{2}\lambda$ from point A, there are points at which only destructive interference occurs. These are called **nodal points** or **nodes**.

Between the nodes, the spring goes into a flip-flop motion as the interference in these areas switches from constructive (crest crossing crest) to destructive (crest crossing trough) and back to constructive interference (trough crossing trough). The midpoints of these regions on the spring are called **antinodes**. The first antinode occurs at a distance of $\frac{1}{4}\lambda$ on either side of A, and then at every $\frac{1}{2}\lambda$ after that point. Because the wave seems to oscillate around stationary nodes along the spring, it is known as a **standing wave**. Standing waves are also seen in nature; an example is shown in Figure 8.29.

node: a point on a spring or other medium at which only destructive interference occurs; a point that never vibrates between maximum positive amplitude and maximum negative amplitude; in a standing wave nodes occur at intervals of $\frac{1}{2}\lambda$

antinode: a point in an interference pattern that oscillates with maximum amplitude; in a standing wave antinodes occur at intervals of $\frac{1}{2}\lambda$

standing wave: a condition in a spring or other medium in which a wave seems to oscillate around stationary points called nodes. The wavelength of a standing wave is the distance between alternate nodes or alternate antinodes.

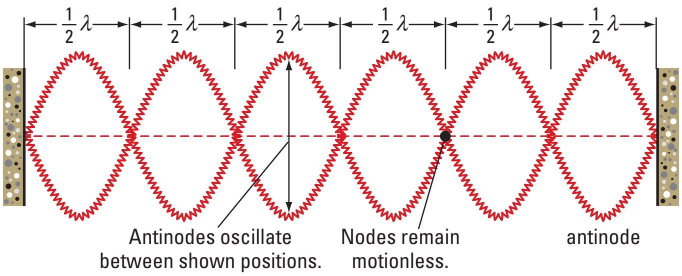
▲ **Figure 8.29** Standing waves occur in nature. This photograph shows a standing wave in a stream crossing a sandy beach in Scotland.

Standing Waves in a Fixed Spring

When you generate a wave train in a spring that is fixed at one end, the reflected wave train must pass back through the incident wave train. These two wave trains have identical wavelengths and nearly identical amplitudes. For incident and reflected wave trains, the initial point of contact is by definition the fixed point at which reflection occurs. This means that the endpoint of the spring is always a nodal point and, as shown in Figure 8.30, nodes occur every $\frac{1}{2}\lambda$ from that point with antinodes between them.

e **WEB**

Find out about the details of a standing wave in a spring. Follow the links at www.pearsoned.ca/school/physicssource.



◀ **Figure 8.30** In a spring with a fixed end, a standing wave must contain a whole number of antinodes. Nodes occur every half-wavelength from the ends.

e **WEB**

To learn more about the Tacoma Narrows Bridge collapse, follow the links at www.pearsoned.ca/school/physicssource.

▲ **Figure 8.31** Resonance, caused by wind, set up a standing wave that destroyed the Tacoma Narrows Bridge.

resonance: an increase in the amplitude of a wave due to a transfer of energy in phase with the natural frequency of the wave

Resonant Frequencies

When a standing wave is present in a spring, the wave reflects from both ends of the spring. There must be a nodal point at both ends with an integral number of antinodes in between. The spring "prefers" to oscillate at those frequencies that will produce a standing wave pattern, called the **resonant frequencies** for the spring. When the generator is oscillating at a resonant frequency, the energy is added to the spring in phase with existing oscillations. This reinforces and enhances the standing wave pattern. The added energy works to construct waves with ever-larger amplitudes. If the generator is not oscillating at a resonant frequency of the medium, the oscillations tend to destroy the standing wave motion.

Amplitude and Resonance

Perhaps the most impressive display of a standing wave occurred when **resonance** set up a standing wave in the bridge across the Tacoma Narrows in the state of Washington (Figure 8.31). Opened in November 1940, the bridge was in operation only a few months before resonance ripped it apart. More recently, in June 2000, the newly opened Millennium Bridge in London had to be closed for modifications when the footsteps of pedestrians set up resonance patterns.

Anyone who has ever "pumped up" a swing has used the principle of resonance. To increase the amplitude of its motion, the swing must be given a series of nudges in phase with its natural frequency of motion. Each time the swing begins to move forward, you give it a little push. Since these little pushes are produced in resonance with the swing's natural motion, they are added to its energy and the amplitude increases. If you pushed out of phase with its natural motion, the swing would soon come to rest.

e **WEB**

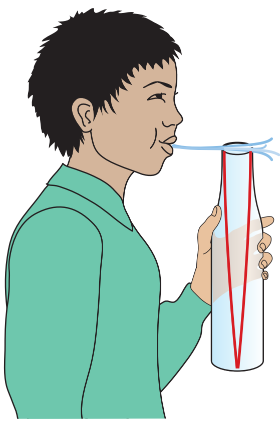
To learn more about the giant shock absorbers added to the Millennium Bridge, follow the links at www.pearsoned.ca/school/physicssource.

Concept Check

Why does it take so little energy to sustain a standing wave in a spring?

Resonating Air Columns

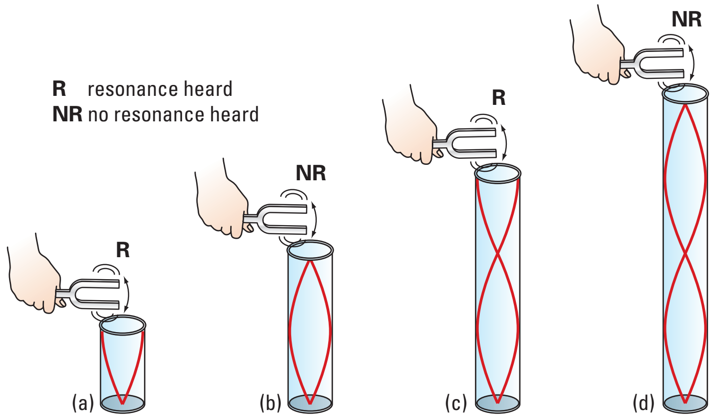
All wind instruments use the principle of resonance to produce music. The simplest example of resonance in music is the note produced when you blow over the top of a bottle (Figure 8.32). Blowing across the top of the bottle oscillates the air in the bottle and generates a standing wave. This standing wave is like the waves travelling in a spring, but unlike a spring that is fixed at both ends, the air column is fixed only at the end where reflection occurs and is free to oscillate at the open end. The resonant frequency of the note produced depends on the length of the air column because, to resonate, the standing wave must have a node at the closed end of the bottle and an antinode at the open end (Figure 8.33).



▲ **Figure 8.32** The tone produced when you blow across the top of an open bottle depends on the length of the air column.

Closed-Pipe or Closed-Tube Resonance

When a wave source is held at the open end of a pipe, it sends down a wave that reflects from the closed end of the pipe and establishes a standing wave pattern. The sound one hears depends on the length of the air column in the pipe relative to the length of the standing wave. If an antinode occurs at the open end of the pipe (Figure 8.33 (a) and (c)), a point of resonance (resulting from constructive interference) occurs at the open end of the pipe and the sound appears to be amplified. This phenomenon is known as **closed-pipe** or **closed-tube** resonance. However, if the open end of the pipe coincides with the position of a node (destructive interference), then almost no sound can be heard because the source (tuning fork) and the standing wave are out of phase (Figure 8.33 (b) and (d)).



▲ **Figure 8.33** Resonance series. A tuning fork sets up a standing wave in the air column. The volume of the sound one hears will vary depending on whether there is an antinode, (a) and (c), or a node, (b) and (d), at the end of the pipe.

Nodes and Antinodes in Closed-Pipe Resonance

In the air column, nodes are located every half-wavelength from the end at which the wave is reflected, just as they are in a standing wave in a spring. If the pipe length is equal to any multiple of $\frac{1}{2}\lambda$, there will be a node at the upper end of the pipe, and destructive interference will occur. Thus, when the air column is $\frac{1}{2}\lambda$, $\frac{2}{2}\lambda$, $\frac{3}{2}\lambda$, $\frac{4}{2}\lambda$, … in length, little or no sound will be heard.

Antinodes in the air column are located one quarter-wavelength from the end of the pipe where reflection occurs, and then every half-wavelength from that point. Thus, resonance is heard when the pipe is $\frac{1}{4}\lambda$, $\frac{3}{4}\lambda$, $\frac{5}{4}\lambda$, … long. When resonance is heard for an air column closed at one end, we know that the open end of the column coincides with the location of one of the antinodes. This information can be used to measure the wavelength of sound in gases. If the frequency of the sound is known, then the wavelength can be used to calculate the speed of sound in the gas.

Concept Check

Is the volume of a sound related to speed, wavelength, amplitude, or frequency of the wave? What evidence is there to support your answer?

Example 8.3

A tuning fork with a frequency of 384 Hz is held above an air column. As the column is lengthened, a closed-pipe resonant point is found when the length of the air column is 67.5 cm. What are possible wavelengths for this data? If the speed of sound is known to be slightly greater than 300 m/s, what is (a) the actual wavelength, and (b) the actual speed of sound?

Practice Problems

1. A tuning fork of frequency 512 Hz is used to generate a standing wave pattern in a closed pipe, 0.850 m long. A strong resonant note is heard indicating that an antinode is located at the open end of the pipe.
   (a) What are the possible wavelengths for this note?
   (b) Which wavelength will give the most reasonable value for the calculation of the speed of sound in air?
2. A tuning fork with a frequency of 256 Hz is held above a closed air column while the column is gradually increased in length. At what lengths for this air column would the first 4 resonant points be found, if the speed of sound is 330 m/s?
3. A standing wave is generated in a spring that is stretched to a length of 6.00 m. The standing wave pattern consists of three antinodes. If the frequency used to generate this wave is 2.50 Hz, what is the speed of the wave in the spring?
4. When a spring is stretched to a length of 8.00 m, the speed of waves in the spring is 5.00 m/s. The simplest standing wave pattern for this spring is that of a single antinode between two nodes at opposite ends of the spring.
   (a) What is the frequency that produces this standing wave?
   (b) What is the next higher frequency for which a standing wave exists in this spring?

Answers

1. (a) 3.40 m @ 1.74×10^3 m/s; 1.13 m @ 580 m/s; 0.680 m @ 348 m/s; 0.486 m @ 249 m/s
   (b) 0.680 m
2. 0.322 m, 0.967 m, 1.61 m, 2.26 m
3. 10.0 m/s
4. 0.313 Hz, 0.625 Hz

Given

$f = 384$ Hz
$l = 67.5$ cm $= 0.675$ m

Required

wavelength and speed of sound

Analysis and Solution

The resonant point might represent $\frac{1}{4}\lambda$, $\frac{3}{4}\lambda$, $\frac{5}{4}\lambda$,…, etc., for this tuning fork. Assume that 67.5 cm is the first resonant point; that means 67.5 cm is $\frac{1}{4}\lambda$. Calculate the wavelength and the speed of sound from that data.

Assume that $l = \frac{1}{4}\lambda$. Therefore,

$$\lambda = 4l = 4(0.675\text{ m}) = 2.70\text{ m}$$

$$v = f\lambda = (384\text{ Hz})(2.70\text{ m}) = 1037\text{ m/s} = 1.04 \times 10^3\text{ m/s}$$

This value is larger than the speed of sound in air.

If the speed of sound is not of the proper order of magnitude, then assume that the resonant point is the second point of resonance and that 67.5 cm is $\frac{3}{4}\lambda$. Calculate the wavelength and the speed of sound from that data.

Assume that $l = \frac{3}{4}\lambda$. Therefore,

$$\lambda = \frac{4l}{3} = \frac{4(0.675\text{ m})}{3} = 0.900\text{ m}$$

$$v = f\lambda = (384\text{ Hz})(0.900\text{ m}) = 345.6\text{ m/s} = 346\text{ m/s}$$

This is a reasonable speed for sound in air.

Complete the analysis by assuming that $l = \frac{5}{4}\lambda$. Therefore,

$$\lambda = \frac{4l}{5} = \frac{4(0.675\text{ m})}{5} = 0.540\text{ m}$$

$$v = f\lambda = (384\text{ Hz})(0.540\text{ m}) = 207.4\text{ m/s} = 207\text{ m/s}$$

This value is less than the speed of sound in air.

Paraphrase and Verify

The calculations for the speed of sound indicate that the data must have been for the second point of resonance. This assumption gives the speed for sound of 346 m/s. The assumption that the pipe length is for the first resonant point results in a speed about three times that of sound. The assumption that the pipe length is for the third resonant point produces a speed less than 300 m/s.

8-7 Inquiry Lab

Required Skills
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Measuring the Speed of Sound Using Closed-pipe Resonance

When a sound wave travels down a closed pipe, the incident wave reflects off the end of the pipe and back toward the source. The interaction of the incident and reflected waves sets up an interference pattern inside the pipe, known as a standing wave. This standing wave can be used to determine the wavelength of the sound.

Problem

What is the speed of sound in air?

Variables

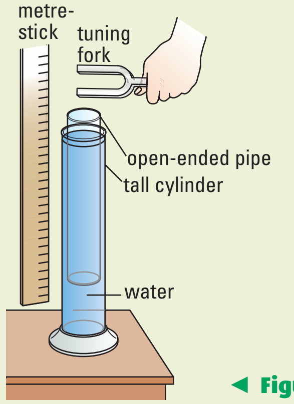
The universal wave equation relates the speed (v) of a wave to its frequency (f) and wavelength (λ). The wavelength is determined from the length of the pipe (l) and the number of the resonant point as counted from the reflecting surface.

Materials and Equipment

tuning forks and tuning fork hammer or an audio frequency generator
glass or plastic pipe
tall cylinder

Procedure

1. Assemble the apparatus as shown in Figure 8.34.



◄ **Figure 8.34**

2. Place the pipe in the water-filled cylinder so that the column of air in the pipe is quite short.
3. Strike the tuning fork with the hammer.
4. Hold the tuning fork as shown over the end of the pipe and lift the pipe slowly so that the length of the column of air in the pipe increases.
5. As you approach a point where the volume of the sound increases, move the pipe slowly up and down to find the point where the resonance is greatest. Strike the tuning fork as often as necessary to maintain the sound source.
6. Determine the length of the column of air that gives the greatest resonance and record it in a table like Table 8.1. Measure the length from the surface of the water to the location of the tuning fork.
7. Beginning with the column of air at the previously recorded length, gradually increase the length until you have determined the length of the air column that gives the next point of resonance. Record this length.
8. Repeat step 7 to find the length of the column for the third resonant point.

▼ **Table 8.1** Column Length and Resonance

Frequency f (Hz)	Length of column at first resonant point l_1 (m)	Length of column at second resonant point l_2 (m)	Length of column at third resonant point l_3 (m)

Analysis

1. In terms of wavelength, how far is each of the first three resonant points from the reflecting surface of the water at the bottom of the air column?
2. Calculate the wavelength of the sound from the tuning fork for each resonant point. Record your answers in a table similar to Table 8.2. Calculate the speed of sound for each of the wavelengths.
3. When you calculate the wavelength for different resonant points, do the answers agree? If not, what might cause the differences?
4. Why should you start with a short column of air and increase its length if you are to be sure that you have correctly determined the wavelength?

▼ **Table 8.2** Resonant Points, Wavelength, and Speed of Sound

	First Resonant Point		Second Resonant Point		Third Resonant Point	
Frequency f (Hz)	**Wavelength $\lambda = 4l$ (m)**	**Speed v (m/s)**	**Wavelength $\lambda = 4l/3$ (m)**	**Speed v (m/s)**	**Wavelength $\lambda = 4l/5$ (m)**	**Speed v (m/s)**

5. Why should you measure the length of the column from the reflecting surface to the tuning fork rather than to the top end of the pipe?

6. What is the speed of sound at room temperature?

7. Investigate the effect that air temperature has on the speed of sound. Use hot water or ice water to modify the temperature of the air in the column. Compare the measured speed of sound for at least three temperatures. Suspend a thermometer down the pipe to determine the temperature of the air in the pipe. Plot a graph of the measured speed of sound versus the temperature. Does the graph suggest a linear relationship? Can you use the graph to predict the speed of sound at other temperatures?

8. An alternative technique to determine the speed of sound is to measure the time for an echo to return to you. Stand a measured distance from a wall or other surface that reflects sound. Create an echo by striking together two hard objects, such as metal bars, or, perhaps beating a drum. Listen for the echo. Once you have established an approximate time for the echo to return, strike the bars in a rhythm so that they are in phase with the echo. Have a team member count the number of beats in 1 min. The period of this frequency is the time required for the sound to travel to the wall and back. Use that data to calculate the speed of the sound.

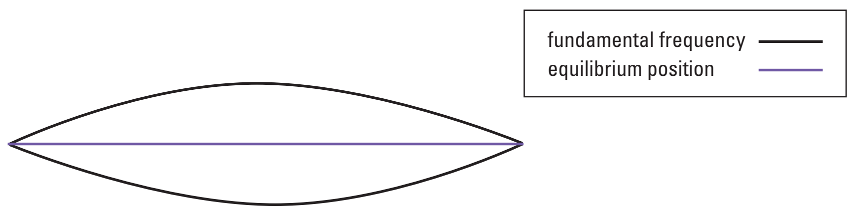
e **LAB**

For a probeware activity, go to www.pearsoned.ca/school/physicssource.

Music and Resonance

fundamental frequency: the lowest frequency produced by a particular instrument; corresponds to the standing wave having a single antinode, with a node at each end of the string

Complex modes of vibration give instruments their distinctive sounds and add depth to the musical tones they create. A string of a musical instrument is simply a tightly stretched spring for which the simplest standing wave possible is a single antinode with a node at either end. For this pattern, the length of the string equals one-half a wavelength and the frequency produced is called the **fundamental frequency** (Figure 8.35(a)).

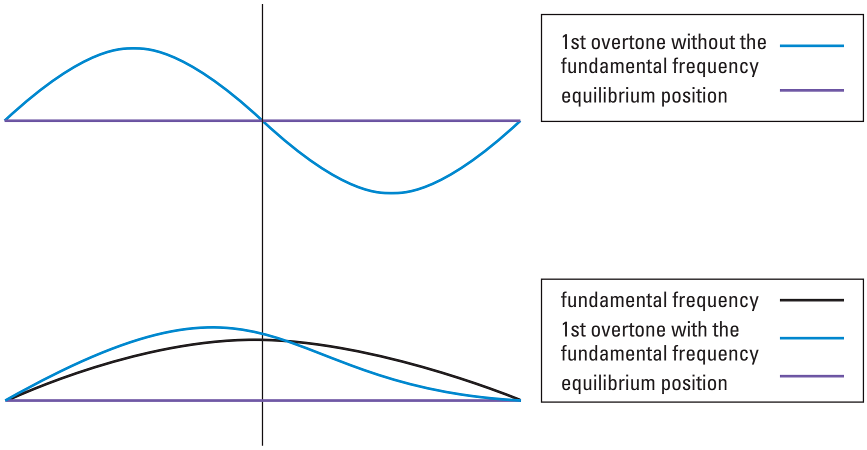


▲ **Figure 8.35 (a)** The fundamental frequency of a vibrating string oscillates as a standing wave with an antinode at the centre of the string.

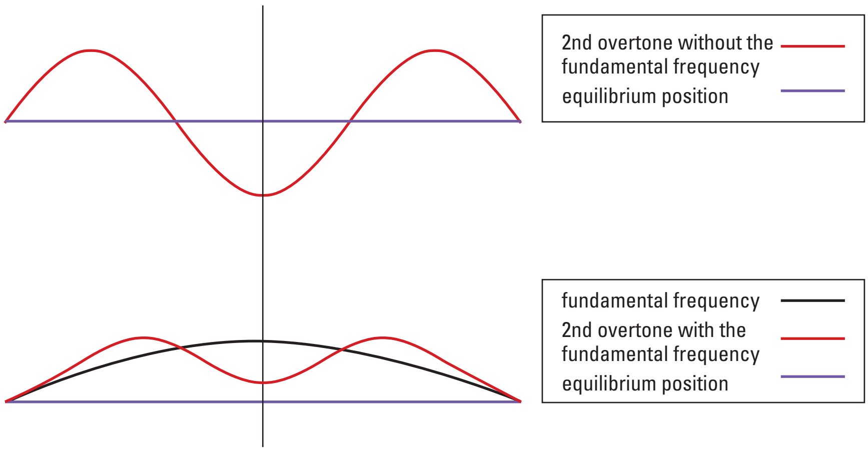
info **BIT**

Assume that the fundamental frequency is f. In physics and in music, the frequency $2f$ is called the first overtone; $3f$ is the second overtone, and so on. These frequencies are said to form a harmonic series. Thus, physicists may also refer to the fundamental frequency (f) as the first harmonic, the frequency $2f$ as the second harmonic, the frequency $3f$ as the third harmonic, and so on.

This is the lowest frequency produced by a particular instrument. But other standing wave patterns can exist in the string at the same time as it oscillates at its fundamental frequency. By plucking or bowing a string nearer its end than its middle, the string is encouraged to vibrate with multiple frequencies. The frequencies above the fundamental frequency that may exist simultaneously with the fundamental frequency are called **overtones.** Figures 8.35 (b) and (c) show the shape of a string vibrating in its first and second overtones, respectively. Figure 8.36 shows a violinist bowing and fingering the strings of her violin to produce notes.



▲ **Figure 8.35 (b)** The first overtone has the form of a standing wave with two antinodes. A node exists at the midpoint of the string. The lower portion of the diagram shows a string vibrating with both the fundamental frequency and the first overtone simultaneously.

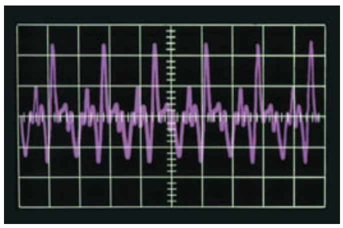


▲ **Figure 8.35(c)** The vibration that produces the second overtone has three antinodes. The lower portion of the diagram shows a string vibrating with both the fundamental frequency and second overtone.

The actual form of a vibrating string can be very complex as many overtones can exist simultaneously with the fundamental frequency. The actual wave form for a vibrating string is the result of the constructive and destructive interference of the fundamental wave with all the existing overtones that occur in the string. For example, Figure 8.37 shows the wave trace on an oscilloscope for the sound of a violin.

▲ **Figure 8.36** The violinist's fingering technique changes the length of the string and thus changes the fundamental frequency of vibration.

overtone: any frequency of vibration of a string that may exist simultaneously with the fundamental frequency



▲ **Figure 8.37** The interference of the fundamental frequency with the overtones produced by a bowed string creates the wave form that gives the violin its unique sound. The wavelength of the fundamental frequency is the distance between the tall sharp crests.

▲ **Figure 8.38** Tuning a guitar

Tuning a Stringed Instrument

Tuning a stringed instrument involves several principles of physics. The universal wave equation, $v = f\lambda$, indicates that the frequency of a sound wave is directly proportional to the speed of the sound and inversely proportional to its wavelength. The wavelength for the fundamental frequency of the standing wave in a string is fixed at twice the length of the string, but the speed of a wave in a string increases with tension. Thus, if the wavelength does not change, the frequency at which a string vibrates must increase with tension. Changing the tension in the string is known as **tuning** (Figure 8.38).

e **LAB**

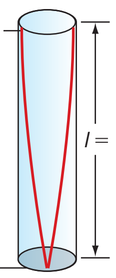
For a probeware activity, go to www.pearsoned.ca/school/physicssource.

Wind Instruments

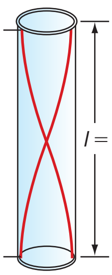
Wind instruments produce different musical notes by changing the length of the air columns (Figure 8.39). In 8-7 Inquiry Lab you used a closed pipe and saw that for resonance to occur, a node must be present at the closed end while an antinode is created at the open end. For a closed pipe, the longest wavelength that can resonate is four times as long as the pipe (Figure 8.40).

If the pipe is open at both ends, then the wavelengths for which resonance occurs must have antinodes at both ends of the **open pipe** or **open tube** (Figure 8.41). The distance from one antinode to the next is one-half a wavelength; thus, the longest wavelength that can resonate in an open pipe is twice as long as the pipe.

▲ **Figure 8.39** The trumpeter produces different notes by opening valves to change the instrument's overall pipe length.



▲ **Figure 8.40** In a closed pipe, the longest possible resonant wavelength is four times the length of the pipe.



▲ **Figure 8.41** In an open pipe, the longest possible resonant wavelength is twice the length of the pipe.

Wind instruments are generally open pipes. The wavelength of the resonant frequency will be decided by the length of the pipe (Figure 8.42). In a clarinet or oboe, for example, the effective length of the pipe is changed by covering or uncovering holes at various lengths down the side of the pipe. The strongest or most resonant frequency will be the wave whose length is twice the distance from the mouthpiece to the first open hole. Overtones are also generated but the note you hear is that with the longest wavelength. As with stringed instruments, the overtones contribute to the wind instrument's characteristic sound.

If the speed of sound in air never varied, then a given wavelength would always be associated with the same frequency. But the speed of sound changes slightly with air temperature and pressure. Thus, in the case of resonance in a pipe, the length of the pipe must be increased or decreased as the speed of sound increases or decreases to ensure that the frequency is that of the desired note.

▲ **Figure 8.42** A variety of wind instruments

e **WEB**

To learn how and why wind instruments are affected by temperature, follow the links at www.pearsoned.ca/school/physicssource.

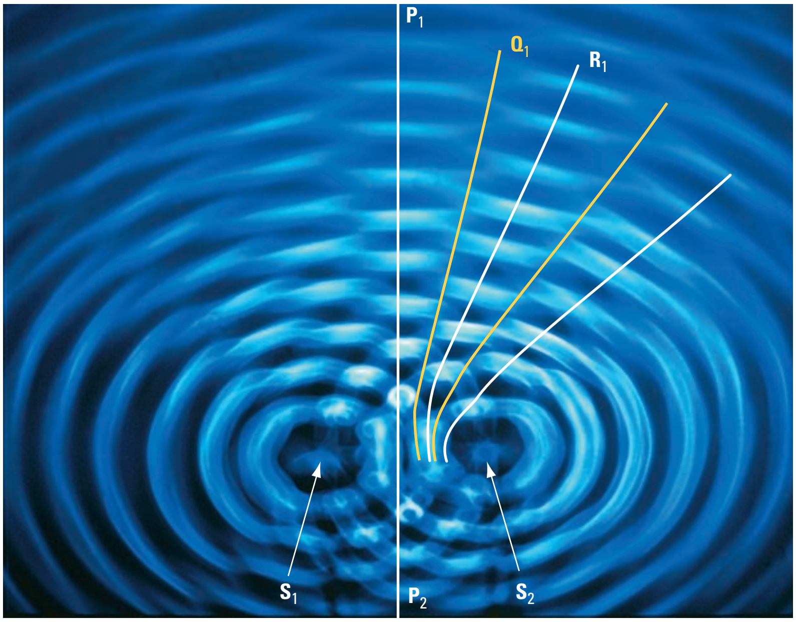
An Interference Pattern from Two In-phase Point Sources

Interference patterns carry information about the waves that create them. For this reason, the patterns are often used to determine the properties of the waves. One of the most interesting interference patterns results from waves generated by two point sources that are in phase. Remember that wave sources are in phase if they generate crests at the same time.

The ripple tank photograph (Figure 8.43) shows the **interference pattern** generated by two **in-phase point sources** that are separated in space. This pattern is the result of constructive and destructive interference as the waves cross. Generally crests appear bright and troughs appear dark. However, in areas where destructive interference occurs, there appear to be fuzzy lines (such as the line indicated by Q_1) that seem to radiate approximately from the midpoint between the sources. While the pattern may appear to be complex, its explanation is fairly simple.

info **BIT**

Common effects of interference patterns result in the "hot" and "cold" spots for sound in an auditorium. In 2005 renovations were completed for the Jubilee Auditoriums in Edmonton and Calgary. During renovations, the auditoriums were retuned to improve their acoustic properties.



▲ **Figure 8.43** The interference pattern generated by two in-phase point sources in a ripple tank. The distance between the sources is 3λ.

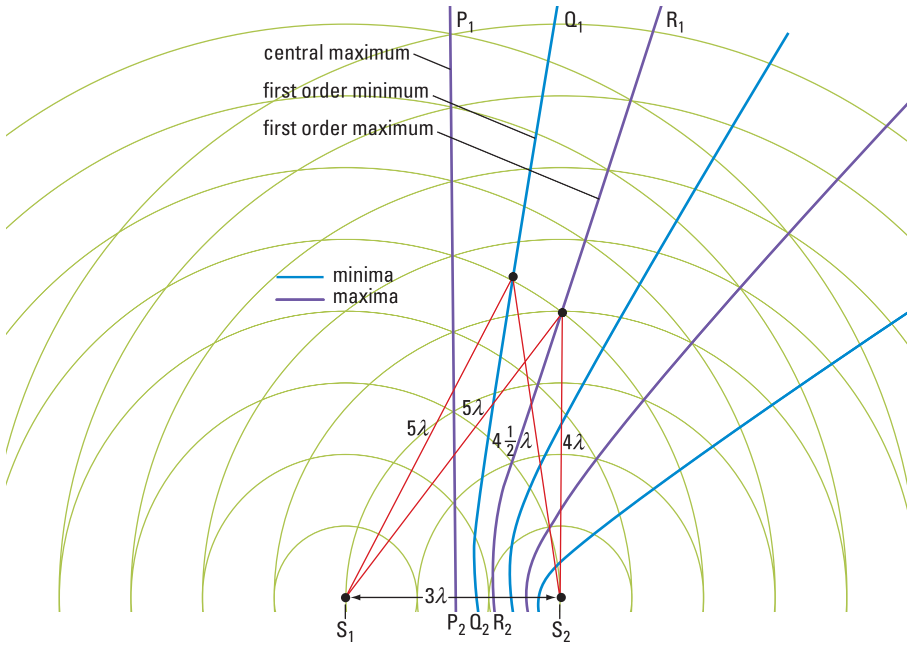
PHYSICS INSIGHT

An interference pattern for sound can result if two loudspeakers, at an appropriate distance apart, are connected to the same audio frequency generator. When the sound waves diverging from the speakers overlap and interfere, regions of loud sound (maxima) and regions of relative quiet (minima) will be created.

Individually, point sources generate waves that are sets of expanding concentric circles. As the crests and troughs from each source move outward, they cross through each other. As with all waves, when the crests from one source overlap crests from the other source (or troughs overlap troughs), constructive interference occurs. In these regions there is increased contrast (as indicated by P_1 and R_1). At locations where the crests from one source overlap troughs from the other source, destructive interference occurs. In these regions, contrast is reduced. Because the sources oscillate in phase, the locations where constructive and destructive interference occur are at predictable, fixed points. Like standing waves in a spring, the positions of the nodes and antinodes depend on the wavelength and the distance between the sources. Can you identify the regions of constructive and destructive interference in Figure 8.43 above?

interference pattern: a pattern of maxima and minima resulting from the interaction of waves, as crests and troughs overlap while the waves move through each other

The pattern in Figure 8.43 can be reproduced by drawing sets of concentric circles about two point sources where each circle represents the crest of a wave front (Figure 8.44). In Figure 8.43 the distance (d) between the sources is equal to three wavelengths (3λ). This can be shown by counting the wavelengths between S_1 and S_2 in Figure 8.44.



▲ **Figure 8.44** The interference pattern for two in-phase point sources results from the overlap of two sets of concentric circles. In this diagram, the centres of the circles are three wavelengths apart.

Maxima, Minima, and Phase Shifts

The central maximum is a line of antinodes.

In Figure 8.44, the line P_1P_2 is the perpendicular bisector of the line S_1S_2. By definition, every point on P_1P_2 is equidistant from the points S_1 and S_2. Thus, crests (or troughs) generated simultaneously at S_1 and S_2 must arrive at P_1P_2 at the same time, resulting in constructive interference. Along the line P_1P_2 only antinodes are created. The line of antinodes along P_1P_2 is called the central **maximum**.

maximum: a line of points linking antinodes that occur as the result of constructive interference between waves

A nodal line, or minimum, marks locations where waves are exactly out of phase.

A little to the right of the central maximum is the line Q_1Q_2. If you follow this line from one end to the other you will notice that it marks the locations where the crests (lines) from S_1 overlap the troughs (spaces) from S_2 and vice versa. Waves leave the sources in phase, but all points on Q_1Q_2 are a one-half wavelength farther from S_1 than they are from S_2. Thus, at any point on Q_1Q_2, the crests from S_1 arrive one-half a wavelength later than the crests from S_2. This means they arrive at the same time as troughs from S_2. The greater distance travelled by waves from S_1 produces what is called a one-half wavelength **phase shift**. *Waves that began in phase arrive at points on* Q_1Q_2 *exactly out of phase.* Thus, at every point on Q_1Q_2 destructive interference occurs. The line, Q_1Q_2, is known as a **nodal line** or a **minimum**.

minimum: a line of points linking nodes that occur as the result of destructive interference between waves

phase shift: the result of waves from one source having to travel farther to reach a particular point in the interference pattern than waves from the other source

A first order maximum is the result of a one wavelength phase shift.
Moving farther right, another region of constructive interference occurs. To arrive at any point on R_1R_2, crests from S_1 travel exactly one wavelength farther than crests from S_2. Crests from S_1 arrive at points on R_1R_2 at the same time as crests from S_2 that were generated one cycle later. This one-wavelength phase shift means that all waves arriving at any point on R_1R_2 are still in phase. The line of antinodes resulting from a one-wavelength shift is known as a **first order maximum**. An identical first order maximum exists on the left side. The interference pattern is symmetrical about the central maximum.

Phase shifts equal to whole wavelengths produce maxima.
Moving farther outward from the central maximum, you pass through lines of destructive and constructive interference (minima and maxima). Each region is the result of a phase shift produced when waves travel farther from one source than the other. When the phase shift equals a whole number of wavelengths (0λ, 1λ, 2λ, . . .), the waves arrive in phase, producing antinodes and resulting in the central, first, second, and third order maxima, etc. In Figure 8.44, since the sources are 3λ apart, the greatest phase shift possible is three wavelengths. This produces the third order maximum directly along the line of S_1S_2.

Phase shifts equal to an odd number of half-wavelengths produce minima.
When the phase shift equals an odd number of half-wavelengths $\left(\frac{1}{2}\lambda, \frac{3}{2}\lambda, \frac{5}{2}\lambda, \ldots\right)$ the waves arrive out of phase, producing a nodal line or minimum. In Figure 8.44, the greatest phase shift to produce destructive interference is one-half wavelength less than the three-wavelength separation of the sources, or $\left(3\lambda - \frac{1}{2}\lambda\right) = \frac{5}{2}\lambda$. Because the sources are three wavelengths apart, there are exactly three maxima and three minima to the right and to the left of the central maximum.

e WEB

To learn more about two-point interference systems, follow the links at www.pearsoned.ca/school/physicssource.

8-8 Design a Lab

Interference Patterns and In-phase Sound Sources

The Question

Do interference patterns exist for two in-phase sound sources?

Design and Conduct Your Investigation

An audio frequency generator and two speakers can be used to create an interference pattern for sound. Design a set-up that will enable you to measure the wavelength of sound of known frequencies. If electronic equipment (probeware or waveport) is available, design lab 8-8 to incorporate this equipment. Measure the wavelengths using several maxima and minima to compare measurements. Which type of line gives the best results? How well do the results from this experiment compare with the results from measuring wavelengths using closed-pipe resonance?

8.3 Check and Reflect

Knowledge

1. What is meant by the term interference?

2. For a standing wave, what is the relationship between the amplitude of an antinode and the amplitude of the waves that combine to create the standing wave?

3. In terms of the length of an air column, what is the longest standing wavelength that can exist in an air column that is (a) closed at one end and (b) open at both ends?

4. An air column is said to be closed if it is closed at one end. Consider a pipe of length (l). For a standing wave in this pipe, what are the lengths of the three longest wavelengths for which an antinode exists at the open end of the pipe?

5. What does it mean to say that two wave generators are in phase? What does it mean to say that two waves are in phase?

Applications

6. Two pulses of the same length (l) travel along a spring in opposite directions. The amplitude of the pulse from the right is three units while the amplitude of the pulse from the left is four units. Describe the pulse that would appear at the moment when they exactly overlap if (a) the pulses are on the same side of the spring and (b) the pulses are on opposite sides of the spring.

7. A standing wave is generated in a closed air column by a source that has a frequency of 768 Hz. The speed of sound in air is 325 m/s. What is the shortest column for which resonance will occur at the open end?

8. Draw the interference pattern for two in-phase point sources that are 5λ apart, as follows. Place two points, S_1 and S_2, 5 cm apart near the centre of a sheet of paper. Using each of these points as a centre, draw two sets of concentric circles with increasing radii of 1 cm, 2 cm, 3 cm, . . . , until you reach the edge of the paper. On the diagram, draw solid lines along maxima and dotted lines along minima. Label the maxima according to their order. Explain why there are five minima on either side of the central maximum.

9. An interference pattern from two in-phase point sources is generated in a ripple tank. On the screen, a point on the second order maximum is measured to be 8.0 cm from one point source and 6.8 cm from the other source. What is the wavelength of this pattern?

Extension

10. Do pipe organs, such as those found in churches and concert halls, use closed or open pipes to produce music? What is the advantage of using a real pipe organ as opposed to an electronic organ that synthesizes the sound?

eTEST

To check your understanding of superposition and interference of pulses and waves, follow the eTest links at www.pearsoned.ca/school/physicssource.

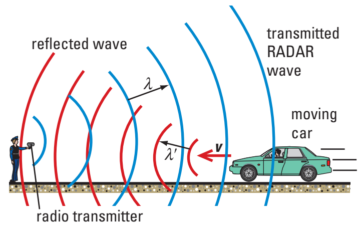
8.4 The Doppler Effect

Have you ever stood at the side of a road and listened to the cars pass? If you listen carefully, you will detect a very interesting phenomenon. At the instant a car passes you, the sound it makes suddenly becomes lower in pitch. This phenomenon was explained by an Austrian physicist named Christian Doppler (1803–1853).

Doppler realized that the motion of the source affected the wavelength of the sound. Those waves that moved in the same direction as the source was moving were shortened, making the pitch of the sound higher. Moving in the direction opposite to the motion of the source, the sound waves from the source were lengthened, making the pitch lower.

info BIT

It is common to see police officers using radar to measure the speed of cars on the highway. The radar gun emits waves that are reflected back to it from an oncoming car. A computer in the gun measures the change in frequency and uses that change to calculate the speed of the car.



▲ **Figure 8.45**

Wavelength and Frequency of a Source at Rest

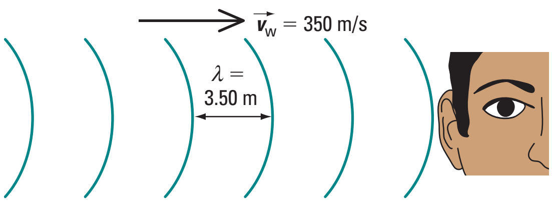
Assume that the frequency of a source is 100 Hz and the speed of sound is 350 m/s (Figure 8.46). According to the universal wave equation, if this source is at rest, the wavelength of the sound is 3.50 m.

$$v = f\lambda$$

$$\lambda = \frac{v}{f}$$

$$= \frac{350 \frac{\text{m}}{\cancel{\text{s}}}}{\frac{100}{\cancel{\text{s}}}}$$

$$= 3.50 \text{ m}$$



◀ **Figure 8.46** When a wavelength of 3.50 m travels toward you at a speed of 350 m/s, you hear sound that has a frequency of 100 Hz (diagram not to scale).

You hear the sound at a frequency of 100 Hz because at a speed of 350 m/s, the time lapse between crests that are 3.50 m apart is 1/100 s. If, however, the wavelengths that travel toward you were 7.0 m long, the time lapse between successive crests would be 1/50 s, a frequency equal to 50 Hz.

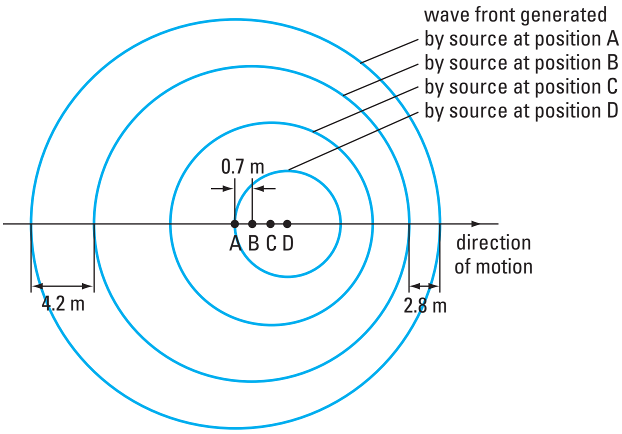
$$f = \frac{v}{\lambda}$$

$$= \frac{350 \frac{\cancel{\text{m}}}{\text{s}}}{7.0 \cancel{\text{m}}}$$

$$= 50 \frac{1}{\text{s}}$$

$$= 50 \text{ Hz}$$

Wavelength and Frequency of a Moving Source



▲ **Figure 8.47** When a sound source moves toward you, the wavelengths in the direction of the motion are decreased.

Imagine that the source generating the 100-Hz sound is moving toward you at a speed of 70 m/s. Assume that the source is at point A (Figure 8.47) when it generates a crest. While the first crest moves a distance of 3.5 m toward you, the source also moves toward you. The distance the source moves while it generates one wavelength is the distance the source travels in 1/100 s at 70 m/s, or 0.7 m. Because of the motion of the source, the next crest is generated (at point B) only 2.8 m behind the first crest. As long as the source continues at the speed of 70 m/s toward you, the crests travelling in your direction will be only 2.8 m apart. Hence, for a car moving toward you, the sound waves emitted by the car will be "squashed together" and thus reach you more frequently than if the car were stationary.

If waves that are 2.8 m long travel toward you at a speed of 350 m/s, then the frequency of the sound arriving at your ear will be 125 Hz. The pitch of the sound that you hear will have been increased because the source is moving toward you.

$$v = f\lambda$$

$$f = \frac{v}{\lambda}$$

$$= \frac{350 \frac{\cancel{\text{m}}}{\text{s}}}{2.80\ \cancel{\text{m}}}$$

$$= 125\ \frac{1}{\text{s}}$$

$$= 125\ \text{Hz}$$

***e*SIM**

Research examples of shock waves and the variation of wavelength with a moving source. Go to www.pearsoned.ca/school/physicssource.

At the same time, along a line in the direction opposite to the motion of the source, the wavelengths are increased by the same amount that the waves in front of the source are shortened. For the 100-Hz sound source moving at 70 m/s, the waves behind the source are increased by 0.7 m, to a length of 4.2 m. The time lapse between these crests, which are 4.2 m apart and travelling at 350 m/s, is 0.012 s. Therefore, the perceived frequency in the direction opposite to the motion of the source is about 83 Hz. The pitch of the sound has been lowered.

Analysis of the Doppler Effect

If the velocity of the sound waves in air is v_w, then the wavelength (λ_s) that a stationary source(s) with a frequency of f_s generates is given by

$$\lambda_s = v_w / f_s.$$

The key to this Doppler's analysis is to calculate the distance the source moves in the time required to generate one wavelength (the period (T_s) of the source). If the source is moving at speed v_s, then in the period (T_s) the source moves a distance (Δd_s) that is given by

$\Delta d_s = v_s T_s$. Since, by definition

$$T_s = 1/f_s, \text{ then}$$

$$\Delta d_s = v_s/f_s.$$

Sources Moving Toward You

For sources that are moving toward you, Δd_s is the distance by which the wavelengths are shortened. Subtracting Δd_s from λ_s gives the lengths of the waves (λ_d) that reach the listener. Therefore,

$$\lambda_d = \lambda_s - \Delta d_s.$$

Replacing λ_s and Δd_s by their equivalent forms gives

$$\lambda_d = \frac{v_w}{f_s} - \frac{v_s}{f_s}$$

$$\lambda_d = \frac{(v_w - v_s)}{f_s}$$

This is the apparent wavelength (Doppler wavelength) of the sound generated by a source that is moving toward you at a speed v_s. Dividing the speed of the waves (v_w) by the Doppler wavelength (λ_d) produces the Doppler frequency (f_d) of the sound that you hear as the source approaches you. Therefore,

$$\begin{aligned} f_d &= \frac{v_w}{\lambda_d} \\ &= \frac{v_w}{\left(\frac{v_w - v_s}{f_s}\right)} \\ &= v_w\left(\frac{f_s}{v_w - v_s}\right) \\ &= \left(\frac{v_w}{v_w - v_s}\right)f_s \end{aligned}$$

is the Doppler frequency when the source is approaching the listener.

Sources Moving Away from You

If the source is moving away from the listener, the value of Δd_s is added to the value of λ_s, giving

$$\lambda_d = \lambda_s + \Delta d_s.$$

If you replace λ_s and Δd_s by their equivalent forms and complete the development to find f_d, it is easy to see that the Doppler frequency for a sound where the source moves away from the listener is given by

$$f_d = \left(\frac{v_w}{v_w + v_s}\right)f_s$$

General Form of the Doppler Equation

The equations for the Doppler effect are usually written as a single equation of the form

$$f_d = \left(\frac{v_w}{v_w \mp v_s}\right)f_s$$

PHYSICS INSIGHT

When the distance between you and the source is decreasing, you must subtract to calculate the Doppler effect on frequency and wavelength.

Concept Check

If you are travelling in your car beside a train that is blowing its whistle, is the pitch that you hear for the whistle higher or lower than the true pitch of the whistle? Explain.

Example 8.4

A train is travelling at a speed of 30.0 m/s. Its whistle generates a sound wave with a frequency of 224 Hz. You are standing beside the tracks as the train passes you with its whistle blowing. What change in frequency do you detect for the pitch of the whistle as the train passes, if the speed of sound in air is 330 m/s?

Given

$f_s = 224$ Hz

$v_w = 330$ m/s

$v_s = 30.0$ m/s

Required

(a) Doppler frequency for the whistle as the train approaches

(b) Doppler frequency for the whistle as the train moves away

(c) change in frequency

Analysis and Solution

Use the equations for Doppler shifts to find the Doppler frequencies of the whistle.

(a) For the approaching whistle,

$$f_d = \left(\frac{v_w}{v_w - v_s}\right)f_s$$

$$f_d = \left(\frac{330\frac{\text{m}}{\text{s}}}{330\frac{\text{m}}{\text{s}} - 30.0\frac{\text{m}}{\text{s}}}\right)224\text{ Hz}$$

$$= \left(\frac{330\cancel{\frac{\text{m}}{\text{s}}}}{300\cancel{\frac{\text{m}}{\text{s}}}}\right)224\text{ Hz}$$

$= 246.4$ Hz

$= 246$ Hz

(b) For the receding whistle,

$$f_d = \left(\frac{v_w}{v_w + v_s}\right)f_s$$

$$f_d = \left(\frac{330\frac{\text{m}}{\text{s}}}{330\frac{\text{m}}{\text{s}} + 30.0\frac{\text{m}}{\text{s}}}\right)224\text{ Hz}$$

$$= \left(\frac{330\cancel{\frac{\text{m}}{\text{s}}}}{360\cancel{\frac{\text{m}}{\text{s}}}}\right)224\text{ Hz}$$

$= 205.3$ Hz

$= 205$ Hz

(c) The change in pitch is the difference in the two frequencies.
Therefore, the pitch change is

$$\Delta f = 246.4\text{ Hz} - 205.3\text{ Hz}$$
$$= 41.1\text{ Hz}$$

Paraphrase and Verify

As the train passes, the pitch of its whistle is lowered by a frequency of about 41.1 Hz.

Practice Problems

1. You are crossing in a crosswalk when an approaching driver blows his horn. If the true frequency of the horn is 264 Hz and the car is approaching you at a speed of 60.0 km/h, what is the apparent (or Doppler) frequency of the horn? Assume that the speed of sound in air is 340 m/s.
2. An airplane is approaching at a speed of 360 km/h. If you measure the pitch of its approaching engines to be 512 Hz, what must be the actual frequency of the sound of the engines? The speed of sound in air is 345 m/s.
3. An automobile is travelling toward you at a speed of 25.0 m/s. When you measure the frequency of its horn, you obtain a value of 260 Hz. If the actual frequency of the horn is known to be 240 Hz, calculate v_w, the speed of sound in air.
4. As a train moves away from you, the frequency of its whistle is determined to be 475 Hz. If the actual frequency of the whistle is 500 Hz and the speed of sound in air is 350 m/s, what is the train's speed?

Answers

1. 278 Hz
2. 364 Hz
3. 325 m/s
4. 18.4 m/s

The Sound Barrier

Jet planes are not allowed to break or exceed the sound barrier in the airspace over most cities. When an object travels at speeds at, or greater than, the speed of sound, it creates a sonic boom. The boom is the result of the **shock wave** created by the motion of the object.

Bow Waves

A boat moving through water produces a bow wave. The crest of the wave moves sideways away from the object, producing the wave's characteristic V-shape. For an airplane moving through the fluid medium of the atmosphere, a V-shaped bow wave, or pressure wave, travels outward at the speed of sound (Figure 8.48). If the speed of the airplane is less than the speed of sound, the bow wave produced at any instant lags behind the bow wave produced just an instant earlier. The bow wave carries energy away from the plane in a continuous stream (Figure 8.49(a)).

e **WEB**

To learn more about possible health effects of sonic booms at close range, and the recent concerns of the Innu Nation, follow the links at www.pearsoned.ca/school/physicssource.

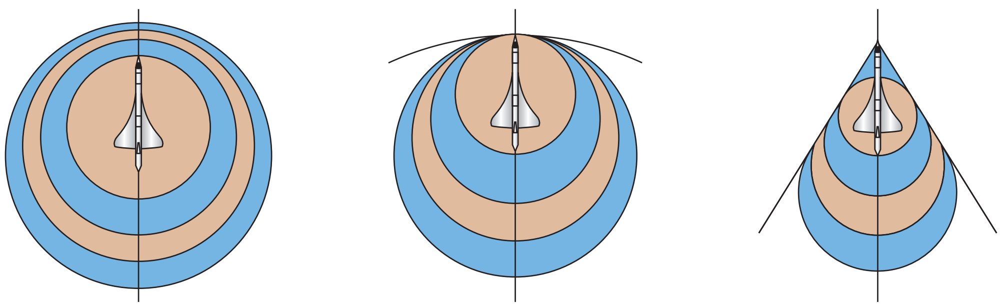
Sonic Boom

However, for an airplane travelling at the speed of sound, the bow wave and the airplane travel at the *same* speed. Instant by instant, crests of the bow wave are produced at the same location as the crest of the bow wave produced by the plane an instant earlier (Figure 8.49). The energy stored in the bow wave becomes very intense. To the ear of an observer, crests of successively produced bow waves arrive simultaneously in what is known as a sonic boom. In early attempts to surpass the speed of sound, many airplanes were damaged. At the speed of sound, there is a marked increase in drag and turbulence. This effect damaged planes not designed to withstand it. A reporter assumed the increased drag acted like a barrier to travelling faster than sound and coined the term **sound barrier**.

Mathematically, from the arguments presented above, the Doppler wavelength is given by

$$\lambda_d = \frac{(v_w - v_s)}{f_s}.$$

▲ **Figure 8.48** When conditions are right, the change in pressure produced by the airplane's wings can cause sufficient cooling of the atmosphere so that a cloud forms. The extreme conditions present when a jet is travelling near the speed of sound often result in the type of cloud seen in this photo.



(a) Slower than speed of sound: Pressure waves move out around plane.

(b) At speed of sound: Pressure waves at nose form a shock wave.

(c) At supersonic speed: Shock waves form a cone, resulting in a sonic boom.

▲ **Figure 8.49** As an airplane accelerates from subsonic to supersonic speeds, the changing relationship between the plane and the bow waves or pressure waves results in a sonic boom.

If a plane is travelling at the speed of sound, then $v_s = v_w$, which means that for any sound produced by the jet, the Doppler wavelength in the direction of the jet's motion is zero. Even if the plane's speed is greater than that of sound, the bow waves still combine to form a shock wave. In this way a sonic boom can be heard for any object, such as a rifle bullet, that has a supersonic speed.

THEN, NOW, AND FUTURE Ultrasound

While impressive given the technology available at the time, the results of early attempts at using ultrasound in medicine were of poor quality. Initially, ultrasound images from within a body were very blurry and two-dimensional. By today's standards, the technology was extremely crude and there was virtually no scientific understanding of how the sound would behave when it encountered different types of tissue.

Today, computers have made it possible to form three-dimensional images that can be rotated so that you can see all sides. Doppler ultrasound is used to detect blood flow through an organ. Today, 4-D ultrasound (time is the 4th dimension) is a real-time 3-D image that moves.

1. What are the advantages and disadvantages of ultrasound imaging compared with other imaging techniques such as CT scans and MRI?

▲ **Figure 8.50** A 3-D ultrasound picture of a developing fetus

8.4 Check and Reflect

Knowledge

1. What causes the Doppler effect?
2. Two sound sources have the same frequency when at rest. If they are both moving away from you, how could you tell if one was travelling faster than the other?
3. Explain the cause of a sonic boom.

Applications

4. The siren of a police car has a frequency of 660 Hz. If the car is travelling toward you at 40.0 m/s, what do you perceive to be the frequency of the siren? The speed of sound in air is 340 m/s.
5. A police car siren has a frequency of 850 Hz. If you hear this siren to have a frequency that is 40.0 Hz greater than its true frequency, what was the speed of the car? The speed of sound is 350 m/s.
6. A jet, travelling at the speed of sound (Mach 1), emits a sound wave with a frequency of 1000 Hz. Use the Doppler effect equations to calculate the frequency of this sound as the jet first approaches you, then moves away from you. Explain what these answers mean in terms of what you would hear as the jet moved toward, then past, you.

Extensions

7. Astronomers have shown that the colour of light from distant stars is shifted from the blue end toward the red end of the spectrum. This is known as **red shift**. Astronomers realized that since light energy is transmitted as a wave, the red shift was the result of the Doppler effect applied to light. What does the red shift indicate about the motions of the star, which emits light that we see as a red shift? **Hint:** Investigate the relationship between the frequency and colour for light.

e **TEST**

To check your understanding of the Doppler effect, follow the eTest at www.pearsoned.ca/school/physicssource.

Key Terms and Concepts

medium
wave
equilibrium position
crest
trough
amplitude
wavelength
wave front
incident wave
reflected wave
wave train
point source
ray
pulse
interference
principle of superposition
constructive interference
destructive interference
node
antinode
standing wave
resonance
closed pipe
fundamental frequency
overtone
open pipe
interference pattern
maximum
minimum
phase shift

Key Equations

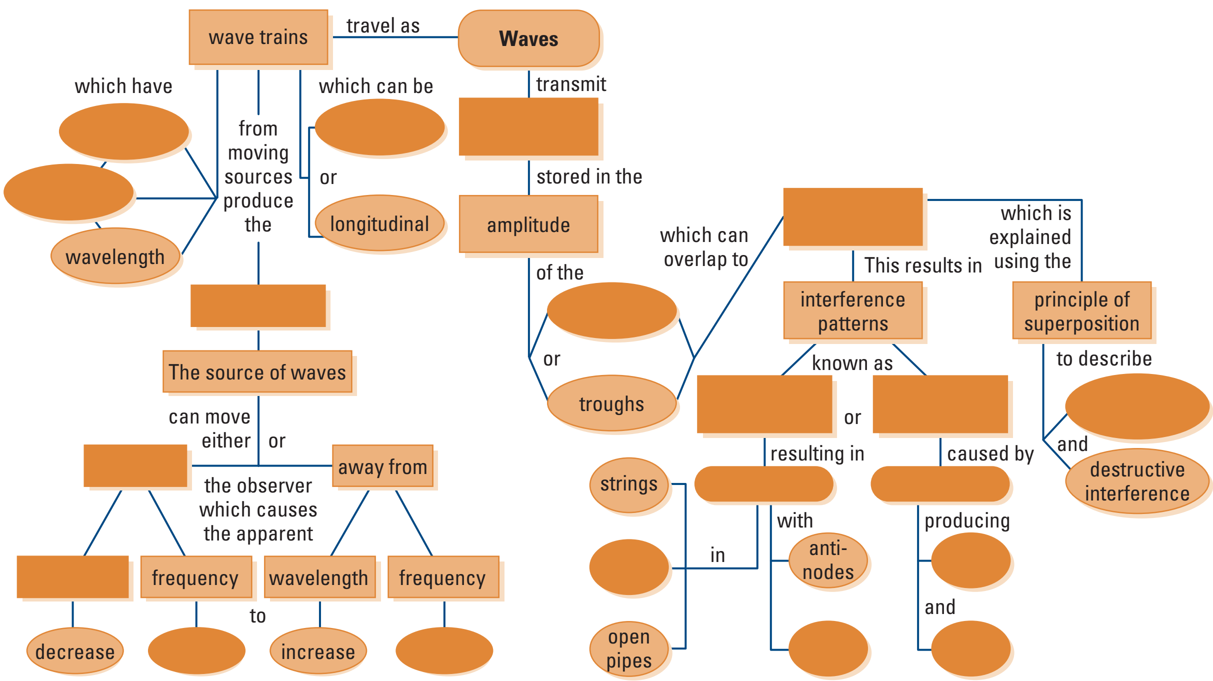
$\lambda = vT$

$v = f\lambda$

$f_d = \left(\dfrac{v_w}{v_w \mp v_s}\right) f_s$

Conceptual Overview

The concept map below summarizes many of the concepts and equations in this chapter. Copy and complete the map to produce a full summary of the chapter.



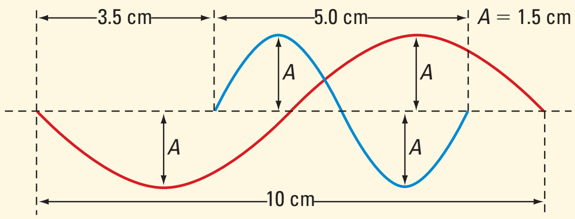
Knowledge

1. (8.1) (a) When a wave moves on water, what is the nature of the motion of the water within the wave?
   (b) What is the relationship between the direction of an incident wave and a reflected wave?
   (c) If you were able see the sound waves emitted when a tuning fork was struck, what would you record as your observation?
2. (8.2) (a) What affects the speed of a water wave?
   (b) What is the nature of the motion of the medium when a longitudinal wave moves through it?
   (c) Describe how the speed of a wave affects its wavelength and its amplitude.
   (d) Explain why waves are considered a form of Simple Harmonic Motion.
   (e) If speed is constant, how does wavelength vary with frequency?
3. (8.3) (a) Describe the conditions required to produce constructive and destructive interference in waves.
   (b) Describe how the principle of superposition applies to what happens when two pulses of identical length and amplitude interfere to produce no apparent pulse.
   (c) Define node, antinode, and standing wave.
   (d) In terms of the wavelength of the waves that have combined to form a standing wave, describe the position of the nodes and antinodes as you move away from the fixed end of a spring.
   (e) Why can a standing wave be generated only by what is defined as resonant frequency?
4. (8.4) (a) Does the Doppler effect apply only to sound or can it apply to any form of wave motion? Explain.
   (b) How are the waves in the direction of a source's motion affected as the speed of the source increases?

Applications

5. The speed of a wave in a spring is 15.0 m/s. If the length of a pulse moving in the spring is 2.00 m, how long did it take to generate the pulse? Why don't we talk about the frequency for a pulse?
6. Waves are generated by a straight wave generator. The waves move toward and reflect from a straight barrier. The angle between the wave front and the barrier is 30°. Draw a diagram that shows what you would observe if this occurred in a ripple tank. Use a line drawn across the middle of a blank sheet of paper to represent the barrier. Draw a series of wave fronts about 1 cm apart intersecting the barrier at 30°. Use a protractor to make sure the angle is correct. Now draw the reflected waves. Draw a ray to indicate the motion of the incident wave front and continue this ray to indicate the motion of the reflected wave front. **Hint:** Draw the reflected ray as if it had a new source.
7. A ripple tank is set up so that the water in it is 0.7 cm deep. In half of the tank, a glass plate is placed on the bottom to make the water in that half shallower. The glass plate is 0.5 cm thick. Thus, the tank has a deep section (0.7 cm) and a shallow section (0.2 cm). In the deep section the wave velocity is 15.0 cm/s while in the shallow section the velocity is 10.0 cm/s. Straight waves, parallel to the edge of the glass, move toward the line between the deep and shallow sections. If the waves have a frequency of 12.0 Hz, what changes in wavelength would you observe as they enter the shallow section? What would happen to the direction of the motion?
8. A ripple tank is set up as described in question 7. For this ripple tank you measure the speed of the waves to be 12.0 cm/s and 9.0 cm/s in the deep and shallow sections, respectively. If waves in the deep section that are 11.5 cm long cross over to the shallow section, what would be the wavelength in the shallow section?
9. The term ultrasound means the frequency is higher than those that our ears can detect (about 20 kHz). Animals can often hear sounds that, to our ears, are ultrasound. For example, a dog whistle has a frequency of 22 kHz. If the speed of sound in air is 350 m/s, what is the wavelength of the sound generated by this whistle?
10. A spring is stretched to a length of 7.0 m. A frequency of 2.0 Hz generates a standing wave in the spring that has six nodes.
    (a) Sketch the standing wave pattern for the spring.
    (b) Calculate the velocity of the wave.

11. The figure shows two waves that occupy the same point in space. Copy the sketch onto a sheet of paper using the dimensions indicated. Draw the wave that results from the interference of these two waves.



12. If a frequency of 1.5 Hz generates a standing wave in a spring that has three antinodes, (a) what frequency generates a standing wave with five antinodes in the same spring, and (b) what is the fundamental frequency for this spring?

13. A violin string is 33.0 cm long. The thinnest string on the violin is tuned to vibrate at a frequency of 659 Hz.
    (a) What is the wave velocity in the string?
    (b) If you place your finger on the string so that its length is shortened to 28.0 cm, what is the frequency of the note that the string produces?

14. (a) What is the shortest closed pipe for which resonance is heard when a tuning fork with a frequency of 426 Hz is held at the open end of the pipe? The speed of sound in air is 335 m/s.
    (b) What is the length of the next longest pipe that produces resonance?

15. Draw the interference pattern generated by two in-phase point sources that are four wavelengths apart.

16. In the interference pattern for two in-phase point sources, a point on a second order maximum is 2.8 cm farther from one source than the other. What is the wavelength generated by these sources?

17. The horn on a car has a frequency of 290 Hz. If the speed of sound in air is 340 m/s and the car is moving toward you at a speed of 72.0 km/h, what is the apparent frequency of the sound?

18. How fast is a sound source moving toward you if you hear the frequency to be 580 Hz when the true frequency is 540 Hz? The speed of sound in air is 350 m/s. Express your answer in km/h.

19. If the speed of sound in air is 350 m/s, how fast would a sound source need to travel away from you if the frequency that you hear is to be one-half the true frequency? What would you hear if this sound source had been moving toward you?

20. When a police car is at rest, the wavelength of the sound from its siren is 0.550 m. If the car is moving toward you at a speed of 120 km/h, what is the frequency at which you hear the siren? Assume that the speed of sound is 345 m/s.

21. If the speed of sound in air is 350 m/s, how fast must a sound source move toward you if the frequency that you hear is twice the true frequency of the sound? What frequency would you hear if this sound source had been moving away from you?

Extensions

22. Describe an arrangement that you might use if you wanted to create an interference pattern similar to the one in Figure 8.44 on page 426 by using sound waves that have a frequency of 512 Hz. Except for standing waves in strings or pipes, why do you think that we do not often find interference patterns in nature?

23. Explain why the number of maxima and minima in the interference pattern generated by two in-phase point sources depends on the ratio of the distance between the sources to the wavelength.

e TEST

To check your understanding of waves and wave motion, follow the eTest links at www.pearsoned.ca/school/physicssource.

Consolidate Your Understanding

Answer each of the following questions in your own words. Provide examples to illustrate your explanation.

1. What are the advantages and disadvantages of using a spring as a model for wave motion?
2. What are the conditions for which a standing wave pattern is generated? Why are standing waves not often seen in nature?
3. Explain how the energy in a wave is transmitted from one place to another.
4. Describe what is meant by the principle of superposition. How does this principle explain standing waves?
5. What is meant by resonance?

Think About It

Review your answers to the Think About It questions on page 393. How would you answer each question now?

Earthquakes

Scenario

The tsunami that swept coastal regions of the Indian Ocean on December 26, 2004, was set off by an earthquake centred off the coast of the island of Sumatra in Indonesia. Seismographs around the world identified the location and strength of the earthquake. It was determined that the earthquake rated about 9.0–9.3 on the Richter scale. You have been asked by your government to make a presentation on the seismology of earthquakes. Your challenge is threefold.

- First: you are to explain the nature of earthquake shock waves, their movement through Earth, and how the location of the earthquake epicentre is identified by seismographs around the world.
- Second: you are to explain how the intensity of earthquakes is measured. This means that you must explain what the Richter scale is, and how it is used to rate earthquake intensity.
- Third: you are to demonstrate the operation of a seismograph.

Planning

Your team should consist of three to five members. Choose a team manager and a record keeper. Assign other tasks as they arise. The first task is to decide the structure of your presentation and the research questions you will need to investigate. Questions you will need to consider are: How will you present the information to your audience? What are the resources at your disposal? Do you have access to computers and presentation programs such as PowerPoint®? Which team members will design, build, and demonstrate the model seismograph?

Brainstorm strategies for research and create a schedule for meeting the deadlines for all phases of the project. Where is your team going to look for the information necessary to complete the project? What types of graphics will be most effective to assist your presentation? How will you best demonstrate the function of your seismograph? Your final report should include written, graphic, and photographic analyses of your presentation.

Assessing Results

Assess the success of your project based on a rubric* designed in class that considers:

- research strategies
- thoroughness of the experimental design
- effectiveness of the experimental technique
- effectiveness of the team's public presentation

Materials

- materials, as needed, for the construction of your model seismograph

Procedure

1. Research the nature of the shock waves set off by an earthquake. Be alert to Internet sites that may contain unreliable or inaccurate information. Make sure that you evaluate the reliability of the sources of information that you use for your research. If you gather information from the Internet, make sure you identify who sponsors the site and decide whether or not it is a reputable source of information. Maintain a list of your references and include it as an appendix to your report. Use graphics to explain how the shock waves move through Earth, and how seismologists locate the epicentre of an earthquake.
2. Research the history of the Richter scale and its use in identifying the intensity of an earthquake.
3. Design and build your model of a seismograph. Decide how you will demonstrate its use in your presentation.
4. Prepare an audio-visual presentation that would inform your audience on the nature of earthquakes and how they are detected.

Thinking Further

Write a short appendix (three or four paragraphs) to your report to suggest steps that governments might take to make buildings safer in earthquake zones.

Answer questions such as: What types of structures are least susceptible to damage by earthquakes? What types are most susceptible?

*Note: Your instructor will assess the project using a similar assessment rubric.

UNIT IV SUMMARY

Unit Concepts and Skills: Quick Reference

Concepts	Summary	Resources and Skill Building
Chapter 7	**Oscillatory motion requires a set of conditions.**	
	7.1 Period and Frequency	
Period	Period is the time for one complete cycle, measured in seconds (s). If the period of each cycle remains constant, the object is moving with oscillatory motion.	QuickLab 7-1; Inquiry Lab 7-2; Minds On; Figures 7.4, 7.5
Frequency	Frequency is the number of cycles per second, measured in Hertz (Hz).	QuickLab 7-1; Inquiry Lab 7-2; Example 7.1; Figure 7.5
	7.2 Simple Harmonic Motion	
Spring constant	The spring constant is the amount of force needed to stretch or compress the spring 1 m and is measured in N/m. It can also be thought of as the stiffness of a spring.	QuickLab 7-3; Examples 7.2–7.4
Hooke's law	Hooke's law states that the deformation of an object is proportional to the force causing it.	Figures 7.9–7.16
Simple harmonic motion	SHM refers to anything that moves with uniform oscillatory motion and conforms to Hooke's law.	Figures 7.19–7.23; eSIM
Pendulum motion	The pendulum is a simple harmonic oscillator for angles less than 15°.	Figures 7.25–7.27; Example 7.5; Inquiry Lab 7-4; Table 7.5
	7.3 Position, Velocity, Acceleration, and Time Relationships	
Acceleration of a mass-spring system	The acceleration of a mass-spring system depends on displacement, mass, and the spring constant, and it varies throughout the motion of the mass-spring system.	Figure 7.28
Relationship between acceleration and velocity of a mass-spring system	The acceleration and velocity of a mass-spring system are continually changing. The velocity of a mass-spring system is determined by its displacement, spring constant, and mass.	Figures 7.29–7.33; Example 7.6
Period of a mass-spring system	The period of a mass-spring oscillator is determined by its mass and spring constant, but not its amplitude.	Figures 7.35–7.37; Example 7.7
Period of a pendulum	A pendulum's period is determined by its length and the gravitational field strength, but not the mass of the bob.	Figures 7.39, 7.40; eSIM; Example 7.8
	7.4 Applications of Simple Harmonic Motion	
Resonance	Resonance is the natural frequency of vibration of an object.	Figure 7.41; QuickLab 7-5
Forced frequency	Forced frequency is the frequency at which an external force is applied to an oscillating object.	Figure 7.41; QuickLab 7-5
Resonance effects on buildings and bridges	Bridges and buildings can resonate due to the force of the wind.	Figures 7.44, 7.45; Then, Now, and Future
Chapter 8	**Mechanical waves transmit energy in a variety of ways.**	
	8.1 The Properties of Waves	
Wave properties may be qualitative or quantitative.	Waves have many properties that can be used to analyze the nature of the wave and the way it behaves as it moves through a medium. Some of these properties are qualitative (crest, trough, wave front, medium, incident wave, reflected wave, wave train) while others are quantitative (amplitude, wavelength, frequency, wave velocity).	QuickLab 8-1; Inquiry Lab 8-2; Inquiry Lab 8-3
	8.2 Transverse and Longitudinal Waves	
Universal wave equation	Waves can move through a medium either as transverse or longitudinal waves. The relationship among the frequency, wavelength, and wave velocity is given by the universal wave equation.	Inquiry Lab 8-4; Inquiry Lab 8-5; Example 8.1; Example 8.2
	8.3 Superposition and Interference	
Interference patterns may result when more than one wave moves through a medium.	When two or more waves travel in different directions through the same point in space, their amplitudes combine according to the principle of superposition. Depending on the properties of the waves, they may form an interference pattern. Interference patterns can often be used to determine the properties of the waves from which they are formed.	Inquiry Lab 8-6; Example 8.3; Inquiry Lab 8-7; Design a Lab 8-8
	8.4 The Doppler Effect	
Doppler effect	When a sound source moves either toward or away from a sensor (ear or microphone), the frequency of the sound that is detected will be different from the frequency emitted by the source.	Example 8.4
Sonic boom	When an object is travelling at the speed of sound, it creates a shock wave known as a sonic boom.	Figure 8.49

UNIT IV REVIEW

Vocabulary

1. Use your own words to define the following terms, concepts, principles, or laws. Give examples where appropriate.

amplitude
antinodes
closed-pipe air column
constructive interference
crest
destructive interference
diverging
Doppler effect
equilibrium
forced frequency
frequency
fundamental frequency
Hooke's law
incident wave
in phase
interference
longitudinal wave
maximum
mechanical resonance
medium
minimum
nodes or nodal points
open-pipe air column
oscillation
oscillatory motion
overtone
period
phase shift
principle of superposition
pulse
ray
reflected wave
resonance
resonant frequency
restoring force
shock wave
simple harmonic motion
simple harmonic oscillator
sonic boom
sound barrier
spring constant
standing waves
transverse wave
trough
two-point-source interference pattern
wave
wave front
wave train
wave velocity
wavelength

Knowledge

CHAPTER 7

2. How are the units of frequency and period similar? How are they different?

3. The SI unit for frequency is Hz. What are two other accepted units?

4. For any simple harmonic oscillator, in what position is

(a) the velocity zero?

(b) the restoring force the greatest?

5. Why doesn't a pendulum act like a simple harmonic oscillator for large amplitudes?

6. The equation for Hooke's law uses a negative sign ($F = -kx$). Why is this sign necessary?

7. Aboriginal bows used for hunting were made from wood. Assuming the wood deforms according to Hooke's law, explain how you would go about measuring the spring constant of the wood.

8. Suppose the same pendulum was tested in both Calgary and Jasper. In which location would you expect the pendulum to oscillate more slowly? Explain.

9. Explain why the sound from one tuning fork can make a second tuning fork hum. What conditions must be necessary for this to happen?

10. A pendulum in a clock oscillates with a resonant frequency that depends on several factors. From the list below, indicate what effect (if any) the following variables have on the pendulum's resonant frequency.

(a) length of pendulum arm

(b) latitude of clock's position

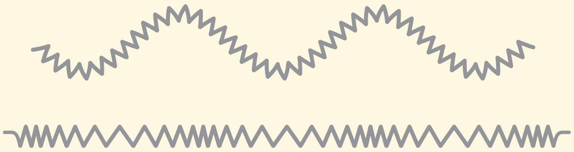
(c) longitude of clock's position

(d) elevation

(e) restoring force

CHAPTER 8

11. The diagram below shows waves in two springs. For each of the springs, how many wavelengths are shown?



12. Sound waves, travelling through air, are reflected from the wall of a building. Describe how the reflection affects
(a) the speed,
(b) the wavelength,
(c) the amplitude, and
(d) the direction of a wave train.

13. Points of zero displacement on a transverse wave have the greatest kinetic energy. Which points on a longitudinal wave have the greatest kinetic energy?

14. How is the shape of a circular wave front changed when it reflects from a straight barrier?

15. What aspect of a pulse determines the amount of energy it transfers?

16. When water waves enter a region where they travel slower, what happens to the
(a) frequency,
(b) wavelength, and
(c) direction of the waves?

17. In the interference pattern from two in-phase point sources, what name is given to a line along which destructive interference occurs?

18. What determines the speed at which a wave travels through a spring?

19. What causes a standing wave in a spring?

20. Draw a transverse wave train that consists of two wavelengths. On your diagram, label the equilibrium position for the medium, a crest, a trough, the amplitude, a wavelength, and the direction of the wave velocity. Along the wavelength that you identified above, draw several vector arrows to indicate the direction of the motion of the medium.

21. Why does moving your finger along the string of a violin alter the note that it produces?

22. What property of the sound produced by a tuning fork is affected by striking the tuning fork with different forces? What does that tell you about the relationship between the properties of the sound and the sound wave created by striking the tuning fork?

23. When two in-phase point sources generate an interference pattern, what conditions are required to create (a) the central maximum and (b) a second order maximum?

24. In terms of the length of an open pipe, what is the longest wavelength for which resonance can occur?

25. You are walking north along a street when a police car with its siren on comes down a side street (travelling east) and turns northward on the street in front of you. Describe what you would hear, in terms of frequency of the sound of its siren, before and after the police car turns.

26. What is the relationship between frequency, wavelength, and wave velocity?

27. Why does the frequency of a sound source that is moving toward you seem to be higher than it would be if the source were at rest?

Applications

28. Determine the force necessary to stretch a spring ($k = 2.55$ N/m) to a distance of 1.20 m.

29. A musician plucks a guitar string. The string has a frequency of 400.0 Hz and a spring constant of 5.0×10^4 N/m. What is the mass of the string?

30. When a pendulum is displaced 90.0° from the vertical, what proportion of the force of gravity is the restoring force?

31. While performing a demonstration to determine the spring constant of an elastic band, a student pulls an elastic band to different displacements and measures the applied force. The observations were recorded in the table below. Plot the graph of this data. Can the spring constant be determined? Why or why not?

Displacement (m)	Force (N)
0.1	0.38
0.2	1.52
0.3	3.42
0.4	6.08
0.5	9.5
0.6	13.68

32. A force of 40.0 N is required to move a 10.0-kg horizontal mass-spring system through a displacement of 80.0 cm. Determine the acceleration of the mass when its displacement is −25.0 cm.

33. Use the following table to determine the spring constant of a spring.

Displacement (cm)	Force (mN)
2.5	10.0
5.0	21.0
7.5	31.0
10.0	39.0
12.5	49.0

34. A 50.0-g mass oscillates on the end of a vertical mass-spring system (k = 25.0 N/m) with a maximum acceleration of 50.0 m/s^2.
    (a) What is its amplitude of vibration?
    (b) What is the maximum velocity of the mass?
35. A bee's wing has a mass of 1.0×10^{-5} kg and makes one complete oscillation in 4.5×10^{-3} s. What is the maximum wing speed if the amplitude of its motion is 1.10 cm?
36. A skyscraper begins resonating in a strong wind. A tuned mass damper (m = 10.0 t) at the top of the building moves through a maximum displacement of 1.50 m in the opposite direction to dampen the oscillations. If the mass damper is attached to a horizontal spring and has a maximum speed of 1.40 m/s, what is the period of its oscillations?
37. A branch at the top of a tree sways with simple harmonic motion. The amplitude of motion is 0.80 m and its speed is 1.5 m/s in the equilibrium position. What is the speed of the branch at the displacement of 0.60 m?
38. A tuned mass damper at the top of a skyscraper is a mass suspended from a thick cable. If the building sways with a frequency of 0.125 Hz, what length must the cable supporting the weight be to create a resonance in the damper?
39. When a wave slows down, what property of the wave is not affected? What effect does this have on the other properties of the wave? Explain.
40. Explain how a wave can transmit energy through a medium without actually transmitting any matter.
41. A light wave is transmitted through space at 3.00×10^8 m/s. If visible light has wavelengths ranging from about 4.30×10^{-7} m to 7.50×10^{-7} m long, what range of frequencies are we able to see?
42. Radio waves travel at the speed of light waves (3.00×10^8 m/s). If your radio is tuned to a station broadcasting at 1250 kHz, what is the length of the waves arriving at the radio antenna?
43. A pendulum oscillates with a period of 0.350 s. Attached to the pendulum is a pen that marks a strip of paper on the table below the pendulum as it oscillates. When the strip of paper is pulled sideways at a steady speed, the pen draws a sine curve on the paper. What will be the wavelength of the sine curve if the speed of the paper is 0.840 m/s?
44. A submarine sends out a sonar wave that has a frequency of 545 Hz. If the wavelength of the sound is 2.60 m, how long does it take for the echo to return when the sound is reflected from a submarine that is 5.50 km away?
45. A wire is stretched between two points that are 3.00 m apart. A generator oscillating at 480 Hz sets up a standing wave in the wire that consists of 24 antinodes. What is the velocity at which waves move in this wire?
46. A spring is stretched to a length of 5.40 m. At that length the speed of waves in the spring is 3.00 m/s.
    (a) If a standing wave with a frequency 2.50 Hz were generated in this spring, how many nodes and antinodes would there be along the spring?
    (b) What is the next lower frequency for which a standing wave pattern could exist in this spring?
47. The second string on a violin is tuned to the note D with a frequency of 293 Hz. This is the fundamental frequency for the open string, which is 33.0 cm long.
    (a) What is the speed of the waves in the string?
    (b) If you press on the string with your finger so that the oscillating portion of the string is 2/3 the length of the open string, what is the frequency of the note that is created?
48. An audio frequency generator set at 154 Hz is used to generate a standing wave in a closed-pipe resonator, where the speed of sound is 340 m/s.
    (a) What is the shortest air column for which resonance is heard?
    (b) What is the next longer column length for which resonance is heard?
49. A submarine's sonar emits a sound with a frequency of 875 Hz. The speed of sound in seawater is about 1500 m/s. If you measure the frequency of the sound to be 870 Hz, what is the velocity of the submarine?
50. A police car is travelling at a speed of 144 km/h. It has a siren with a frequency of 1120 Hz. Assume that the speed of sound in air is 320 m/s.
    (a) If the car is moving toward you, what frequency will you hear for the siren?
    (b) If the car had been moving away from you at the same speed, what frequency would you have heard?

Extensions

51. What generalization can be made about the frequency of vibration with regard to the mass for a mass-spring system? (Assume all other qualities remain constant.)

52. An alien crash-lands its spaceship on a planet in our solar system. Unfortunately, it is unable to tell which planet it is. From the wreckage of the spaceship the alien constructs a 1.0-m-long pendulum from a piece of wire with four metal nuts on the end. If this pendulum swings with a period of 3.27 s, on which planet did the alien land: Mercury, Venus, or Earth?

53. Use a compass to draw a simulation of the wave pattern generated by two in-phase point source generators that are 3.5 wavelengths apart. Near the middle of the page, place two points (S_1 and S_2) 3.5 cm apart to represent the positions of the sources. Draw wavelengths 1.0 cm long by drawing concentric circles that increase in radii by 1.0-cm increments. Locate on the diagram all the maxima and minima that are generated by this set-up and draw lines to indicate their positions. How does this pattern differ from the one in Figure 8.44 on page 426? Explain why these differences occur.

54. In a stereo system, there are two speakers set at some distance apart. Why does a stereo system not result in an interference pattern?

55. If a sound source is at rest, the frequency you hear and the actual frequency are equal. Their ratio equals one ($f_d/f_s = 1$). If the sound source moves toward you at an ever-increasing speed, this frequency ratio also increases. Plot a graph for the ratio of the frequencies vs. the speed of the sound source as the speed of the source increases from zero to Mach 1. What is the value of the ratio when the speed of the source is Mach 1?

Skills Practice

56. Use a graphing calculator or another suitable means to plot a graph of period against frequency. What type of relationship is this?

57. Outline an experimental procedure that you could perform to determine the spring constant of a vertical mass-spring system.

58. Sketch a diagram of a horizontal mass-spring system in three positions: at both extremes of its motion, and in its equilibrium position. In each diagram, draw vector arrows representing the restoring force, velocity, and acceleration. State whether these are at a maximum or a minimum.

59. Outline a procedure that you could use to determine the mass of a horizontal mass-spring system without measuring the mass on a scale.

60. A student wants to determine the mass of the bob on a pendulum but only has access to a stopwatch and a ruler. She decides to pull the pendulum bob back through a displacement of 10° and time 20 complete oscillations. Will it be possible to determine the mass from the data gathered? Explain.

61. Construct a concept map for the simple harmonic motion of a pendulum. Include the following terms: period, displacement, restoring force, velocity, length, and gravitational field strength.

62. In a paragraph, explain why Huygens's pendulum clock was a revolution in clock making and what the limitations were in its design. Be sure to use these terms: pendulum length, resonant frequency, forced frequency, and gravitational field strength.

63. Research the term "red shift" as used in astronomy. Prepare a report on the importance of red shift to our understanding of the nature of the universe.

64. Describe how to use springs to explore what happens to pulses transmitted from one medium to another in which the wave speed is different.

65. Explain to someone who has not studied physics the differences in the ways objects and waves transport energy between points on Earth.

Self-assessment

66. Identify a concept or issue that you studied in this unit and would like to learn more about.

67. Learning often requires that we change the way we think about things. Which concept in this unit required the greatest change in your thinking about it? Explain how your thinking changed.

68. Which of the concepts in this unit was most helpful in explaining to you how objects interact?

eTEST

To check your understanding of oscillatory motion and waves, follow the eTest links at www.pearsoned.ca/school/physicssource.