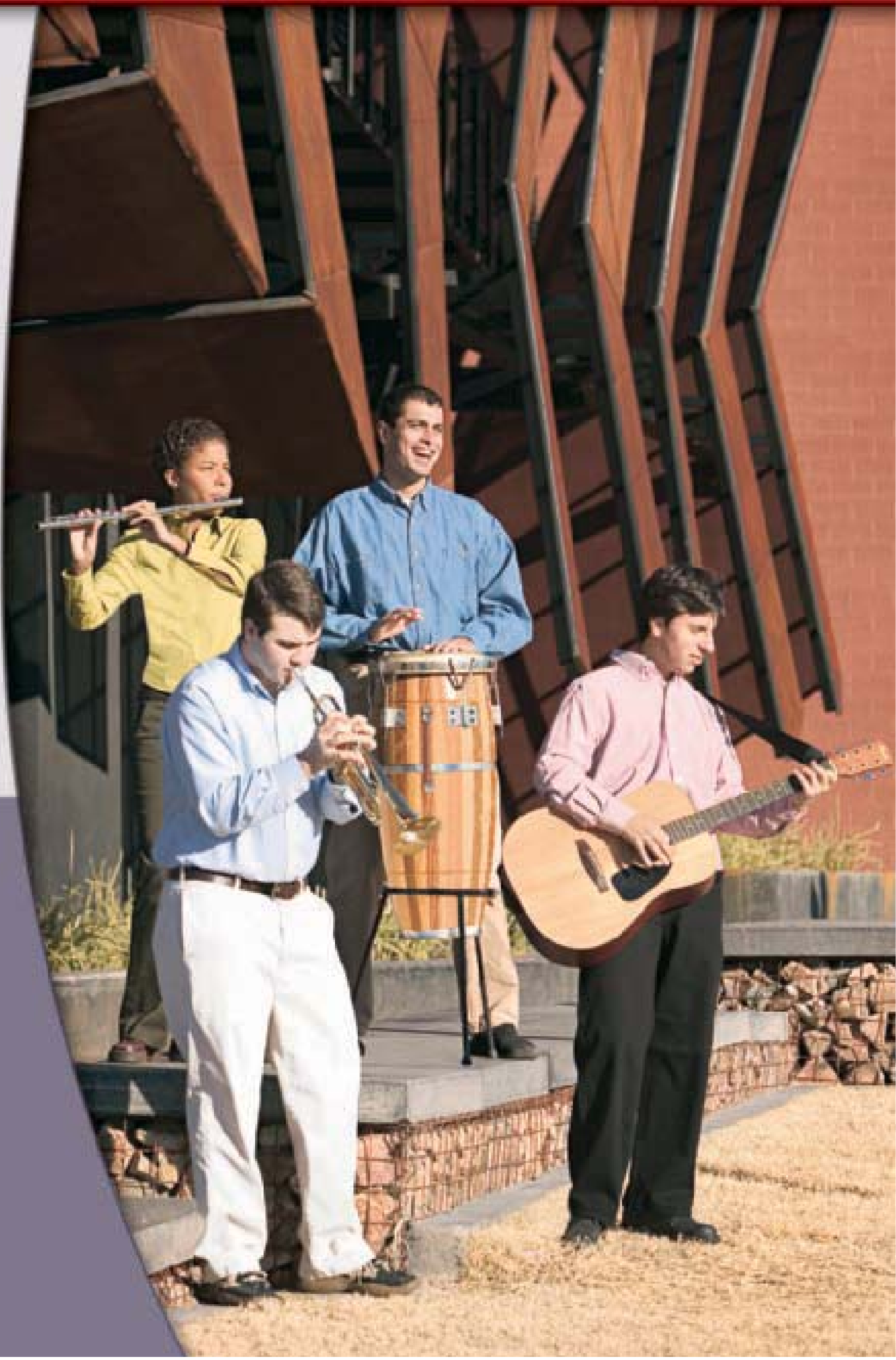
Chapter 15 Sound



What You'll Learn

- You will describe sound in terms of wave properties and behavior.
- You will examine some of the sources of sound.
- You will explain properties that differentiate between music and noise.

Why It's Important

Sound is an important means of communication and, in the form of music, cultural expression.

Musical Groups A small musical group might contain two or three instruments, while a marching band can contain 100 or more. The instruments in these groups form sounds in different ways, but they can create exciting music when they are played together.

Think About This ▶

How do the instruments in a musical group create the sounds that you hear? Why do various instruments sound different even when they play the same note?

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Tim Fuller

LAUNCH Lab

How can glasses produce musical notes?

Question

How can you use glasses to produce different musical notes, and how do glasses with stems compare to those without stems?

Procedure

1. Select a stemmed glass with a thin rim.
2. **Prepare** Carefully inspect the top edge of the glass for sharp edges. Notify your teacher if you observe any sharp edges. Be sure to repeat this inspection every time you select a different glass.
3. Place the glass on the table in front of you. Firmly hold the base with one hand. Wet your finger and slowly rub it around the top edge of the glass. ***CAUTION: Glass is fragile. Handle carefully.***
4. Record your observations. Increase or decrease the speed a little. What happens?
5. Select a stemmed glass that is larger or smaller than the first glass. Repeat steps 2-4.
6. Select a glass without a stem and repeat steps 2–4.

Analysis

Summarize your observations. Which glasses—stemmed, not stemmed, or both—were able to produce ringing tones? What factors affected the tones produced?

Critical Thinking

Propose a method for producing different notes from the same glass. Test your proposed method. Suggest a test to further investigate the properties of glasses that can produce ringing tones.

15.1 Properties and Detection of Sound

Sound is an important part of existence for many living things. Animals can use sound to hunt, attract mates, and warn of the approach of predators. In humans, the sound of a siren can heighten our awareness of our surroundings, while the sound of music can soothe and relax us. From your everyday experiences, you already are familiar with several of the characteristics of sound, including volume, tone, and pitch. Without thinking about it, you can use these, and other characteristics, to categorize many of the sounds that you hear; for example, some sound patterns are characteristic of speech, while others are characteristic of a musical group. In this chapter, you will study the physical principles of sound, which is a type of wave.

In Chapter 14, you learned how to describe waves in terms of speed, frequency, wavelength, and amplitude. You also discovered how waves interact with each other and with matter. Knowing that sound is a type of wave allows you to describe some of its properties and interactions. First, however, there is a question that you need to answer: exactly what type of wave is sound?

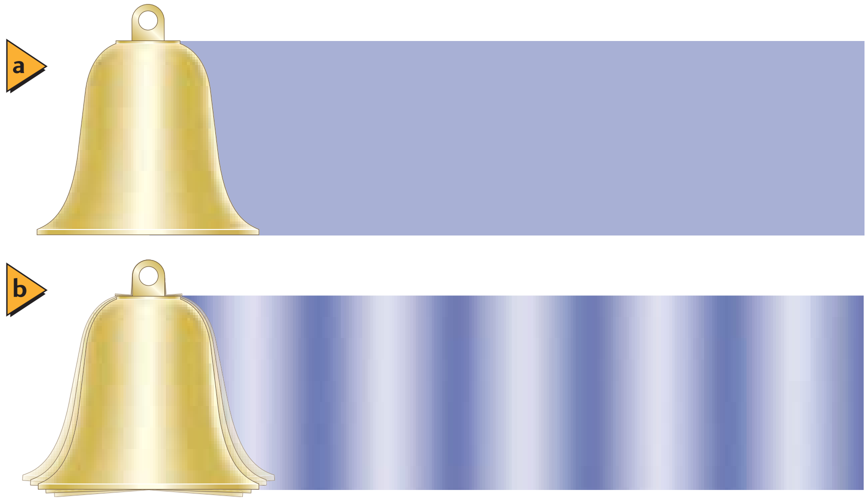
Objectives

- **Demonstrate** the properties that sound shares with other waves.
- **Relate** the physical properties of sound waves to our perception of sound.
- **Identify** some applications of the Doppler effect.

Vocabulary

sound wave
pitch
loudness
sound level
decibel
Doppler effect

■ **Figure 15-1** Before the bell is struck, the air around it is a region of average pressure **(a).** Once the bell is struck, however, the vibrating edge creates regions of high and low pressure. The dark areas represent regions of higher pressure; the light areas represent regions of lower pressure **(b).** For simplicity, the diagram shows the regions moving in one direction; in reality, the waves move out from the bell in all directions.



Sound Waves

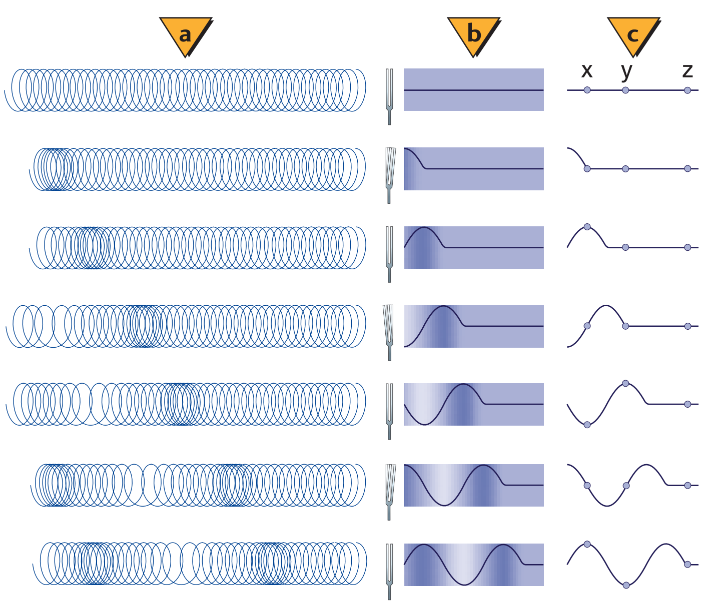
Put your fingers against your throat as you hum or speak. Can you feel the vibrations? Have you ever put your hand on the loudspeaker of a boom box? **Figure 15-1** shows a vibrating bell that also can represent your vocal cords, a loudspeaker, or any other sound source. As it moves back and forth, the edge of the bell strikes the particles in the air. When the edge moves forward, air particles are driven forward; that is, the air particles bounce off the bell with a greater velocity. When the edge moves backward, air particles bounce off the bell with a lower velocity.

The result of these velocity changes is that the forward motion of the bell produces a region where the air pressure is slightly higher than average. The backward motion produces slightly below-average pressure. Collisions among the air particles cause the pressure variations to move away from the bell in all directions. If you were to focus at one spot, you would see the value of the air pressure rise and fall, not unlike the behavior of a pendulum. In this way, the pressure variations are transmitted through matter.

Describing sound A pressure variation that is transmitted through matter is a **sound wave.** Sound waves move through air because a vibrating source produces regular variations, or oscillations, in air pressure. The air particles collide, transmitting the pressure variations away from the source of the sound. The pressure of the air oscillates about the mean air pressure, as shown in **Figure 15-2.** The frequency of the wave is the number of oscillations in pressure each second. The wavelength is the distance between successive regions of high or low pressure. Because the motion of the particles in air is parallel to the direction of the wave's motion, sound is a longitudinal wave.

The speed of sound in air depends on the temperature, with the speed increasing by about 0.6 m/s for each 1°C increase in air temperature. At room temperature (20°C), sound moves through air at sea level at a speed of 343 m/s. Sound also travels through solids and liquids. In general, the speed of sound is greater in

■ **Figure 15-2** A coiled spring models the compressions and rarefactions of a sound wave **(a).** The pressure of the air rises and falls as the sound wave propagates through the atmosphere **(b).** You can use a sine curve alone to model changes in pressure. Note that the positions of *x*, *y*, and *z* show that the wave, not matter, moves forward **(c).**



solids and liquids than in gases. **Table 15-1** lists the speeds of sound waves in various media. Sound cannot travel in a vacuum because there are no particles to collide.

Sound waves share the general properties of other waves. For example, they reflect off hard objects, such as the walls of a room. Reflected sound waves are called echoes. The time required for an echo to return to the source of the sound can be used to find the distance between the source and the reflective object. This principle is used by bats, by some cameras, and by ships that employ sonar. Two sound waves can interfere, causing dead spots at nodes where little sound can be heard. As you learned in Chapter 14, the frequency and wavelength of a wave are related to the speed of the wave by the equation $\lambda = v/f$.

Table 15-1
Speed of Sound in Various Media

Medium	m/s
Air (0°)	331
Air (20°)	343
Helium (0°)	972
Water (25°)	1493
Seawater (25°)	1533
Copper (25°)	3560
Iron (25°)	5130

PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

1. Find the wavelength in air at 20°C of an 18-Hz sound wave, which is one of the lowest frequencies that is detectable by the human ear.
2. What is the wavelength of an 18-Hz sound wave in seawater at 25°C?
3. Find the frequency of a sound wave moving through iron at 25°C with a wavelength of 1.25 m.
4. If you shout across a canyon and hear the echo 0.80 s later, how wide is the canyon?
5. A 2280-Hz sound wave has a wavelength of 0.655 m in an unknown medium. Identify the medium.

Detection of Pressure Waves

Sound detectors convert sound energy—the kinetic energy of the vibrating air particles—into another form of energy. A common detector is a microphone, which converts sound waves into electrical energy. A microphone consists of a thin disk that vibrates in response to sound waves and produces an electrical signal. You will learn about this transformation process in Chapter 25, during your study of electricity and magnetism.

The human ear As shown in **Figure 15-3,** the human ear is a detector that receives pressure waves and converts them to electrical impulses. Sound waves entering the auditory canal cause vibrations of the tympanic membrane. Three tiny bones then transfer these vibrations to fluid in the cochlea. Tiny hairs lining the spiral-shaped cochlea detect certain frequencies in the vibrating fluid. These hairs stimulate nerve cells, which send impulses to the brain and produce the sensation of sound.

The ear detects sound waves over a wide range of frequencies and is sensitive to an enormous range of amplitudes. In addition, human hearing can distinguish many different qualities of sound. Knowledge of both physics and biology is required to understand the complexities of the ear. The interpretation of sounds by the brain is even more complex, and it is not totally understood.

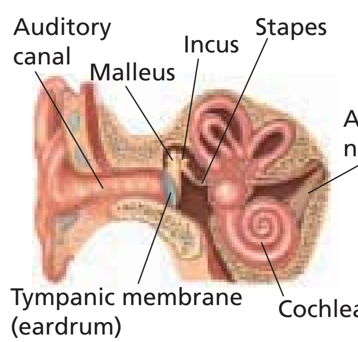


Figure 15-3 The human ear is a complex sense organ that translates sound vibrations into nerve impulses that are sent to the brain for interpretation. The malleus, incus, and stapes are the three bones of the middle ear that sometimes are referred to as the hammer, anvil, and stirrup.

Perceiving Sound

Pitch Marin Mersenne and Galileo first determined that the **pitch** we hear depends on the frequency of vibration. Pitch can be given a name on the musical scale. For instance, the middle C note has a frequency of 262 Hz. The ear is not equally sensitive to all frequencies. Most people cannot hear sounds with frequencies below 20 Hz or above 16,000 Hz. Older people are less sensitive to frequencies above 10,000 Hz than are young people. By age 70, most people cannot hear sounds with frequencies above 8000 Hz. This loss affects the ability to understand speech.

Loudness Frequency and wavelength are two physical characteristics of sound waves. Another physical characteristic of sound waves is amplitude. Amplitude is the measure of the variation in pressure along a wave. In humans, sound is detected by the ear and interpreted by the brain. The **loudness** of a sound, as perceived by our sense of hearing, depends primarily on the amplitude of the pressure wave.

The human ear is extremely sensitive to pressure variations in sound waves, which is the amplitude of the wave. Recall from Chapter 13 that 1 atm of pressure equals 1.01×10^{5} Pa. The ear can detect pressure-wave amplitudes of less than one-billionth of an atmosphere, or 2×10^{-5} Pa. At the other end of the audible range, pressure variations of approximately 20 Pa or greater cause pain. It is important to remember that the ear detects only pressure variations at certain frequencies. Driving over a mountain pass changes the pressure on your ears by thousands of pascals, but this change does not take place at audible frequencies.

Because humans can detect a wide range in pressure variations, these amplitudes are measured on a logarithmic scale called the **sound level.** The unit of measurement for sound level is the **decibel** (dB). The sound level depends on the ratio of the pressure variation of a given sound wave to the pressure variation in the most faintly heard sound, 2×10^{-5} Pa. Such an amplitude has a sound level of 0 dB. A sound with a pressure amplitude ten times larger (2×10^{-4} Pa) is 20 dB. A pressure amplitude ten times larger than this is 40 dB. Most people perceive a 10-dB increase in sound level as about twice as loud as the original level. **Figure 15-4** shows the sound level for a variety of sounds. In addition to pressure variations, power and intensity of sound waves can be described by decibel scales.

Exposure to loud sounds, in the form of noise or music, has been shown to cause the ear to lose its sensitivity, especially to high frequencies. The longer a person is exposed to loud sounds, the greater the effect. A person can recover from short-term exposure in a period of hours, but the effects

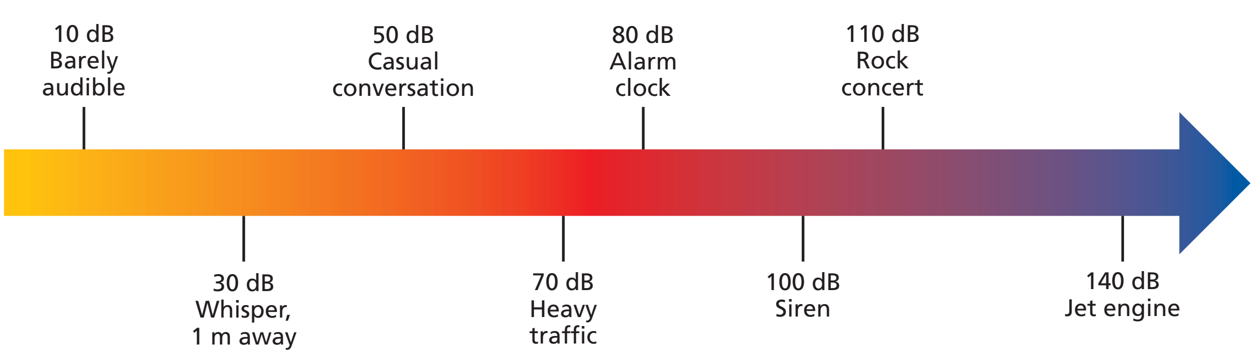


Figure 15-4 This decibel scale shows the sound levels of some familiar sounds.

of long-term exposure can last for days or weeks. Long exposure to 100-dB or greater sound levels can produce permanent damage. Many rock musicians have suffered serious hearing loss, some as much as 40 percent. Hearing loss also can result from loud music being transmitted to stereo headphones from personal radios and CD players. In some cases, the listeners are unaware of just how high the sound levels really are. Cotton earplugs reduce the sound level only by about 10 dB. Special ear inserts can provide a 25-dB reduction. Specifically designed earmuffs and inserts as shown in **Figure 15-5,** can reduce the sound level by up to 45 dB.

Loudness, as perceived by the human ear, is not directly proportional to the pressure variations in a sound wave. The ear's sensitivity depends on both pitch and amplitude. Also, perception of pure tones is different from perception of a mixture of tones.

Figure 15-5 Continuous exposure to loud sounds can cause serious hearing loss. In many occupations, workers, such as this flight controller, must wear ear protection.

The Doppler Effect

Have you ever noticed that the pitch of an ambulance, fire, or police siren changed as the vehicle sped past you? The pitch was higher when the vehicle was moving toward you, then it dropped to a lower pitch as the source moved away. This frequency shift is called the **Doppler effect** and is shown in **Figure 15-6.** The sound source, *S*, is moving to the right with a speed of v_s. The waves that it emits spread in circles centered on the source at the time it produced the waves. As the source moves toward the sound detector, Observer A in **Figure 15-6a,** more waves are crowded into the space between them. The wavelength is shortened to λ_A. Because the speed of sound is not changed, more crests reach the ear per second, which means that the frequency of the detected sound increases. When the source is moving away from the detector, Observer B in Figure 15-6a, the wavelength is lengthened to λ_B and the detected frequency is lower. **Figure 15-6b** illustrates the Doppler effect for a moving source of sound on water waves in a ripple tank.

A Doppler shift also occurs if the detector is moving and the source is stationary. In this case, the Doppler shift results from the relative velocity of the sound waves and the detector. As the detector approaches the stationary source, the relative velocity is larger, resulting in an increase in the wave crests reaching the detector each second. As the detector recedes from the source, the relative velocity is smaller, resulting in a decrease in the wave crests reaching the detector each second.

Figure 15-6 As a sound-producing source moves toward an observer, the wavelength is shortened to λ_A; the wavelength is λ_B for waves produced by a source moving away from an observer **(a).** A moving wave-producing source illustrates the Doppler effect in a ripple tank **(b).**

Concepts In Motion

Interactive Figure To see an animation on the Doppler effect, visit physicspp.com.

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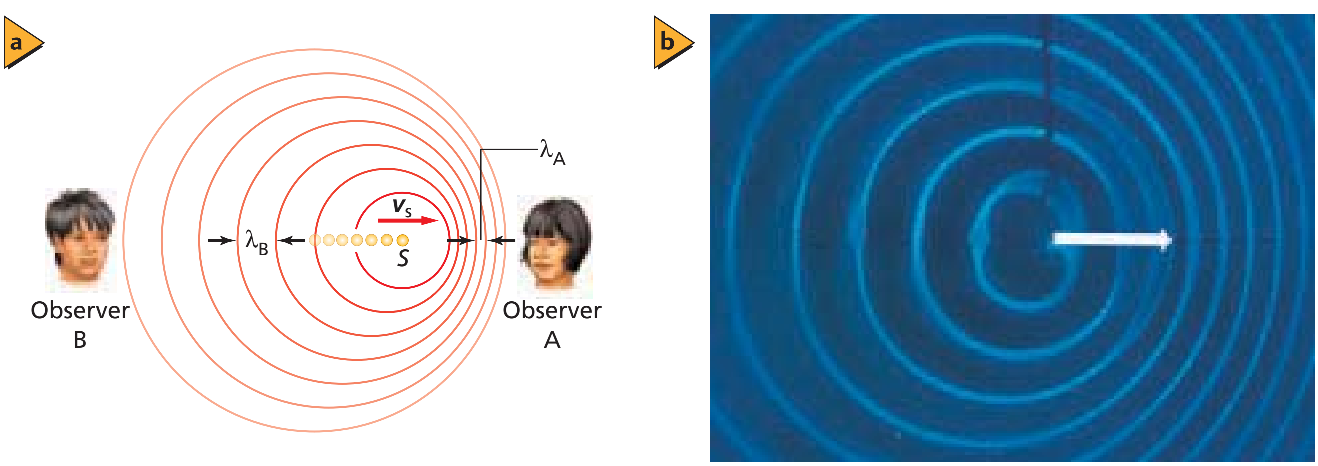

For both a moving source and a moving observer, the frequency that the observer hears can be calculated using the equation below.

Doppler Effect $f_d = f_s\left(\frac{v - v_d}{v - v_s}\right)$

The frequency perceived by a detector is equal to the velocity of the detector relative to the velocity of the wave, divided by the velocity of the source relative to the velocity of the wave, multiplied by the wave's frequency.

In the Doppler effect equation, v is the velocity of the sound wave, v_d is the velocity of the detector, v_s is the velocity of the sound's source, f_s is the frequency of the wave emitted by the source, and f_d is the frequency received by the detector. This equation applies when the source is moving, when the observer is moving, and when both are moving.

As you solve problems using the above equation, be sure to define the coordinate system so that the positive direction is from the source to the detector. The sound waves will be approaching the detector from the source, so the velocity of sound is always positive. Try drawing diagrams to confirm that the term $(v - v_d)/(v - v_s)$ behaves as you would predict based on what you have learned about the Doppler effect. Notice that for a source moving toward the detector (positive direction, which results in a smaller denominator compared to a stationary source) and for a detector moving toward the source (negative direction and increased numerator compared to a stationary detector), the detected frequency, f_d, increases. Similarly, if the source moves away from the detector or if the detector moves away from the source, then f_d decreases. Read the Connecting Math to Physics feature below to see how the Doppler effect equation reduces when the source or observer is stationary.

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Personal Tutor For an online tutorial on reducing equations, visit physicspp.com.

▶ Connecting **Math to Physics**

Reducing Equations When an element in a complex equation is equal to zero, the equation might reduce to a form that is easier to use.

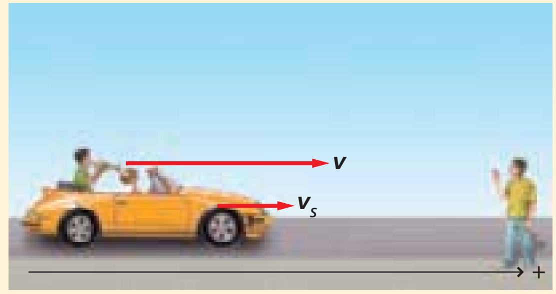
Stationary detector, source in motion: $v_d = 0$	Stationary source, detector in motion: $v_s = 0$
$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right)$	$f_d = f_s\left(\frac{v - v_d}{v - v_s}\right)$
$= f_s\left(\frac{v}{v - v_s}\right)$	$= f_s\left(\frac{v - v_d}{v}\right)$
$= f_s\left(\frac{\frac{v}{v}}{\frac{v}{v} - \frac{v_s}{v}}\right)$	$= f_s\left(\frac{\frac{v}{v} - \frac{v_d}{v}}{\frac{v}{v}}\right)$
$= f_s\left(\frac{1}{1 - \frac{v_s}{v}}\right)$	$= f_s\left(\frac{1 - \frac{v_d}{v}}{1}\right)$
	$= f_s\left(1 - \frac{v_d}{v}\right)$

EXAMPLE Problem 1

The Doppler Effect A trumpet player sounds C above middle C (524 Hz) while traveling in a convertible at 24.6 m/s. If the car is coming toward you, what frequency would you hear? Assume that the temperature is 20°C.

1 Analyze and Sketch the Problem

- Sketch the situation.
- Establish a coordinate axis. Make sure that the positive direction is from the source to the detector.
- Show the velocities of the source and detector.



Known:

$v = +343$ m/s

$v_s = +24.6$ m/s

$v_d = 0$ m/s

$f_s = 524$ Hz

Unknown:

$f_d = ?$

2 Solve for the Unknown

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Use $f_d = f_s\left(\frac{v - v_d}{v - v_s}\right)$ with $v_d = 0$ m/s.

$$f_d = f_s\left(\frac{1}{1 - \frac{v_s}{v}}\right)$$

$$= 524\ \text{Hz}\left(\frac{1}{1 - \frac{24.6\ \text{m/s}}{343\ \text{m/s}}}\right)$$

Substitute $v = +343$ m/s, $v_s = +24.6$ m/s, and $f_s = 524$ Hz

$$= 564\ \text{Hz}$$

3 Evaluate the Answer

- **Are the units correct?** Frequency is measured in hertz.
- **Is the magnitude realistic?** The source is moving toward you, so the frequency should be increased.

PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

6. Repeat Example Problem 1, but with the car moving away from you. What frequency would you hear?

7. You are in an auto traveling at 25.0 m/s toward a pole-mounted warning siren. If the siren's frequency is 365 Hz, what frequency do you hear? Use 343 m/s as the speed of sound.

8. You are in an auto traveling at 55 mph (24.6 m/s). A second auto is moving toward you at the same speed. Its horn is sounding at 475 Hz. What frequency do you hear? Use 343 m/s as the speed of sound.

9. A submarine is moving toward another submarine at 9.20 m/s. It emits a 3.50-MHz ultrasound. What frequency would the second sub, at rest, detect? The speed of sound in water is 1482 m/s.

10. A sound source plays middle C (262 Hz). How fast would the source have to go to raise the pitch to C sharp (271 Hz)? Use 343 m/s as the speed of sound.

Figure 15-7 In a process called echolocation, bats use the Doppler effect to locate prey.

Biology Connection

The Doppler effect occurs in all wave motion, both mechanical and electromagnetic. It has many applications. Radar detectors use the Doppler effect to measure the speed of baseballs and automobiles. Astronomers observe light from distant galaxies and use the Doppler effect to measure their speeds and infer their distances. Physicians can detect the speed of the moving heart wall in a fetus by means of the Doppler effect in ultrasound. Bats use the Doppler effect to detect and catch flying insects. When an insect is flying faster than a bat, the reflected frequency is lower, but when the bat is catching up to the insect, as in **Figure 15-7,** the reflected frequency is higher. Not only do bats use sound waves to navigate and locate their prey, but they often must do so in the presence of other bats. This means they must discriminate their own calls and reflections against a background of many other sounds of many frequencies. Scientists continue to study bats and their amazing abilities to use sound waves.

15.1 Section Review

11. Graph The eardrum moves back and forth in response to the pressure variations of a sound wave. Sketch a graph of the displacement of the eardrum versus time for two cycles of a 1.0-kHz tone and for two cycles of a 2.0-kHz tone.

12. Effect of Medium List two sound characteristics that are affected by the medium through which the sound passes and two characteristics that are not affected.

13. Sound Properties What physical characteristic of a sound wave should be changed to change the pitch of the sound? To change the loudness?

14. Decibel Scale How much greater is the sound pressure level of a typical rock band's music (110 dB) than a normal conversation (50 dB)?

15. Early Detection In the nineteenth century, people put their ears to a railroad track to get an early warning of an approaching train. Why did this work?

16. Bats A bat emits short pulses of high-frequency sound and detects the echoes.

a. In what way would the echoes from large and small insects compare if they were the same distance from the bat?

b. In what way would the echo from an insect flying toward the bat differ from that of an insect flying away from the bat?

17. Critical Thinking Can a trooper using a radar detector at the side of the road determine the speed of a car at the instant the car passes the trooper? Explain.

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15.2 The Physics of Music

In the middle of the nineteenth century, German physicist Hermann Helmholtz studied sound production in musical instruments and the human voice. In the twentieth century, scientists and engineers developed electronic equipment that permits not only a detailed study of sound, but also the creation of electronic musical instruments and recording devices that allow us to listen to music whenever and wherever we wish.

▶ **Objectives**

- **Describe** the origin of sound.
- **Demonstrate** an understanding of resonance, especially as applied to air columns and strings.
- **Explain** why there are variations in sound among instruments and among voices.

▶ **Vocabulary**

closed-pipe resonator
open-pipe resonator
fundamental
harmonics
dissonance
consonance
beat

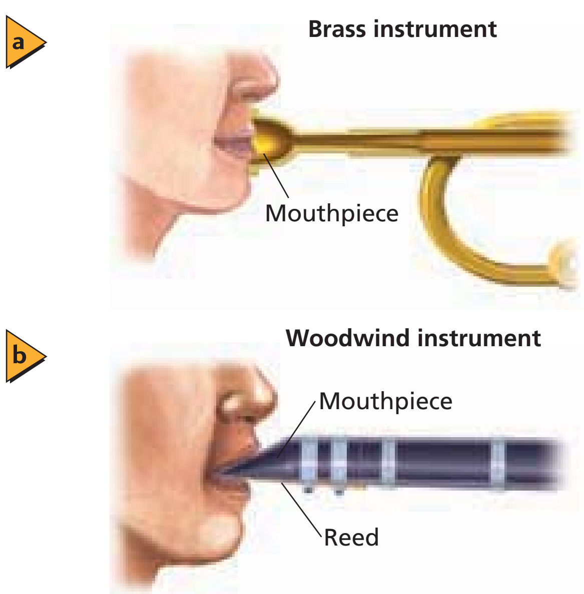
Sources of Sound

Sound is produced by a vibrating object. The vibrations of the object create particle motions that cause pressure oscillations in the air. A loudspeaker has a cone that is made to vibrate by electrical currents. The surface of the cone creates the sound waves that travel to your ear and allow you to hear music. Musical instruments such as gongs, cymbals, and drums are other examples of vibrating surfaces that are sources of sound.

The human voice is produced by vibrations of the vocal cords, which are two membranes located in the throat. Air from the lungs rushing through the throat starts the vocal cords vibrating. The frequency of vibration is controlled by the muscular tension placed on the vocal cords.

In brass instruments, such as the trumpet and tuba, the lips of the performer vibrate, as shown in **Figure 15-8a.** Reed instruments, such as the clarinet and saxophone, have a thin wooden strip, or reed, that vibrates as a result of air blown across it, as shown in **Figure 15-8b.** In flutes and organ pipes, air is forced across an opening in a pipe. Air moving past the opening sets the column of air in the instrument into vibration.

In stringed instruments, such as the piano, guitar, and violin, wires or strings are set into vibration. In the piano, the wires are struck; in the guitar, they are plucked; and in the violin, the friction of the bow causes the strings to vibrate. Often, the strings are attached to a sounding board that vibrates with the strings. The vibrations of the sounding board cause the pressure oscillations in the air that we hear as sound. Electric guitars use electronic devices to detect and amplify the vibrations of the guitar strings.



■ **Figure 15-8** The shapes of the mouthpieces of a brass instrument **(a)** and a reed instrument **(b)** help determine the characteristics of the sound each instrument produces.

Resonance in Air Columns

If you have ever used just the mouthpiece of a brass or reed instrument, you know that the vibration of your lips or the reed alone does not make a sound with any particular pitch. The long tube that makes up the instrument must be attached if music is to result. When the instrument is played, the air within this tube vibrates at the same frequency, or in resonance, with a particular vibration of the lips or reed. Remember that resonance increases the amplitude of a vibration by repeatedly applying a small external force at the same natural frequency. The length of the air column determines the frequencies of the vibrating air that will be set into resonance. For many instruments, such as flutes, saxophones, and trombones, changing the length of the column of vibrating air varies the pitch of the instrument. The mouthpiece simply creates a mixture of different frequencies, and the resonating air column acts on a particular set of frequencies to amplify a single note, turning noise into music.

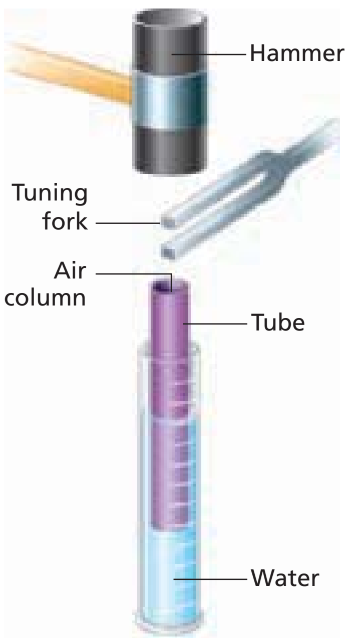


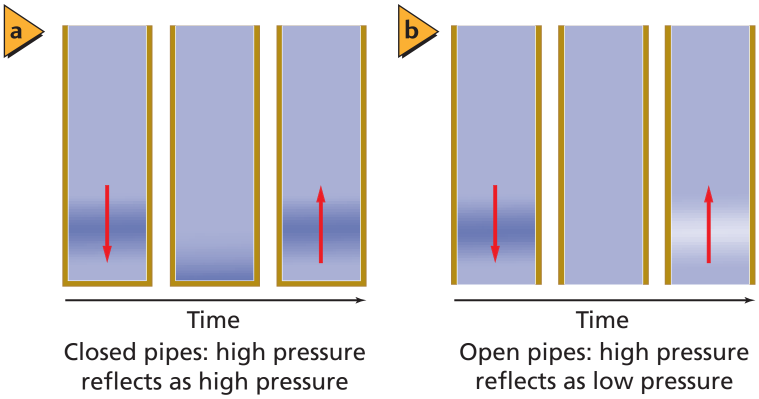
Figure 15-9 Raising or lowering the tube changes the length of the air column. When the column is in resonance with the tuning fork, the sound is loudest.

A tuning fork above a hollow tube can provide resonance in an air column, as shown in **Figure 15-9.** The tube is placed in water so that the bottom end of the tube is below the water surface. A resonating tube with one end closed to air is called a **closed-pipe resonator.** The length of the air column is changed by adjusting the height of the tube above the water. If the tuning fork is struck with a rubber hammer and the length of the air column is varied as the tube is lifted up and down in the water, the sound alternately becomes louder and softer. The sound is loud when the air column is in resonance with the tuning fork. A resonating air column intensifies the sound of the tuning fork.

Standing pressure wave How does resonance occur? The vibrating tuning fork produces a sound wave. This wave of alternate high- and low-pressure variations moves down the air column. When the wave hits the water surface, it is reflected back up to the tuning fork, as indicated in **Figure 15-10a.** If the reflected high-pressure wave reaches the tuning fork at the same moment that the fork produces another high-pressure wave, then the emitted and returning waves reinforce each other. This reinforcement of waves produces a standing wave, and resonance is achieved.

An **open-pipe resonator** is a resonating tube with both ends open that also will resonate with a sound source. In this case, the sound wave does not reflect off a closed end, but rather off an open end. The pressure of the reflected wave is inverted; for example, if a high-pressure wave strikes the open end, a low-pressure wave will rebound, as shown in **Figure 15-10b.**

Figure 15-10 A tube placed in water is a closed-pipe resonator. In closed pipes, high pressure waves reflect as high pressure **(a).** In open pipes, the reflected waves are inverted **(b).**



Resonance lengths A standing sound wave in a pipe can be represented by a sine wave, as shown in **Figure 15-11.** Sine waves can represent either the air pressure or the displacement of the air particles. You can see that standing waves have nodes and antinodes. In the pressure graphs, the nodes are regions of mean atmospheric pressure, and at the antinodes, the pressure oscillates between its maximum and minimum values.

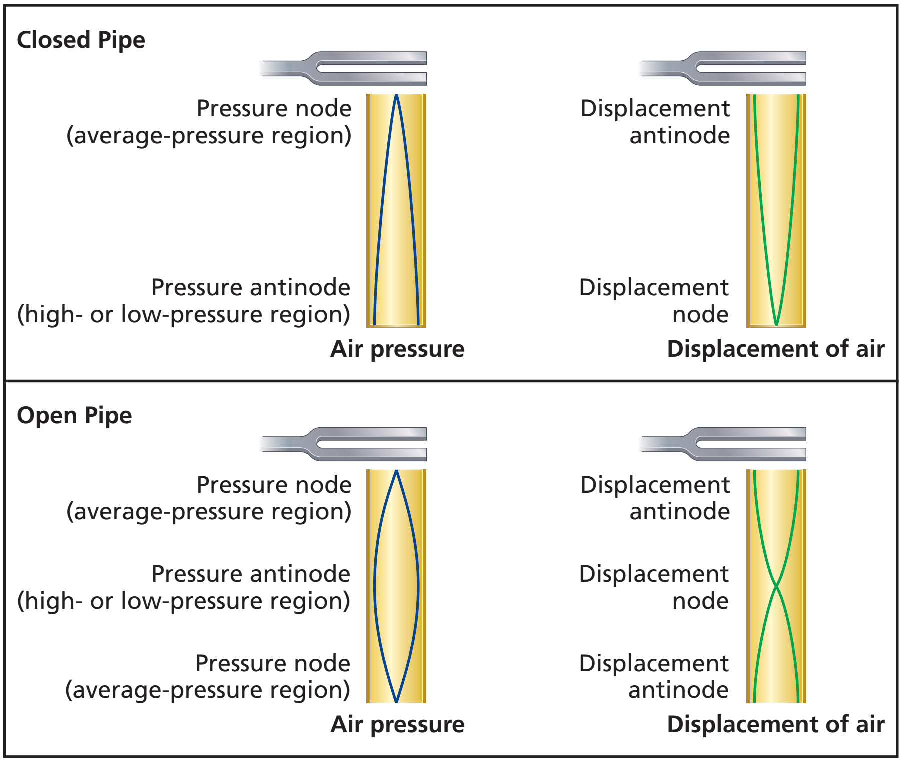


Figure 15-11 Sine waves represent standing waves in pipes.

Concepts In Motion

Interactive Figure To see an animation of resonance in closed and open pipes, visit physicspp.com.

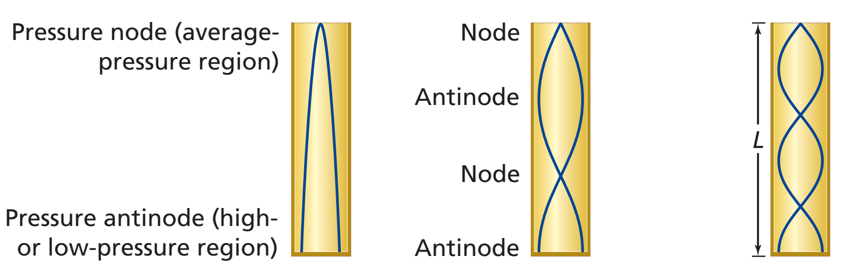
In the case of the displacement graph, the antinodes are regions of high displacement and the nodes are regions of low displacement. In both cases, two antinodes (or two nodes) are separated by one-half wavelength.

Resonance frequencies in a closed pipe The shortest column of air that can have an antinode at the closed end and a node at the open end is one-fourth of a wavelength long, as shown in **Figure 15-12.** As the frequency is increased, additional resonance lengths are found at half-wavelength intervals. Thus, columns of length $\lambda/4$, $3\lambda/4$, $5\lambda/4$, $7\lambda/4$, and so on will all be in resonance with a tuning fork.

In practice, the first resonance length is slightly longer than one-fourth of a wavelength. This is because the pressure variations do not drop to zero exactly at the open end of the pipe. Actually, the node is approximately 0.4 pipe diameters beyond the end. Additional resonance lengths, however, are spaced by exactly one-half of a wavelength. Measurements of the spacing between resonances can be used to find the velocity of sound in air, as shown in the next Example Problem.

APPLYING PHYSICS

Hearing and Frequency The human auditory canal acts as a closed-pipe resonator that increases the ear's sensitivity for frequencies between 2000 and 5000 Hz, but the full range of frequencies that people hear extends from 20 to 20,000 Hz. A dog's hearing extends to frequencies as high as 45,000 Hz, and a cat's extends to frequencies as high as 100,000 Hz.



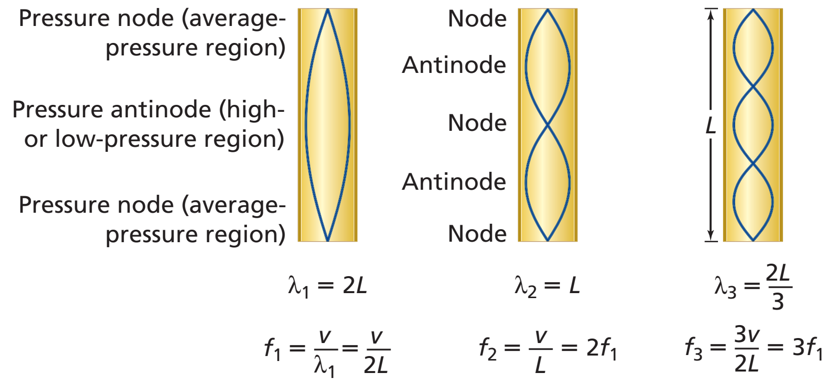
$\lambda_1 = 4L$ $\qquad$ $\lambda_3 = \frac{4}{3}L$ $\qquad$ $\lambda_5 = \frac{4}{5}L$

$f_1 = \frac{v}{\lambda_1} = \frac{v}{4L}$ $\qquad$ $f_3 = \frac{3v}{4L} = 3f_1$ $\qquad$ $f_5 = \frac{5v}{4L} = 5f_1$

CLICK HERE

Figure 15-12 A closed pipe resonates when its length is an odd number of quarter wavelengths.

■ **Figure 15-13** An open pipe resonates when its length is an even number of quarter wavelengths.



Resonance frequencies in an open pipe The shortest column of air that can have nodes at both ends is one-half of a wavelength long, as shown in **Figure 15-13.** As the frequency is increased, additional resonance lengths are found at half-wavelength intervals. Thus, columns of length $\lambda/2$, λ, $3\lambda/2$, 2λ, and so on will be in resonance with a tuning fork.

If open and closed pipes of the same length are used as resonators, the wavelength of the resonant sound for the open pipe will be half as long as that for the closed pipe. Therefore, the frequency will be twice as high for the open pipe as for the closed pipe. For both pipes, resonance lengths are spaced by half-wavelength intervals.

Hearing resonance Musical instruments use resonance to increase the loudness of particular notes. Open-pipe resonators include flutes and saxophones. Clarinets and the hanging pipes under marimbas and xylophones are examples of closed-pipe resonators. If you shout into a long tunnel, the booming sound you hear is the tunnel acting as a resonator. The seashell in **Figure 15-14** acts as a closed-pipe resonator.

Resonance on Strings

Although the waveforms on vibrating strings vary in shape, depending upon how they are produced, such as by plucking, bowing, or striking, they have many characteristics in common with standing waves on springs and ropes, which you studied in Chapter 14. A string on an instrument is clamped at both ends, and therefore, the string must have a node at each end when it vibrates. In **Figure 15-15,** you can see that the first mode of vibration has an antinode at the center and is one-half of a wavelength long. The next resonance occurs when one wavelength fits on the string, and additional standing waves arise when the string length is $3\lambda/2$, 2λ, $5\lambda/2$, and so on. As with an open pipe, the resonant frequencies are whole-number multiples of the lowest frequency.

The speed of a wave on a string depends on the tension of the string, as well as its mass per unit length. This makes it possible to tune a stringed instrument by changing the tension of its strings. The tighter the string, the faster the wave moves along it, and therefore, the higher the frequency of its standing waves.

■ **Figure 15-14** A seashell acts as a closed-pipe resonator to amplify certain frequencies from the background noise.

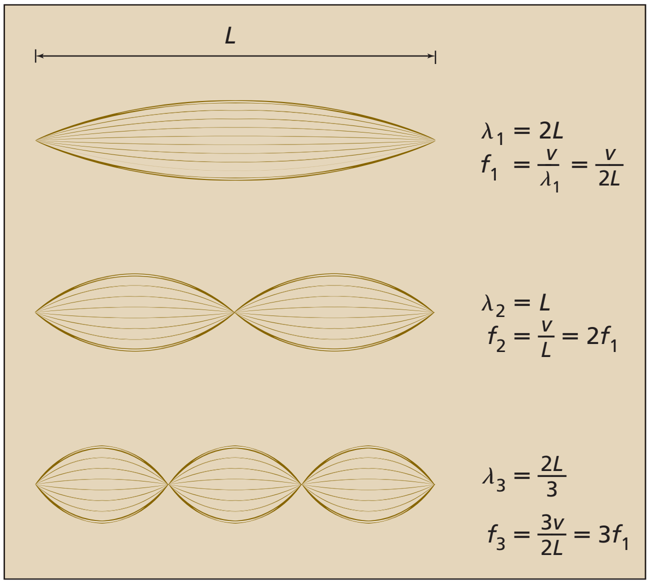


Figure 15-15 A string resonates with standing waves when its length is a whole number of half wavelengths.

Because strings are so small in cross-sectional area, they move very little air when they vibrate. This makes it necessary to attach them to a sounding board, which transfers their vibrations to the air and produces a stronger sound wave. Unlike the strings themselves, the sounding board should not resonate at any single frequency. Its purpose is to convey the vibrations of all the strings to the air, and therefore it should vibrate well at all frequencies produced by the instrument. Because of the complicated interactions among the strings, the sounding board, and the air, the design and construction of stringed instruments are complex processes, considered by many to be as much an art as a science.

Sound Quality

A tuning fork produces a soft and uninteresting sound. This is because its tines vibrate like simple harmonic oscillators and produce the simple sine wave shown in **Figure 15-16a.** Sounds made by the human voice and musical instruments are much more complex, like the wave in **Figure 15-16b.** Both waves have the same frequency, or pitch, but they sound very different. The complex wave is produced by using the principle of superposition to add waves of many frequencies. The shape of the wave depends on the relative amplitudes of these frequencies. In musical terms, the difference between the two waves is called timbre, tone color, or tone quality.

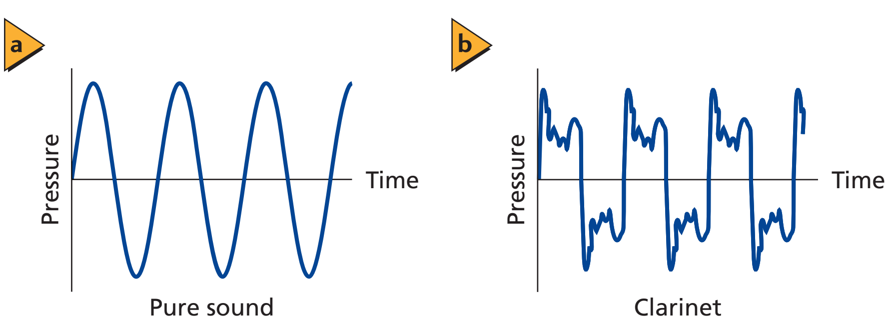


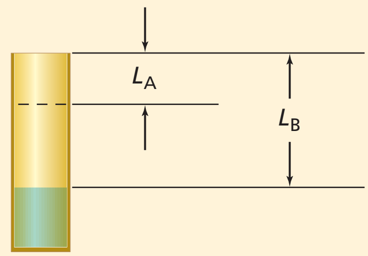
Figure 15-16 A graph of pure sound versus time **(a)** and a graph of clarinet sound waves versus time **(b)** are shown.

EXAMPLE Problem 2

Finding the Speed of Sound Using Resonance When a tuning fork with a frequency of 392 Hz is used with a closed-pipe resonator, the loudest sound is heard when the column is 21.0 cm and 65.3 cm long. What is the speed of sound in this case? Is the temperature warmer or cooler than normal room temperature, which is 20°C? Explain your answer.

1 Analyze and Sketch the Problem

- Sketch the closed-pipe resonator.
- Mark the resonance lengths.



Known:	Unknown:
$f = 392$ Hz	$v = ?$
$L_A = 21.0$ cm	
$L_B = 65.3$ cm	

2 Solve for the Unknown

Math Handbook
Order of Operations
page 843

Solve for the length of the wave using the length-wavelength relationship for a closed pipe.

$$L_B - L_A = \frac{1}{2}\lambda$$

$$\lambda = 2(L_B - L_A)$$ Rearrange the equation for λ.

$$= 2(0.653 \text{ m} - 0.210 \text{ m})$$ Substitute $L_B = 0.653$ m, $L_A = 0.210$ m

$$= 0.886 \text{ m}$$

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

$$v = f\lambda$$ Rearrange the equation for v.

$$= (392 \text{ Hz})(0.886 \text{ m})$$ Substitute $f = 392$ Hz, $\lambda = 0.886$ m

$$= 347 \text{ m/s}$$

The speed is slightly greater than the speed of sound at 20°C, indicating that the temperature is slightly higher than normal room temperature.

3 Evaluate the Answer

- **Are the units correct?** (Hz)(m) = (1/s)(m) = m/s. The answer's units are correct.
- **Is the magnitude realistic?** The speed is slightly greater than 343 m/s, which is the speed of sound at 20°C.

PRACTICE Problems

• Additional Problems, Appendix B
• Solutions to Selected Problems, Appendix C

18. A 440-Hz tuning fork is held above a closed pipe. Find the spacing between the resonances when the air temperature is 20°C.

19. A 440-Hz tuning fork is used with a resonating column to determine the velocity of sound in helium gas. If the spacings between resonances are 110 cm, what is the velocity of sound in helium gas?

20. The frequency of a tuning fork is unknown. A student uses an air column at 27°C and finds resonances spaced by 20.2 cm. What is the frequency of the tuning fork? Use the speed calculated in Example Problem 2 for the speed of sound in air at 27°C.

21. A bugle can be thought of as an open pipe. If a bugle were straightened out, it would be 2.65-m long.

a. If the speed of sound is 343 m/s, find the lowest frequency that is resonant for a bugle (ignoring end corrections).

b. Find the next two resonant frequencies for the bugle.

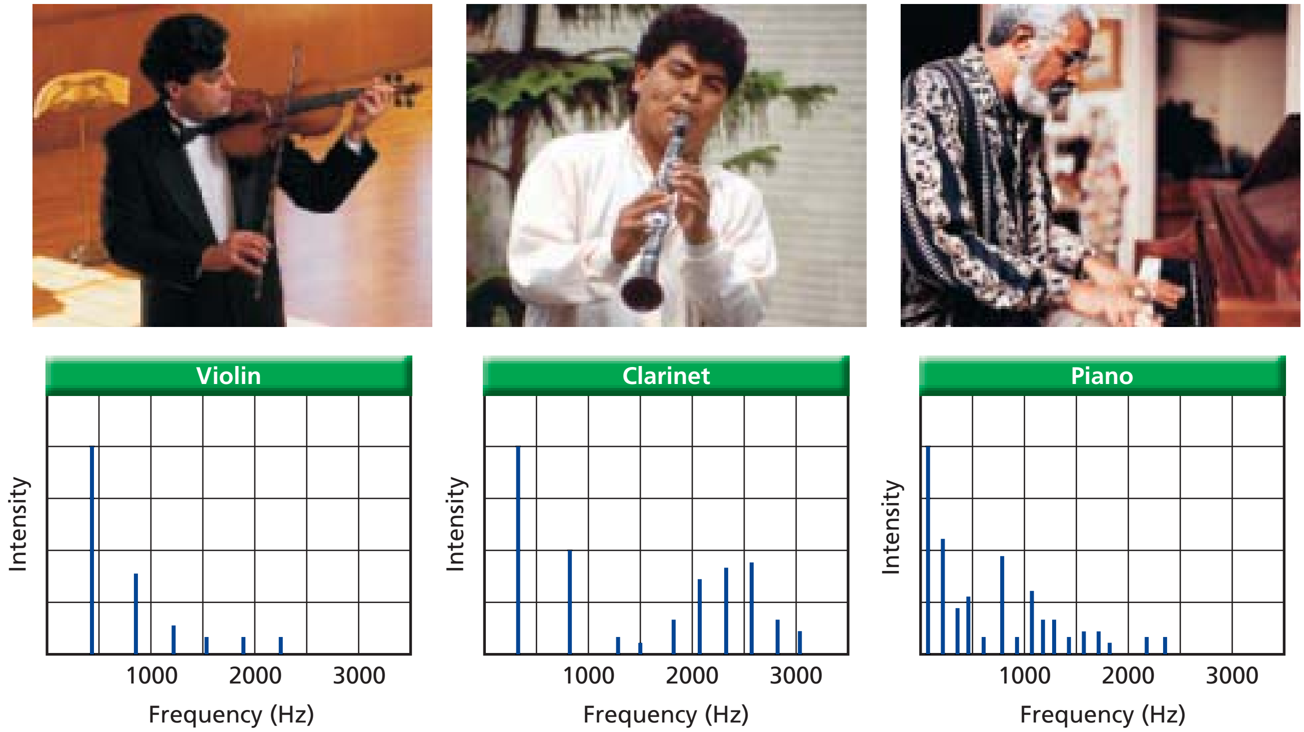


Figure 15-17 A violin, a clarinet, and a piano produce characteristic sound spectra. Each spectrum is unique, as is the timbre of the instrument.

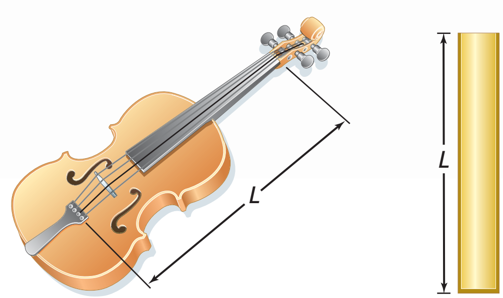
The sound spectrum: fundamental and harmonics The complex sound wave in Figure 15-16b was made by a clarinet. Why does the clarinet produce such a sound wave? The air column in a clarinet acts as a closed pipe. Look back at Figure 15-12, which shows three resonant frequencies for a closed pipe. Because the clarinet acts as a closed pipe, for a clarinet of length L the lowest frequency, f_1, that will be resonant is $v/4L$. This lowest frequency is called the **fundamental.** A closed pipe also will resonate at $3f_1$, $5f_1$, and so on. These higher frequencies, which are odd-number multiples of the fundamental frequency, are called **harmonics.** It is the addition of these harmonics that gives a clarinet its distinctive timbre.

Some instruments, such as an oboe, act as open-pipe resonators. Their fundamental frequency, which is also the first harmonic, is $f_1 = v/2L$ with subsequent harmonics at $2f_1$, $3f_1$, $4f_1$, and so on. Different combinations and amplitudes of these harmonics give each instrument its own unique timbre. A graph of the amplitude of a wave versus its frequency is called a sound spectrum. The spectra of three instruments are shown in **Figure 15-17.**

CHALLENGE PROBLEM

1. Determine the tension, F_T, in a violin string of mass m and length L that will play the fundamental note at the same frequency as a closed pipe also of length L. Express your answer in terms of m, L, and the speed of sound in air, v. The equation for the speed of a wave on a string is $u = \sqrt{\frac{F_T}{\mu}}$, where F_T is the tension in the string and μ is the mass per unit length of the string.

2. What is the tension in a string of mass 1.0 g and 40.0 cm long that plays the same note as a closed pipe of the same length?



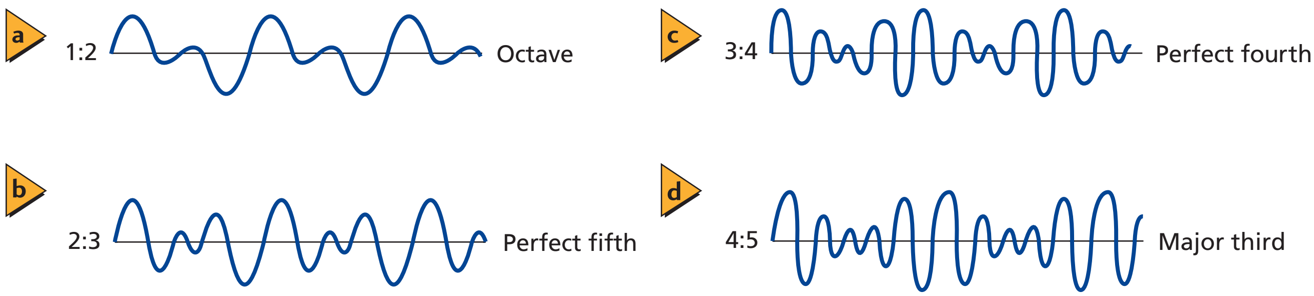


Figure 15-18 These time graphs show the superposition of two waves having the ratios of 1:2, 2:3, 3:4, and 4:5.

Consonance and dissonance When sounds that have two different pitches are played at the same time, the resulting sound can be either pleasant or jarring. In musical terms, several pitches played together are called a chord. An unpleasant set of pitches is called **dissonance.** If the combination is pleasant, the sounds are said to be in **consonance.**

What makes a sound pleasant to listen to? Different cultures have different definitions, but most Western cultures accept the definitions of Pythagoras, who lived in ancient Greece. Pythagoras experimented by plucking two strings at the same time. He noted that pleasing sounds resulted when the strings had lengths in small, whole-number ratios, for example 1:2, 2:3, or 3:4. This means that their pitches (frequencies) will also have small, whole-number ratios.

Musical intervals Two notes with frequencies related by the ratio 1:2 are said to differ by an octave. For example, if a note has a frequency of 440 Hz, a note that is one octave higher has a frequency of 880 Hz. The fundamental and its harmonics are related by octaves; the first harmonic is one octave higher than the fundamental, the second is two octaves higher, and so on. The sum of the fundamental and the first harmonic is shown in **Figure 15-18a.** It is the ratio of two frequencies, not the size of the interval between them, that determines the musical interval.

In other musical intervals, two pitches may be close together. For example, the ratio of frequencies for a "major third" is 4:5. A typical major third is made up of the notes C and E. The note C has a frequency of 262 Hz, so E has a frequency of (5/4)(262 Hz) = 327 Hz. In the same way, notes in a "fourth" (C and F) have a frequency ratio of 3:4, and those in a "fifth" (C and G) have a ratio of 2:3. Graphs of these pleasant sounds are shown in Figure 15-18. More than two notes sounded together also can produce consonance. The three notes called do, mi, and sol make a major chord. For at least 2500 years, this has been recognized as the sweetest of the three-note chords; it has the frequency ratio of 4:5:6.

Beats

You have seen that consonance is defined in terms of the ratio of frequencies. When the ratio becomes nearly 1:1, the frequencies become very close. Two frequencies that are nearly identical interfere to produce high and low sound levels, as illustrated in **Figure 15-19.** This oscillation of wave amplitude is called a **beat.** The frequency of a beat is the magnitude of difference between the frequencies of the two waves, $f_{beat} = |f_A - f_B|$. When the difference is less than 7 Hz, the ear detects this as a pulsation of loudness. Musical instruments often are tuned by sounding one against another and adjusting the frequency of one until the beat disappears.

MINI LAB

Sounds Good

Sometimes it can be pretty tough to tell just by looking whether an instrument will act as an open-pipe resonator or as a closed-pipe resonator. Ask a musician who plays a wind instrument to bring it to class.

1. Measure the length of the instrument.

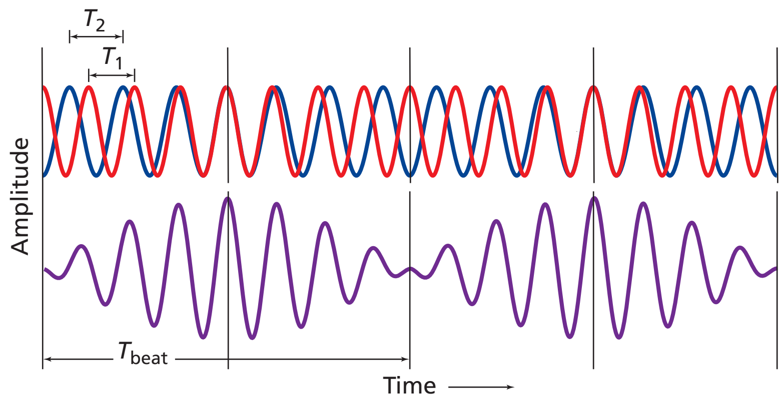
2. Have the musician play the lowest possible note on the instrument.

3. Determine the frequency of the note using a frequency generator.

Analyze and Conclude

4. Draw Conclusions Did the tested instrument behave most like a closed-pipe resonator or most like an open-pipe resonator? Was the frequency the fundamental or one of the subsequent harmonics?

5. Determine the frequencies of the notes that would form an octave, a perfect fifth, a perfect fourth, and a major third with your observed note.

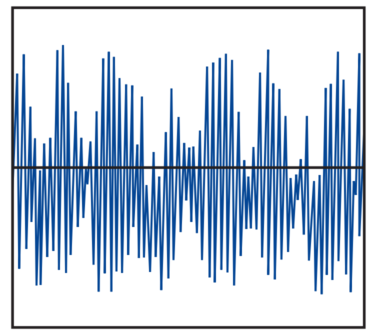


■ **Figure 15-19** Beats occur as a result of the superposition of two sound waves of slightly different frequencies.

Sound Reproduction and Noise

How often do you listen to music produced directly by a human voice or musical instrument? Most of the time, the music has been recorded and played through electronic systems. To reproduce the sound faithfully, the system must accommodate all frequencies equally. A good stereo system keeps the amplitudes of all frequencies between 20 and 20,000 Hz the same to within 3 dB.

A telephone system, on the other hand, needs only to transmit the information in spoken language. Frequencies between 300 and 3000 Hz are sufficient. Reducing the number of frequencies present helps reduce the noise. A noise wave is shown in **Figure 15-20.** Many frequencies are present with approximately the same amplitude. While noise is not helpful in a telephone system, some people claim that listening to noise has a calming effect. For this reason, some dentists use noise to help their patients relax.



■ **Figure 15-20** Noise is composed of several frequencies and involves random changes in frequency and amplitude.

15.2 Section Review

22. Origins of Sound What is the vibrating object that produces sounds in each of the following?

a. a human voice

b. a clarinet

c. a tuba

d. a violin

23. Resonance in Air Columns Why is the tube from which a tuba is made much longer than that of a cornet?

24. Resonance in Open Tubes How must the length of an open tube compare to the wavelength of the sound to produce the strongest resonance?

25. Resonance on Strings A violin sounds a note of F sharp, with a pitch of 370 Hz. What are the frequencies of the next three harmonics produced with this note?

26. Resonance in Closed Pipes One closed organ pipe has a length of 2.40 m.

a. What is the frequency of the note played by this pipe?

b. When a second pipe is played at the same time, a 1.40-Hz beat note is heard. By how much is the second pipe too long?

27. Timbre Why do various instruments sound different even when they play the same note?

28. Beats A tuning fork produces three beats per second with a second, 392-Hz tuning fork. What is the frequency of the first tuning fork?

29. Critical Thinking Strike a tuning fork with a rubber hammer and hold it at arm's length. Then press its handle against a desk, a door, a filing cabinet, and other objects. What do you hear? Why?

PHYSICS LAB

Speed of Sound

Alternate CBL instructions can be found on the Web site.
physicspp.com

If a vibrating tuning fork is held above a closed pipe of the proper length, the air in the pipe will vibrate at the same frequency, f, as the tuning fork. By placing a glass tube in a large, water-filled graduated cylinder, the length of the glass tube can be changed by raising or lowering it in the water. The shortest column of air that will resonate occurs when the tube is one-fourth of a wavelength long. This resonance will produce the loudest sound, and the wavelength at this resonance is described by $\lambda = 4L$, where L is the length from the water to the open end of the pipe. In this lab, you will determine L, calculate λ, and calculate the speed of sound.

Horizons Companies

QUESTION

How can you use a closed-pipe resonator to determine the speed of sound?

Objectives

- **Collect and organize data** to obtain resonant points in a closed pipe.
- **Measure** the length of a closed-pipe resonator.
- **Analyze** the data to determine the speed of sound.

Safety Precautions

- **Immediately wipe up any spilled liquids.**
- **Glass is fragile. Handle with care.**

Materials

three tuning forks of known frequencies
graduated cylinder (1000-mL)
water
tuning fork mallet
metric ruler
thermometer (non-mercury)
glass tube (approximately 40 cm in length and 3.5 cm in diameter)

Procedure

1. Put on your safety goggles. Fill the graduated cylinder nearly to the top with water.
2. Measure the room air temperature and record it in Data Table 1.
3. Select a tuning fork and record its frequency in Data Tables 2 and 3.
4. Measure and record the diameter of the glass tube in Data Table 2.
5. Carefully place the glass tube into the water-filled graduated cylinder.
6. Hold the tuning fork by the base. Swiftly strike it on the side with the tuning fork mallet. Do not strike the tuning fork on the laboratory table or other hard surface.
7. Hold the vibrating fork over the open end of the glass tube and slowly raise the tube and the fork until the loudest sound is heard. Once this point is located, move the tube up and down slightly to determine the exact point of resonance. Measure the distance from the water to the top of the glass tube and record this distance in Data Table 2.
8. Repeat steps 3, 6, and 7 for two additional tuning forks and record your results as trials 2 and 3. The three tuning forks that you test should resonate at three different frequencies.
9. Empty the water from the graduated cylinder.

Data Table 1

Trial	Temperature (°C)	Accepted Speed of Sound (m/s)	Experimental Speed of Sound (m/s)
1			
2			
3			

Data Table 2

Trial	Tuning Fork Frequency (Hz)	Diameter (m)	Length of Tube Above Water (m)	Calculated Wavelength (m)
1				
2				
3				

Data Table 3

Trial	Tuning Fork Frequency (Hz)	Accepted Speed of Sound (m/s)	Corrected Calculated Wavelength (m)	Corrected Experimental Speed of Sound (m/s)
1				
2				
3				

Analyze

1. Calculate the accepted speed of sound using the relationship $v = 331 \text{ m/s} + 0.60T$, where v is the speed of sound at temperature T, and T is the air temperature in degrees Celsius. Record this as the accepted speed of sound in Data Tables 1 and 3 for all the trials.
2. Since the first resonant point is located when the tube is one-fourth of a wavelength above the water, use the measured length of the tube to determine the calculated wavelength for each trial. Record the calculated wavelengths in Data Table 2.
3. Multiply the values in Data Table 2 of wavelength and frequency to determine the experimental speed of sound and record this in Data Table 1 for each of the trials.
4. **Error Analysis** For each trial in Data Table 1, determine the relative error between the experimental and accepted speed of sound.

   Relative error =
   $$\frac{|\text{Accepted value} - \text{Experimental value}|}{\text{Accepted value}} \times 100$$
5. **Critique** To improve the accuracy of your calculations, the tube diameter must be taken into consideration. The following relationship provides a more accurate calculation of wavelength: $\lambda = 4(L + 0.4d)$, where λ is the wavelength, L is the length of the tube above the water, and d is the inside diameter of the tube. Using the values in Data Table 1 for length and diameter, recalculate λ and record it in Data Table 3 as the corrected wavelength. Calculate the corrected experimental speed of sound by multiplying the tuning fork frequency and corrected wavelength and record the new value for the corrected experimental speed of sound in Data Table 3.
6. **Error Analysis** For each trial in Data Table 3, determine the relative error between the corrected experimental speed and the accepted speed of sound. Use the same formula that you used in step 4, above.

Conclude and Apply

1. **Infer** In general, the first resonant point occurs when the tube length = $\lambda/4$. What are the next two lengths where resonance will occur?
2. **Think Critically** If you had a longer tube, would it be possible to locate another position where resonance occurs? Explain your answer.

Going Further

Which result produced the more accurate speed of sound?

Real-World Physics

Explain the relationship between the size of organ pipes and their resonant frequencies.

Physics Online

To find out more about the properties of sound waves, visit the Web site: **physicspp.com**

eXtreme physics

Sound Waves in the Sun

The study of wave oscillations in the Sun is called helioseismology. Naturally occurring sound waves (p waves), gravity waves, and surface gravity waves all occur in the Sun. All of these waves are composed of oscillating particles, but different forces cause the oscillations.

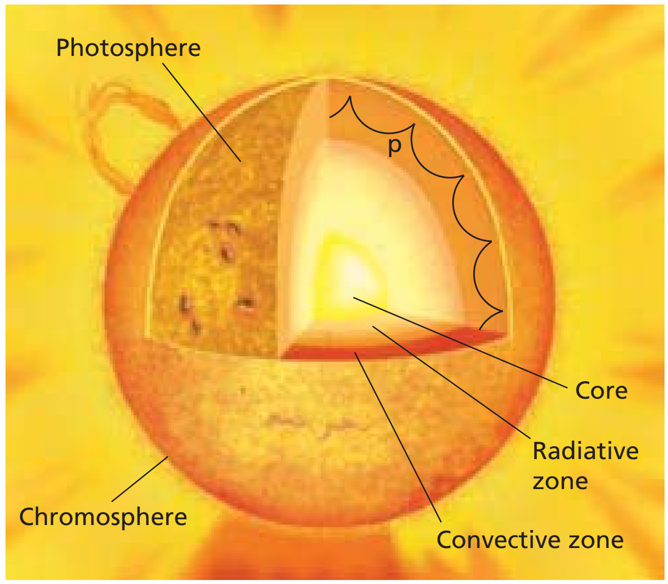
For sound waves, pressure differences cause the particles to oscillate. In the Sun, sound waves travel through the convective zone, which is just under the surface, or photosphere. The sound waves do not travel in a straight line, as shown in the image.

Ringing like a Bell The sound waves in the Sun cause the surface of the Sun to vibrate in the radial direction, much like a ringing bell vibrates. When a bell is rung, a clapper hits the bell in one place and standing waves are created. The surface of the Sun does have standing waves, but they are not caused by one large event. Instead, scientists hypothesize that many smaller disruptions in the convective zone start most of the sound waves in the Sun. Just like boiling water in a pot can be noisy, bubbles that are larger than the state of Texas form on the surface of the Sun and start sound waves.

Unlike a pot of boiling water, the sound coming from the Sun is much too low for us to hear. The A above middle C on the piano has a period of 0.00227 s (f = 440 Hz). The middle mode of oscillation of the waves in the Sun has a period of 5 min (f = 0.003 Hz).

Because we cannot hear the sound waves from the Sun, scientists measure the motion of the surface of the Sun to learn about its sound waves. Because a sound wave takes 2 h to travel from one side of the Sun to the other, the Sun must be observed for long time periods. This necessity makes observations from Earth difficult because the Sun is not visible during the night. In 1995, the *Solar and Heliospheric Observatory* (SOHO) was launched by NASA. This satellite orbits Earth such that it always can observe the Sun.

The motion of the surface of the Sun is measured by observing Doppler shifts in sunlight. The measured vibrations are a complicated pattern that equals the sum of all of the standing waves present in the Sun. Just like a ringing bell, many overtones are present in the Sun. Through careful analysis, the individual standing waves in the Sun and their intensities can be calculated.



Sound waves (p waves) travel through the Sun's convective zone.

Results Because composition, temperature, and density affect the propagation of sound waves, the Sun's wave oscillations provide information about its interior. SOHO results have given insight into the rotation rate of the Sun as a function of latitude and depth, as well as the density and temperature of the Sun. These results are compared to theoretical calculations to improve our understanding of the Sun.

Going Further

1. **Hypothesize** How do scientists separate the surface motion due to sound waves from the motion due to the rotation of the Sun?
2. **Critical Thinking** Would sound waves in another star, similar to the Sun but different in size, have the same wavelength as sound waves in the Sun?

Chapter 15

Study Guide

15.1 Properties and Detection of Sound

Vocabulary

- sound wave (p. 404)
- pitch (p. 406)
- loudness (p. 406)
- sound level (p. 406)
- decibel (p. 406)
- Doppler effect (p. 407)

Key Concepts

- Sound is a pressure variation transmitted through matter as a longitudinal wave.
- A sound wave has frequency, wavelength, speed, and amplitude. Sound waves reflect and interfere.
- The speed of sound in air at room temperature (20°C) is 343 m/s. The speed increases roughly 0.6 m/s with each 1°C increase in temperature.
- Sound detectors convert the energy carried by a sound wave into another form of energy. The human ear is a highly efficient and sensitive detector of sound waves.
- The frequency of a sound wave is heard as its pitch.
- The pressure amplitude of a sound wave can be measured in decibels (dB).
- The loudness of sound as perceived by the ear and brain depends mainly on its amplitude.
- The Doppler effect is the change in frequency of sound caused by the motion of either the source or the detector. It can be calculated with the following equation.

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

15.2 The Physics of Music

Vocabulary

- closed-pipe resonator (p. 412)
- open-pipe resonator (p. 412)
- fundamental (p. 417)
- harmonics (p. 417)
- dissonance (p. 418)
- consonance (p. 418)
- beat (p. 418)

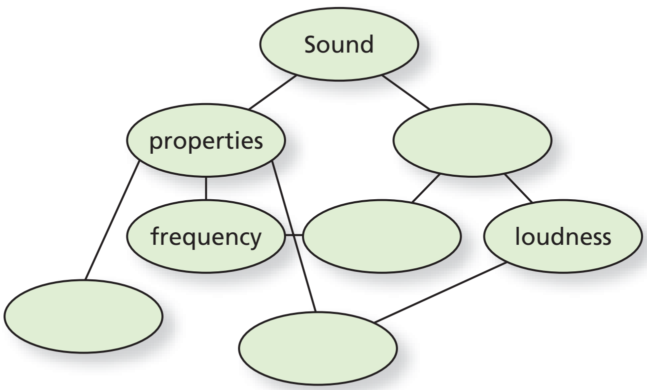
Key Concepts

- Sound is produced by a vibrating object in a material medium.
- Most sounds are complex waves that are composed of more than one frequency.
- An air column can resonate with a sound source, thereby increasing the amplitude of its resonant frequency.
- A closed pipe resonates when its length is $\lambda/4$, $3\lambda/4$, $5\lambda/4$, and so on. Its resonant frequencies are odd-numbered multiples of the fundamental.
- An open pipe resonates when its length is $\lambda/2$, $2\lambda/2$, $3\lambda/2$, and so on. Its resonant frequencies are whole-number multiples of the fundamental.
- A clamped string has a node at each end and resonates when its length is $\lambda/2$, $2\lambda/2$, $3\lambda/2$, and so on, just as with an open pipe. The string's resonant frequencies are also whole-number multiples of the fundamental.
- The frequencies and intensities of the complex waves produced by a musical instrument determine the timbre that is characteristic of that instrument.
- The fundamental frequency and harmonics can be described in terms of resonance.
- Notes on a musical scale differ in frequency by small, whole-number ratios. An octave has a frequency ratio of 1:2.
- Two waves with almost the same frequency interfere to produce beats.

Chapter 15 Assessment

Concept Mapping

30. Complete the concept map below using the following terms: *amplitude, perception, pitch, speed.*



41. **Trombones** Explain how the slide of a trombone, shown in **Figure 15-21,** changes the pitch of the sound in terms of a trombone being a resonance tube. (15.2)

■ **Figure 15-21**

Mastering Concepts

31. What are the physical characteristics of sound waves? (15.1)

32. When timing the 100-m run, officials at the finish line are instructed to start their stopwatches at the sight of smoke from the starter's pistol and not at the sound of its firing. Explain. What would happen to the times for the runners if the timing started when sound was heard? (15.1)

33. Name two types of perception of sound and the physical characteristics of sound waves that correspond to them. (15.1)

34. Does the Doppler shift occur for only some types of waves or for all types of waves? (15.1)

35. Sound waves with frequencies higher than can be heard by humans, called ultrasound, can be transmitted through the human body. How could ultrasound be used to measure the speed of blood flowing in veins or arteries? Explain how the waves change to make this measurement possible. (15.1)

36. What is necessary for the production and transmission of sound? (15.2)

37. **Singing** How can a certain note sung by an opera singer cause a crystal glass to shatter? (15.2)

38. **Marching** In the military, as marching soldiers approach a bridge, the command "route step" is given. The soldiers then walk out-of-step with each other as they cross the bridge. Explain. (15.2)

39. **Musical Instruments** Why don't most musical instruments sound like tuning forks? (15.2)

40. **Musical Instruments** What property distinguishes notes played on both a trumpet and a clarinet if they have the same pitch and loudness? (15.2)

Applying Concepts

42. **Estimation** To estimate the distance in kilometers between you and a lightning flash, count the seconds between the flash and the thunder and divide by 3. Explain how this rule works. Devise a similar rule for miles.

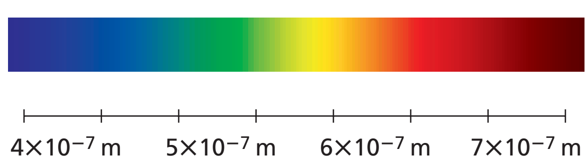
43. The speed of sound increases by about 0.6 m/s for each degree Celsius when the air temperature rises. For a given sound, as the temperature increases, what happens to the following?

a. the frequency

b. the wavelength

44. **Movies** In a science-fiction movie, a satellite blows up. The crew of a nearby ship immediately hears and sees the explosion. If you had been hired as an advisor, what two physics errors would you have noticed and corrected?

45. **The Redshift** Astronomers have observed that the light coming from distant galaxies appears redder than light coming from nearer galaxies. With the help of **Figure 15-22,** which shows the visible spectrum, explain why astronomers conclude that distant galaxies are moving away from Earth.



■ **Figure 15-22**

46. Does a sound of 40 dB have a factor of 100 (10^2) times greater pressure variation than the threshold of hearing, or a factor of 40 times greater?

For more problems, go to Additional Problems, Appendix B.

47. If the pitch of sound is increased, what are the changes in the following?
a. the frequency
b. the wavelength
c. the wave velocity
d. the amplitude of the wave

48. The speed of sound increases with temperature. Would the pitch of a closed pipe increase or decrease when the temperature of the air rises? Assume that the length of the pipe does not change.

49. **Marching Bands** Two flutists are tuning up. If the conductor hears the beat frequency increasing, are the two flute frequencies getting closer together or farther apart?

50. **Musical Instruments** A covered organ pipe plays a certain note. If the cover is removed to make it an open pipe, is the pitch increased or decreased?

51. **Stringed Instruments** On a harp, **Figure 15-23a,** long strings produce low notes and short strings produce high notes. On a guitar, **Figure 15-23b,** the strings are all the same length. How can they produce notes of different pitches?

Figure 15-23

Mastering Problems

15.1 Properties and Detection of Sound

52. You hear the sound of the firing of a distant cannon 5.0 s after seeing the flash. How far are you from the cannon?

53. If you shout across a canyon and hear an echo 3.0 s later, how wide is the canyon?

54. A sound wave has a frequency of 4700 Hz and travels along a steel rod. If the distance between compressions, or regions of high pressure, is 1.1 m, what is the speed of the wave?

55. **Bats** The sound emitted by bats has a wavelength of 3.5 mm. What is the sound's frequency in air?

56. **Photography** As shown in **Figure 15-24,** some cameras determine the distance to the subject by sending out a sound wave and measuring the time needed for the echo to return to the camera. How long would it take the sound wave to return to such a camera if the subject were 3.00 m away?

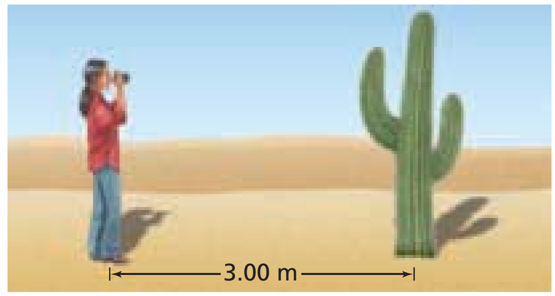


Figure 15-24

57. Sound with a frequency of 261.6 Hz travels through water at 25°C. Find the sound's wavelength in water. Do not confuse sound waves moving through water with surface waves moving through water.

58. If the wavelength of a 4.40×10^{2}-Hz sound in freshwater is 3.30 m, what is the speed of sound in freshwater?

59. Sound with a frequency of 442 Hz travels through an iron beam. Find the wavelength of the sound in iron.

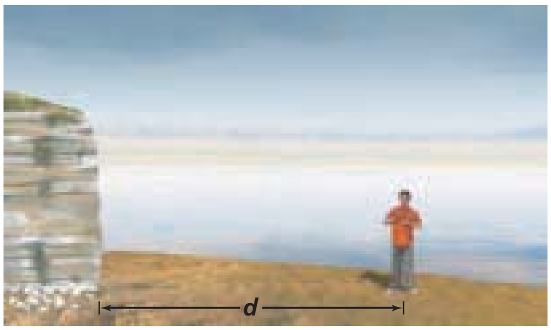
60. **Aircraft** Adam, an airport employee, is working near a jet plane taking off. He experiences a sound level of 150 dB.
a. If Adam wears ear protectors that reduce the sound level to that of a typical rock concert, what decrease in dB is provided?
b. If Adam then hears something that sounds like a barely audible whisper, what will a person not wearing the ear protectors hear?

61. **Rock Music** A rock band plays at an 80-dB sound level. How many times greater is the sound pressure from another rock band playing at each of the following sound levels?
a. 100 dB
b. 120 dB

62. A coiled-spring toy is shaken at a frequency of 4.0 Hz such that standing waves are observed with a wavelength of 0.50 m. What is the speed of propagation of the wave?

63. A baseball fan on a warm summer day (30°C) sits in the bleachers 152 m away from home plate.
a. What is the speed of sound in air at 30°C?
b. How long after seeing the ball hit the bat does the fan hear the crack of the bat?

64. On a day when the temperature is 15°C, a person stands some distance, *d*, as shown in **Figure 15-25,** from a cliff and claps his hands. The echo returns in 2.0 s. How far away is the cliff?



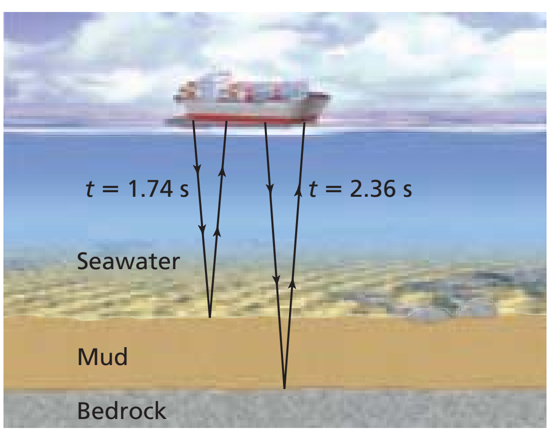
■ **Figure 15-25** (Not to scale)

65. Medical Imaging Ultrasound with a frequency of 4.25 MHz can be used to produce images of the human body. If the speed of sound in the body is the same as in salt water, 1.50 km/s, what is the length of a 4.25-MHz pressure wave in the body?

66. Sonar A ship surveying the ocean bottom sends sonar waves straight down into the seawater from the surface. As illustrated in **Figure 15-26,** the first reflection, off of the mud at the sea floor, is received 1.74 s after it was sent. The second reflection, from the bedrock beneath the mud, returns after 2.36 s. The seawater is at a temperature of 25°C, and the speed of sound in mud is 1875 m/s.

a. How deep is the water?

b. How thick is the mud?



■ **Figure 15-26** (Not to scale)

67. Determine the variation in sound pressure of a conversation being held at a sound level of 60 dB.

68. A fire truck is moving at 35 m/s, and a car in front of the truck is moving in the same direction at 15 m/s. If a 327-Hz siren blares from the truck, what frequency is heard by the driver of the car?

69. A train moving toward a sound detector at 31.0 m/s blows a 305-Hz whistle. What frequency is detected on each of the following?

a. a stationary train

b. a train moving toward the first train at 21.0 m/s

70. The train in the previous problem is moving away from the detector. What frequency is now detected on each of the following?

a. a stationary train

b. a train moving away from the first train at a speed of 21.0 m/s

15.2 The Physics of Music

71. A vertical tube with a tap at the base is filled with water, and a tuning fork vibrates over its mouth. As the water level is lowered in the tube, resonance is heard when the water level has dropped 17 cm, and again after 49 cm of distance exists from the water to the top of the tube. What is the frequency of the tuning fork?

72. Human Hearing The auditory canal leading to the eardrum is a closed pipe that is 3.0 cm long. Find the approximate value (ignoring end correction) of the lowest resonance frequency.

73. If you hold a 1.2-m aluminum rod in the center and hit one end with a hammer, it will oscillate like an open pipe. Antinodes of pressure correspond to nodes of molecular motion, so there is a pressure antinode in the center of the bar. The speed of sound in aluminum is 5150 m/s. What would be the bar's lowest frequency of oscillation?

74. One tuning fork has a 445-Hz pitch. When a second fork is struck, beat notes occur with a frequency of 3 Hz. What are the two possible frequencies of the second fork?

75. Flutes A flute acts as an open pipe. If a flute sounds a note with a 370-Hz pitch, what are the frequencies of the second, third, and fourth harmonics of this pitch?

76. Clarinets A clarinet sounds the same note, with a pitch of 370 Hz, as in the previous problem. The clarinet, however, acts as a closed pipe. What are the frequencies of the lowest three harmonics produced by this instrument?

77. String Instruments A guitar string is 65.0 cm long and is tuned to produce a lowest frequency of 196 Hz.

a. What is the speed of the wave on the string?

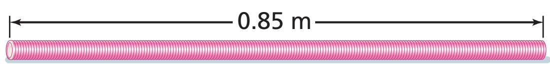
b. What are the next two higher resonant frequencies for this string?

 For more problems, go to Additional Problems, Appendix B.

78. **Musical Instruments** The lowest note on an organ is 16.4 Hz.
   a. What is the shortest open organ pipe that will resonate at this frequency?
   b. What is the pitch if the same organ pipe is closed?

79. **Musical Instruments** Two instruments are playing musical A (440.0 Hz). A beat note with a frequency of 2.5 Hz is heard. Assuming that one instrument is playing the correct pitch, what is the frequency of the pitch played by the second instrument?

80. A flexible, corrugated, plastic tube, shown in **Figure 15-27,** is 0.85 m long. When it is swung around, it creates a tone that is the lowest pitch for an open pipe of this length. What is the frequency?



■ **Figure 15-27**

81. The tube from the previous problem is swung faster, producing a higher pitch. What is the new frequency?

82. During normal conversation, the amplitude of a pressure wave is 0.020 Pa.
   a. If the area of an eardrum is 0.52 cm^2, what is the force on the eardrum?
   b. The mechanical advantage of the three bones in the middle ear is 1.5. If the force in part a is transmitted undiminished to the bones, what force do the bones exert on the oval window, the membrane to which the third bone is attached?
   c. The area of the oval window is 0.026 cm^2. What is the pressure increase transmitted to the liquid in the cochlea?

83. **Musical Instruments** One open organ pipe has a length of 836 mm. A second open pipe should have a pitch that is one major third higher. How long should the second pipe be?

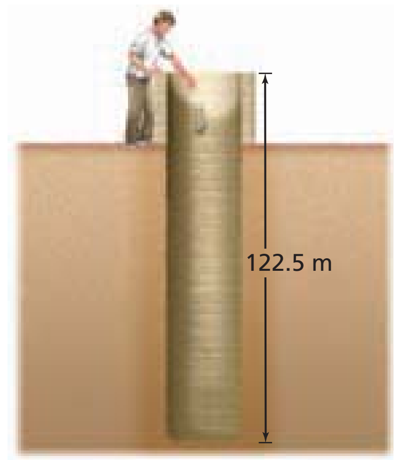
84. As shown in **Figure 15-28,** a music box contains a set of steel fingers clamped at one end and plucked on the other end by pins on a rotating drum. What is the speed of a wave on a finger that is 2.4 cm long and plays a note of 1760 Hz?

■ **Figure 15-28**

Mixed Review

85. An open organ pipe is 1.65 m long. What fundamental frequency note will it produce if it is played in helium at 0°C?

86. If you drop a stone into a well that is 122.5 m deep, as illustrated in **Figure 15-29,** how soon after you drop the stone will you hear it hit the bottom of the well?



■ **Figure 15-29** (Not to scale)

87. A bird on a newly discovered planet flies toward a surprised astronaut at a speed of 19.5 m/s while singing at a pitch of 945 Hz. The astronaut hears a tone of 985 Hz. What is the speed of sound in the atmosphere of this planet?

88. In North America, one of the hottest outdoor temperatures ever recorded is 57°C and one of the coldest is −62°C. What are the speeds of sound at those two temperatures?

89. A ship's sonar uses a frequency of 22.5 kHz. The speed of sound in seawater is 1533 m/s. What is the frequency received on the ship that was reflected from a whale traveling at 4.15 m/s away from the ship? Assume that the ship is at rest.

90. When a wet finger is rubbed around the rim of a glass, a loud tone of frequency 2100 Hz is produced. If the glass has a diameter of 6.2 cm and the vibration contains one wavelength around its rim, what is the speed of the wave in the glass?

91. **History of Science** In 1845, Dutch scientist Christoph Buys-Ballot developed a test of the Doppler effect. He had a trumpet player sound an A note at 440 Hz while riding on a flatcar pulled by a locomotive. At the same time, a stationary trumpeter played the same note. Buys-Ballot heard 3.0 beats per second. How fast was the train moving toward him?

92. You try to repeat Buys-Ballot's experiment from the previous problem. You plan to have a trumpet played in a rapidly moving car. Rather than listening for beat notes, however, you want to have the car move fast enough so that the moving trumpet sounds one major third above a stationary trumpet.

a. How fast would the car have to move?

b. Should you try the experiment? Explain.

93. Guitar Strings The equation for the speed of a wave on a string is $v = \sqrt{\frac{F_T}{\mu}}$, where F_T is the tension in the string and μ is the mass per unit length of the string. A guitar string has a mass of 3.2 g and is 65 cm long. What must be the tension in the string to produce a note whose fundamental frequency is 147 Hz?

94. A train speeding toward a tunnel at 37.5 m/s sounds its horn at 327 Hz. The sound bounces off the tunnel mouth. What is the frequency of the reflected sound heard on the train? *Hint: Solve the problem in two parts. First, assume that the tunnel is a stationary observer and find the frequency. Then, assume that the tunnel is a stationary source and find the frequency measured on the train.*

Thinking Critically

95. Make and Use Graphs The wavelengths of the sound waves produced by a set of tuning forks with given frequencies are shown in **Table 15-2** below.

a. Plot a graph of the wavelength versus the frequency (controlled variable). What type of relationship does the graph show?

b. Plot a graph of the wavelength versus the inverse of the frequency ($1/f$). What kind of graph is this? Determine the speed of sound from this graph.

Table 15-2

Tuning Forks

Frequency (Hz)	Wavelength (m)
131	2.62
147	2.33
165	2.08
196	1.75
220	1.56
247	1.39

96. Make Graphs Suppose that the frequency of a car horn is 300 Hz when it is stationary. What would the graph of the frequency versus time look like as the car approached and then moved past you? Complete a rough sketch.

97. Analyze and Conclude Describe how you could use a stopwatch to estimate the speed of sound if you were near the green on a 200-m golf hole as another group of golfers hit their tee shots. Would your estimate of the speed of sound be too large or too small?

98. Apply Concepts A light wave coming from a point on the left edge of the Sun is found by astronomers to have a slightly higher frequency than light from the right side. What do these measurements tell you about the Sun's motion?

99. Design an Experiment Design an experiment that could test the formula for the speed of a wave on a string. Explain what measurements you would make, how you would make them, and how you would use them to test the formula.

Writing in Physics

100. Research the construction of a musical instrument, such as a violin or French horn. What factors must be considered besides the length of the strings or tube? What is the difference between a quality instrument and a cheaper one? How are they tested for tone quality?

101. Research the use of the Doppler effect in the study of astronomy. What is its role in the big bang theory? How is it used to detect planets around other stars? To study the motions of galaxies?

Cumulative Review

102. Ball A, rolling west at 3.0 m/s, has a mass of 1.0 kg. Ball B has a mass of 2.0 kg and is stationary. After colliding with ball B, ball A moves south at 2.0 m/s. (Chapter 9)

a. Sketch the system, showing the velocities and momenta before and after the collision.

b. Calculate the momentum and velocity of ball B after the collision.

103. Chris carries a 10-N carton of milk along a level hall to the kitchen, a distance of 3.5 m. How much work does Chris do? (Chapter 10)

104. A movie stunt person jumps from a five-story building (22 m high) onto a large pillow at ground level. The pillow cushions her fall so that she feels a deceleration of no more than 3.0 m/s^2. If she weighs 480 N, how much energy does the pillow have to absorb? How much force does the pillow exert on her? (Chapter 11)

Standardized Test Practice

Multiple Choice

1. How does sound travel from its source to your ear?

- (A) by changes in air pressure
- (B) by vibrations in wires or strings
- (C) by electromagnetic waves
- (D) by infrared waves

2. Paulo is listening to classical music in the speakers installed in his swimming pool. A note with a frequency of 327 Hz reaches his ears while he is under water. What is the wavelength of the sound that reaches Paulo's ears? Use 1493 m/s for the speed of sound in water.

- (A) 2.19 nm
- (B) 4.88×10^{-5} m
- (C) 2.19×10^{-1} m
- (D) 4.57 m

3. The sound from a trumpet travels at 351 m/s in air. If the frequency of the note is 298 Hz, what is the wavelength of the sound wave?

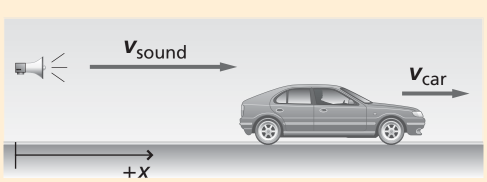
- (A) 9.93×10^{-4} m
- (B) 0.849 m
- (C) 1.18 m
- (D) 1.05×10^{5} m

4. The horn of a car attracts the attention of a stationary observer. If the car is approaching the observer at 60.0 km/h and the horn has a frequency of 512 Hz, what is the frequency of the sound perceived by the observer? Use 343 m/s for the speed of sound in air.

- (A) 488 Hz
- (B) 512 Hz
- (C) 538 Hz
- (D) 600 Hz

5. As shown in the diagram below, a car is receding at 72 km/h from a stationary siren. If the siren is wailing at 657 Hz, what is the frequency of the sound perceived by the driver? Use 343 m/s for the speed of sound.

- (A) 543 Hz
- (B) 620 Hz
- (C) 647 Hz
- (D) 698 Hz



6. Reba hears 20 beats in 5.0 s when she plays two notes on her piano. She is certain that one note has a frequency of 262 Hz. What are the possible frequencies of the second note?

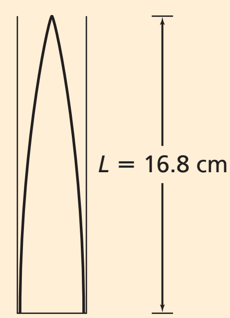
- (A) 242 Hz or 282 Hz
- (B) 258 Hz or 266 Hz
- (C) 260 Hz or 264 Hz
- (D) 270 Hz or 278 Hz

7. Which of the following pairs of instruments have resonant frequencies at each whole-number multiple of the lowest frequency?

- (A) a clamped string and a closed pipe
- (B) a clamped string and an open pipe
- (C) an open pipe and a closed pipe
- (D) an open pipe and a reed instrument

Extended Answer

8. The figure below shows the first resonance length of a closed air column. If the frequency of the sound is 488 Hz, what is the speed of the sound?



✓ Test-Taking TIP

Write It Down

Most tests ask you a large number of questions in a small amount of time. Write down your work whenever possible. Do math on paper, not in your head. Underline and reread important facts in passages and diagrams—do not try to memorize them.