Bat Music

How can a bat determine how far away an insect is? How can it tell when it is getting closer to the insect and how large the insect is?

Look at the text on page 354 for the answer.

CHAPTER

15 Sound

Sound is important to the human experience. You are already familiar with several of the characteristics of sound such as volume, tone, and pitch. Most likely, you can distinguish noise from useful or soothing sounds.

Much of the sound you hear during a day falls into specific patterns; some sound patterns are characteristic of speech, other patterns are characteristic of music. You can produce music by arranging sounds in combinations of rhythm, harmony, and melody. Primitive people made music using the sounds of their voices, as well as drums, rattles, and whistles. Recently, archeologists discovered a 43 000-year-old flute made from a bear's bone. Most likely, the artist played the instrument for pleasure, not for survival.

Some sounds, however, are pivotal to survival. There are animals that use sound to attract mates or to warn of approaching predators. Some animals even use sound to hunt. Bats, in particular, hunt flying insects by emitting pulses of very high-frequency sound. Bats can determine the distance to an insect, the size of the insect, and whether they are moving toward or away from the insect. In addition, because bats live in large colonies, they must separate the echoes of their own sounds from the echoes and sounds of hundreds of other bats. The methods that bats use for interpreting sound are truly amazing. Even more amazing is the fact that human use and enjoyment of sound is based on the same physical principles that allow bats to be exacting hunters. You will study these principles in this chapter.

WHAT YOU'LL LEARN

- You will describe sound in terms of wave phenomena.
- You will discover the principles behind what makes a sound either music or noise.

WHY IT'S IMPORTANT

- Human communication relies on cords vibrating in throats to send waves through gas, liquids, and solids that end up as electrical impulses in listeners' brains.

PHYSICS Online

To find out more about sound, visit the Glencoe Science Web site at **science.glencoe.com**

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15.1 Properties of Sound

In the last chapter, you learned how to describe a wave: its speed, its periodicity, its amplitude. You also figured out how waves interact with each other and with matter. If you were told that sound is a type of wave, then you could immediately start describing its properties and interactions. However, the first question you need to answer is just what type of wave is sound?

OBJECTIVES

- **Demonstrate** knowledge of the nature of sound waves and the properties sound shares with other waves.
- **Solve** problems relating the frequency, wavelength, and velocity of sound.
- **Relate** the physical properties of sound waves to the way we perceive sound.
- **Define** the Doppler shift and **identify** some of its applications.

Sound Waves

How is sound produced? 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 piston that represents your vocal cords, a loudspeaker, or any other sound source. As it moves back and forth, the piston strikes the molecules in the air. When the piston moves forward, air molecules are driven forward; that is, the air molecules bounce off the piston with a greater velocity. When the piston is at rest, air molecules bounce off the piston with little or no change in velocity. When the piston moves backward, air molecules bounce off the piston with a smaller velocity.

The result of these velocity changes is that the forward motion of the piston produces a region where the air pressure is slightly higher than average. The backward motion produces slightly below-average pressure. Collisions among the air molecules cause the pressure variations to move away from the piston. You can see how this happens by looking at the small red arrows that represent the velocities of the air molecules in **Figure 15–1.** The molecules converge just after the passing of a low-pressure region and the molecules diverge just after the passing of a high-pressure region. 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 variation is transmitted through matter.

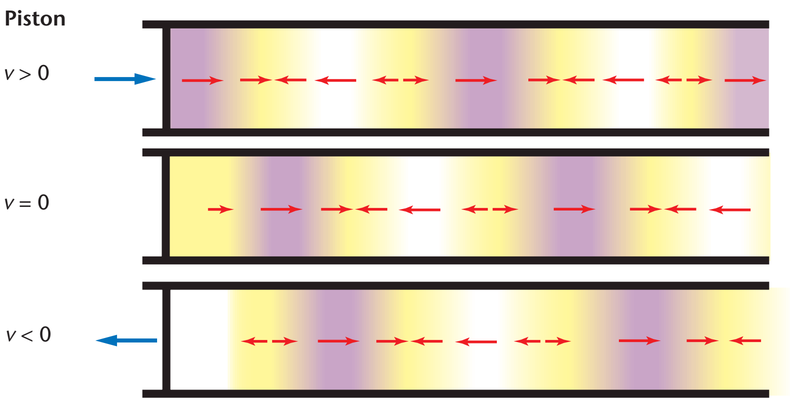


FIGURE 15–1 A vibrating piston produces sound waves. The dark areas represent regions of higher pressure; the light areas regions of lower pressure. Note that these regions move forward in time.

Describing sound A sound wave is simply a pressure variation that is transmitted through matter. Sound waves move through air because a vibrating source produces regular oscillations in air pressure. The air molecules collide, transmitting the pressure variations away from the source of the sound. The pressure of the air varies, or oscillates, about an average value, 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 air molecules is parallel to the direction of motion of the wave, sound is a longitudinal wave.

The speed of a sound wave in air depends on the temperature of the air. Sound waves move through air at sea level at a speed of 343 m/s at room temperature (20°C). Sound can also travel through liquids and solids. In general, the speed of sound is greater in solids and liquids than in gases. Sound cannot travel through a vacuum because there are no particles to move and collide.

Sound waves share the general properties of other waves. 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. Sound waves also can be diffracted, spreading outward after passing through narrow openings. Two sound waves can interfere, causing "dead spots" at nodes where little sound can be heard. And as you learned in Chapter 14, the frequency and wavelength of a wave are related to the speed of the wave by the equation $v = \lambda f$.

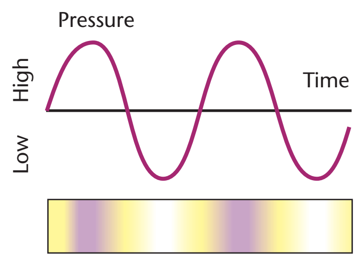


FIGURE 15–2 A graphic representation of the change in pressure over time in a sound wave is shown. Dark areas indicate high pressure; yellow areas indicate average pressure; white areas indicate low pressure.

F.Y.I.

Speed of Sound in Various Media	(m/s)
Air (0°)	331
Air (20°)	343
Water (25°)	1493
Sea water (25°)	1533
Iron (25°)	5130
Rubber (25°)	1550

Example Problem

Finding the Wavelength of Sound

A tuning fork produces a sound wave in air with frequency of 261.6 Hz. At room temperature the speed of sound is 343 m/s. What is the wavelength?

Sketch the Problem

- Draw one wavelength using the sine wave model.
- Label the wavelength.

Calculate Your Answer

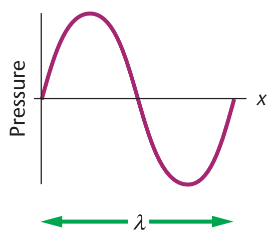
Known:

$f = 261.6$ Hz

$v = 343$ m/s

Unknown:

$\lambda = ?$



Continued on next page

CONTENTS

Strategy:

Speed and frequency are known, so wavelength is found by rearranging the equation $v = \lambda f$.

Calculations:

$$v = \lambda f, \text{ so } \lambda = \frac{v}{f}$$

$$\lambda = \frac{343 \text{ m/s}}{261.6 \text{ Hz}} = 1.31 \text{ m}$$

Check Your Answer

- Are the units correct? Work the algebra on the units to verify that the answer is in meters.
- Does the sign make sense? Positive: v, λ, f are always positive.
- Is the magnitude realistic? Audible sound waves in air have wavelengths from 17 mm to 17 m. The answer falls within this range.

Practice Problems

1. Find the frequency of a sound wave moving in air at room temperature with a wavelength of 0.667 m.

2. The human ear can detect sounds with frequencies between 20 Hz and 16 kHz. Find the largest and smallest wavelengths the ear can detect, assuming that the sound travels through air with a speed of 343 m/s at 20°C.

3. If you clap your hands and hear the echo from a distant wall 0.20 s later, how far away is the wall?

4. What is the frequency of sound in air at 20°C having a wavelength equal to the diameter of a 15 in. (38 cm) woofer loudspeaker? Of a 3.0 in. (7.6 cm) tweeter?

HELP WANTED

AUDIOLOGIST

A private practice seeks a certified audiologist to provide in-office services, as well as to deliver contract services to outside businesses and agencies. Patience, compassion, excellent communication skills, thorough knowledge of current equipment, strong concentration skills, and attention to detail are required for success in this career field. Only candidates with a master's degree need apply. For information contact:

American Speech-Language-Hearing Association
10801 Rockville Pike
Rockville, MD 20852

Loudness The physical characteristics of sound waves are measured by frequency and wavelength, with which you are already familiar. Another physical characteristic of sound waves is amplitude. Amplitude is the measure of the variation in pressure along the 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 the variations in pressure waves, that is, the amplitude of the sound wave. The ear can detect pressure wave amplitudes of less than one billionth of an atmosphere, or 2×10^{-5} Pa. Recall from Chapter 13 that 1 atmosphere of pressure equals 10^5 pascals. At the other end of the audible range, the pressure variations that cause pain are a million times greater, about one thousandth of an atmosphere, or 20 Pa. Remember that the ear can detect only pressure variations. You can easily reduce the external pressure on your ear by thousands of pascals just by driving over a mountain pass, yet a difference of just a few pascals of pressure variation will cause pain.

Because of the wide range in pressure variations that humans can detect, these amplitudes are measured on a logarithmic scale called **sound level.** Sound level is measured in **decibels** (dB). The 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 zero decibels (0 dB). A sound with a ten times larger pressure amplitude (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 15–3** shows the sound level in decibels for a variety of sounds.

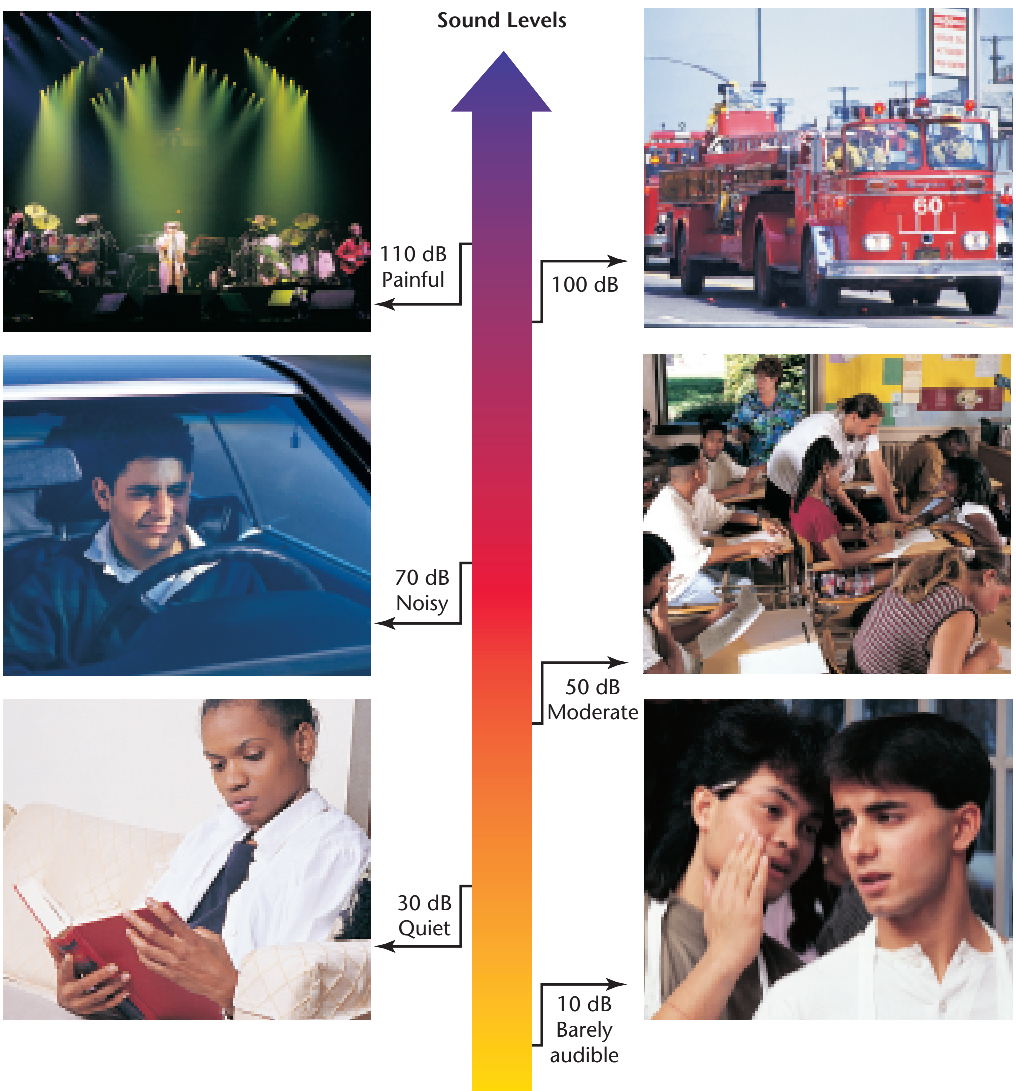


FIGURE 15–3 This decibel scale shows the sound level of some familiar sounds.

FIGURE 15–4 Continuous exposure to loud sounds can cause serious hearing loss. In many occupations, workers such as airline personnel and rock musicians wear ear protection.

Pitch Marin Mersenne (1588-1648) and Galileo (1564-1642) first connected **pitch** with the frequency of vibration. Pitch also can be given a name on the musical scale. For instance, middle C has a frequency of 262 Hz and an E note has a frequency of 327 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. In general, people are most sensitive to sounds with frequencies between 1000 Hz and 5000 Hz. Older people are less sensitive to frequencies above 10 000 Hz than are young people. By age 70, most people can hear nothing above 8000 Hz. This loss affects the ability to understand speech.

Exposure to loud sounds, either 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 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%. Hearing loss also can result from loud music being transmitted to stereo headphones from personal radios and tape players. The wearer may be unaware just how high the sound level is. 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 can reduce the level by up to 45 dB, as shown in **Figure 15–4.**

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 for pure tones is different than it is for mixtures of tones.

Bat Music

Answers question from page 348.

The Doppler Shift

Have you ever noticed the pitch of an ambulance, fire, or police siren as the vehicle sped past you? The frequency is higher when the vehicle is moving toward you, then it suddenly drops to a lower pitch as the source moves away. This effect is called the **Doppler shift** and is shown in **Figure 15–5.** The sound source, *S*, is moving to the right with speed v_s. The waves it emits spread in circles centered on the location of the source at the time it produced the wave. The frequency of the sound source does not change, but when the source is moving toward the sound detector, O_A in **Figure 15–5a,** 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 the frequency of the detected sound increases.

When the source is moving away from the detector, O_B, in **Figure 15–5a,** the wavelength is lengthened to λ_B and the detected frequency is lower. A Doppler shift also occurs if the detector is moving and the source is stationary, as in **Figure 15–5b.**

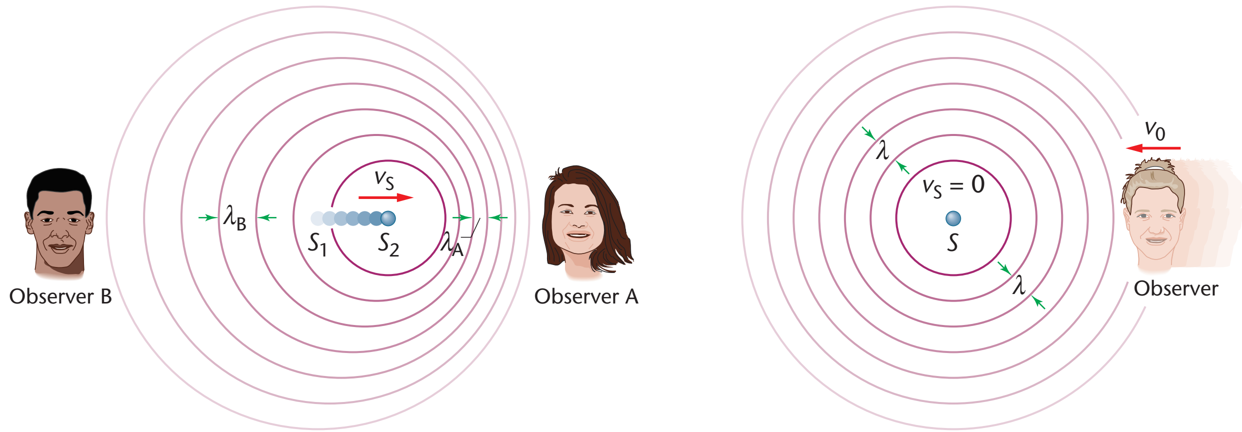


FIGURE 15–5 A Doppler shift can be produced either by the source moving **(a),** or by the receiver moving **(b).**

The Doppler shift occurs in all wave motion, both mechanical and electromagnetic. It has many applications. Radar detectors use the Doppler shift to measure the speed of baseballs and automobiles. Astronomers use the Doppler shift of light from distant galaxies to measure their speed and infer their distance. Physicians can detect the speed of the moving heart wall in a fetus by means of the Doppler shift in ultrasound. A bat uses the Doppler shift to detect and catch flying insects. When an insect is flying faster than the bat, the reflected frequency is lower, but when the bat is catching up to the insect, the reflected frequency is higher.

15.1 Section Review

1. 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-kHz tone and for two cycles of a 2-kHz tone.
2. If you hear a train whistle pitch drop as the train passes you, can you tell from which direction the train was coming?
3. Describe how the medium through which a sound wave travels affects properties of the sound wave.
4. What physical characteristic of a wave would you change to increase the loudness of a sound? To change the pitch?
5. **Critical Thinking** To a person who is hard of hearing, normal conversation (60 dB) sounds like a soft whisper. What increase in sound levels (in dB) must a hearing aid provide? How many times must the sound wave pressure be increased? (Refer to **Figure 15–3.**)

Physics & Society

You *Can* Take It With You!

You or someone you know probably has a cellular phone. Such a device is essentially a sophisticated, two-way radio that sends and receives sound over radio frequencies. Cell phones, as they're often called, are similar to conventional wire-line phones, but a cell phone is mobile—you *can* take it with you to send or receive a phone call even in some of the most remote places on Earth.

The ever-increasing number of wireless communications devices is creating a dilemma between radio astronomers and the users of cellular phones, pagers, and other such devices. Because the wireless devices and radio telescopes operate on similar radio wave frequencies, the amount of radio frequency interference, or RFI, is increasing at an alarming rate.

What's out there?

Anything with a temperature above absolute zero emits radio waves. Stars, planets, and other objects in space give off these waves, which can be used to study many of these celestial objects' physical and chemical properties. Since their inception in the mid-1900s, radio telescopes have discovered clouds of water, ammonia, ethyl alcohol, and other complex molecules in interstellar space. These findings have led some astronomers to hypothesize that because the sun is a typical star, and Earth is a satellite of this star, intelligent life may exist on comparable planets orbiting similar stars somewhere in the more than 100 billion galaxies thought to make up the universe.

Some radio telescopes operate on frequencies ranging from 1610.6 to 1613.8 megahertz (MHz). These frequencies are vital to radio astronomy research because the frequency of a hydroxyl molecule, which is composed of hydrogen and oxygen, lies within this range. Hydroxyl molecules are common in areas of the universe where stars are forming or dying.

Another important frequency to radio astronomical research is 1420.406 MHz, the radio frequency of atomic hydrogen, which makes up over 90% of the universe.

Convenience at the price of research?

Hundreds of mobile communications satellites are currently orbiting Earth. More, no doubt, will soon be launched to keep up with the increasing demand for wireless communications devices. While some international laws and agreements have resulted in the allotment of some portions of the radio spectrum for astronomical research only, many radio astronomers believe that this is not enough. Many argue that their research is being hampered by idle chit-chat.

Investigating the Issue

1. **Acquiring Information** Find out more about how a radio telescope works. Then, suggest what could be done, from the radio astronomy perspective, to help alleviate this problem.
2. **Debating the Issue** Which side of this issue do you support? Explain your position.

CLICK HERE

PHYSICS Online

To find out more about radio astronomy and cell phones, visit the Glencoe Science Web site at **science.glencoe.com**

The Physics of Music

15.2

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 have music whenever and wherever we wish.

OBJECTIVES

- **Describe** the origin of sound.
- **Demonstrate** an understanding of resonance, especially as applied to air columns.
- **Explain** why there is a variation among instruments and among voices using the terms *timbre*, *resonance*, *fundamental*, and *harmonic.*
- **Determine** why beats occur.

Sources of Sound

Sound is produced by a vibrating object. The vibrations of the object create molecular 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 cords.

In brass instruments, such as the trumpet, trombone, and tuba, the lips of the performer vibrate, as shown in **Figure 15–6a.** Reed instruments, like the clarinet, saxophone, and oboe, have a thin wooden strip, or reed, that vibrates as a result of air blown across it, **Figure 15–6b.** In a flute, recorder, organ pipe, and whistle, air is forced across an opening in a pipe. Air moving past the opening sets the column of air in the instrument into vibration.

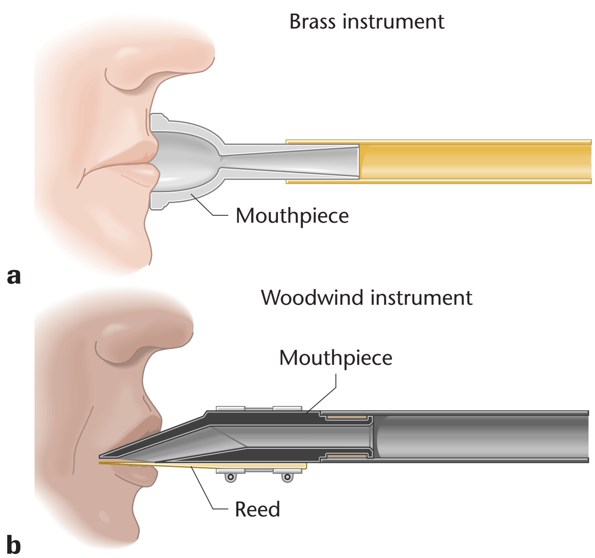


FIGURE 15–6 The shapes of the mouthpieces of a brass instrument **(a)** and a reed instrument **(b)** help determine the characteristics of the sound each instrument produces.

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. 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 15–7 In all the instruments pictured, changes in pitch are brought about by changing the length of the resonating column of air.

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 the instruments shown in **Figure 15–7,** 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.

A tuning fork above a hollow tube can provide resonance in an air column, as shown in **Figure 15–8.** 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 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.

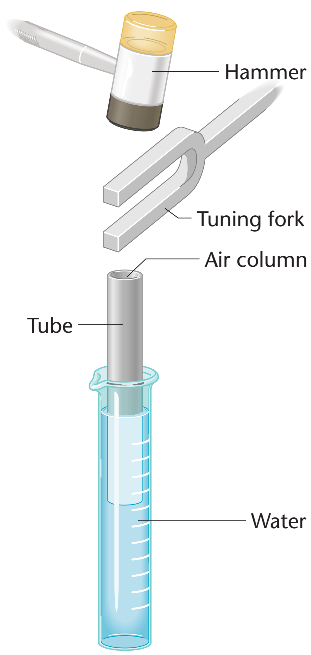


FIGURE 15–8 Raising and lowering the tube changes the length of the air column. When the air column is in resonance with the tuning fork, the sound is loudest.

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 15–9a.** If the reflected high-pressure wave reaches the tuning fork at the same moment that the fork produces another high-pressure wave, then the leaving 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 15–9b.**

Resonance lengths A standing sound wave in a pipe can be represented by a sine wave, as shown in **Figure 15–10.** Sine waves can represent either the air pressure or the displacement of the air molecules. 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 is at its maximum or minimum value. 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.

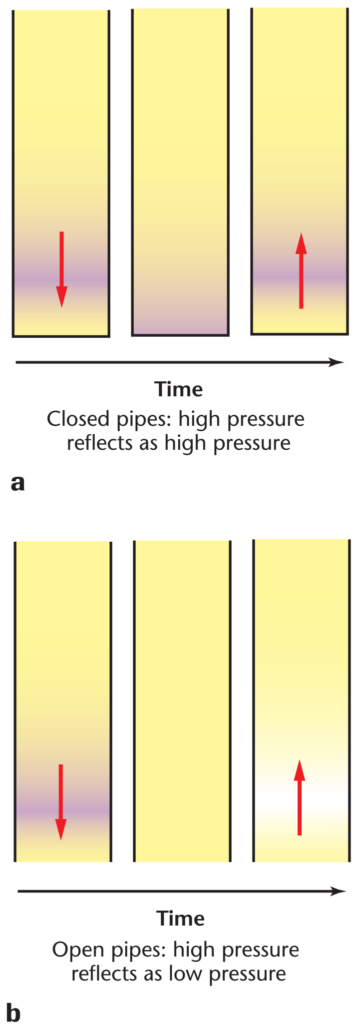


FIGURE 15–9 A wave of high pressure will reflect off the end of a pipe, whether the pipe is open or closed.

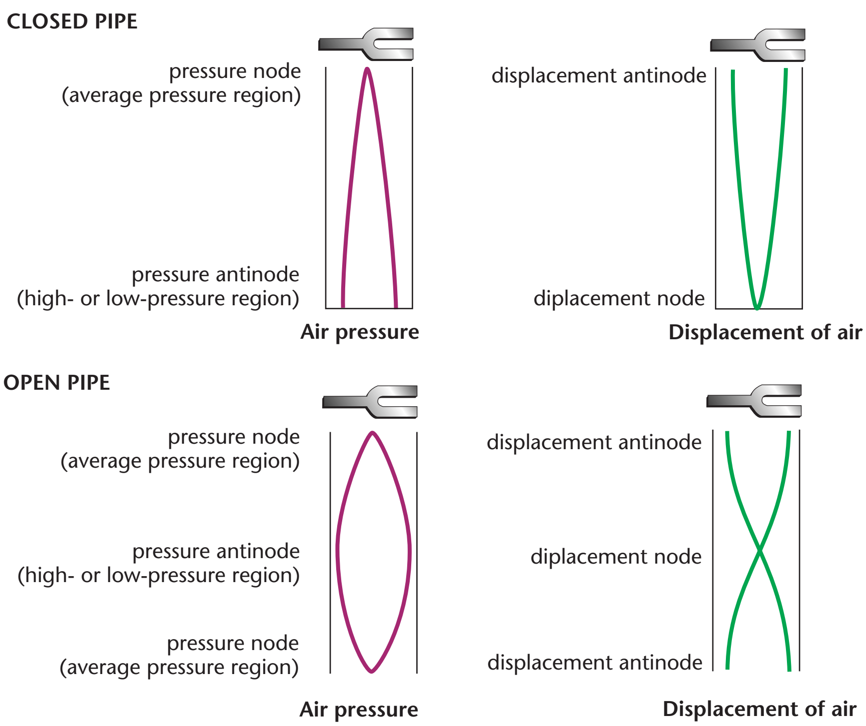


FIGURE 15–10 Sine waves represent standing waves in pipes.

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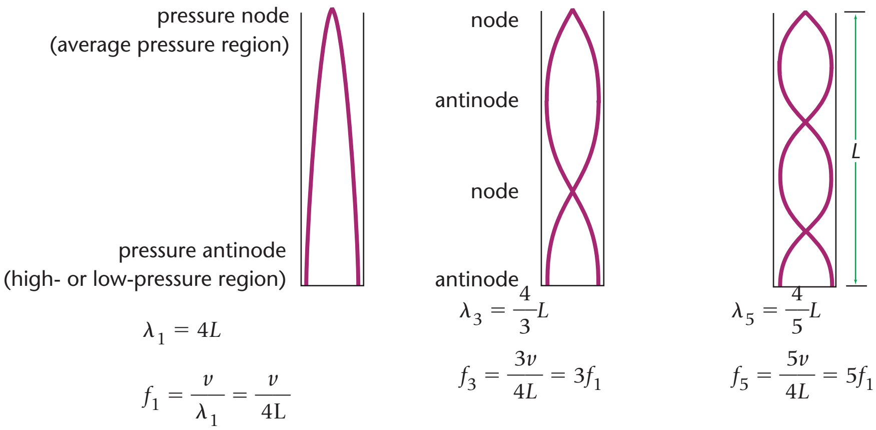


FIGURE 15–11 A closed pipe resonates when its length is an odd number of quarter wavelengths.

Pocket Lab

Sound Off

Take a meterstick and tape recorder to the band room. Measure the entire length of a wind instrument. Ask a musician to play the lowest note possible on her instrument. Make a recording of the lowest note. Return to the physics room.

Analyze and Conclude For the lowest note, $L = \lambda/2$, what is the wavelength played by the instrument? Use this estimate of the wavelength and the wave equation to predict the frequency. **Hint:** $v = \lambda f$. Use a frequency generator to try to match the recorded note. Read the value on the frequency generator. Is this reading close to your prediction?

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 wavelength long, as shown in **Figure 15–11.** 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 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 1.2 pipe diameters beyond the end. Each additional resonance length, however, is spaced by exactly one-half wavelength. Measurement of the spacings between resonances can be used to find the velocity of sound in air, as shown in the next example problem.

Resonance frequencies in an open pipe The shortest column of air that can have nodes at both ends is one-half 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 $\lambda/2$, λ, $3\lambda/2$, 2λ, and so on will be in resonance with a tuning fork.

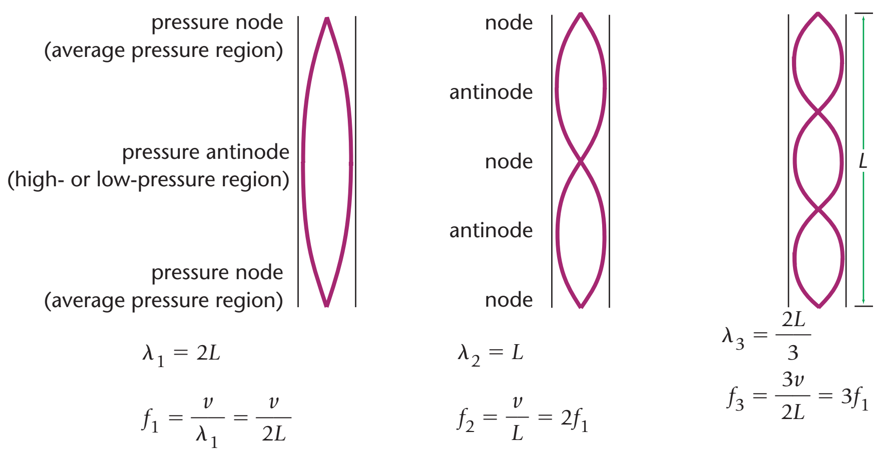


FIGURE 15–12 An open pipe resonates when its length is an even number of quarter wavelengths.

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. 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 brass instruments, flutes, and saxophones. The hanging pipes under marimbas and xylophones are examples of closed-pipe resonators. If you shout into a long tunnel or underpass, the booming sound you hear is the tunnel acting as a resonator.

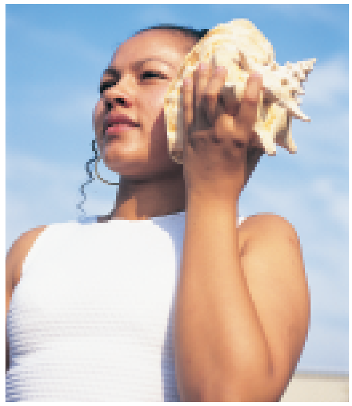
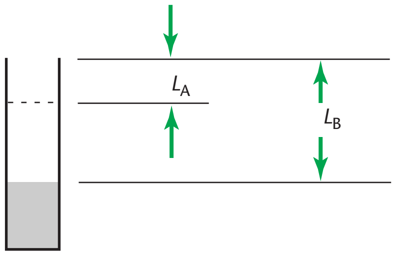


FIGURE 15–13 A shell acts as a closed-pipe resonator to magnify certain frequencies from the background noise.

Example Problem

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. The air temperature is 27.0°C. What is the speed of sound at this temperature?



Sketch the Problem

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

Calculate Your Answer

Known:

$f = 392$ Hz

$L_A = 21.0$ cm

$L_B = 65.3$ cm

$T = 27.0$°C

Unknown:

$v = ?$

Strategy:

In closed pipes, resonant lengths are spaced by one-half wavelength.

Find wavelength from the difference of the two lengths.

Speed is found using frequency and wavelength.

Calculations:

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

$$\lambda = 2(L_B - L_A)$$

$$\lambda = 2(65.3\text{ cm} - 21.0\text{ cm}) = 88.6\text{ cm}$$

$$v = f\lambda$$

$$v = (392\text{ Hz})(0.886\text{ m}) = 347\text{ m/s}$$

Check Your Answer

- Are the units correct? (Hz)(m) = (1/s)(m) = m/s. The answer's units are correct.
- Does the sign make sense? Positive: speed, wavelength, and frequency are always positive.
- Is the magnitude realistic? Check using the relationship that v_{sound} increases approximately 0.6 m/s per °C. v_{sound} at 20°C is 343 m/s. (7°C)(0.6m/s·°C) = 4.2 m/s higher. The answer is reasonable.

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Speed of Sound

Problem

How can you measure the speed of sound?

Materials

tuning fork
hollow glass tube
1000-mL graduated cylinder
hot water
ice water
thermometer
tuning fork hammer
tape measure

Procedure

1. Place cylinders with hot water on one side of the classroom and ice water on the other side of the classroom.
2. Record the value of the frequency that is stamped on the tuning fork and record the temperature of the water.
3. Wear goggles while using tuning forks next to the glass tubes. With the tube lowered in the cylinder, carefully strike the tuning fork with the rubber hammer.
4. Hold the tuning fork above the glass tube while you slowly raise the tube until the sound is amplified, and is loudest by the tube.
5. Measure *L*, the distance from the water to the top of the tube, to the nearest 0.5 cm.
6. Trade places with another group on the other side of the room and repeat steps 2–5 using the same tuning fork.
7. Repeat steps 2–6 using a different tuning fork.
8. Dispose of the water as instructed by your teacher. Make sure materials are dry before you put them away.

Data and Observations

Hot Water		Ice Water	
Known	f =	Known	f =
Measure	T =	Measure	T =
	L =		L =
Calculate	λ =	Calculate	λ =
	v =		v =

Analyze and Conclude

1. **Calculating Results** Calculate the values for λ and v.
2. **Comparing Results** Were the values of v different for cold and hot air? How do the values of v compare for different tuning forks?
3. **Making Inferences** Write a general statement describing how the speed of sound depends on the variables tested in this experiment.
4. **Forming an Explanation** Describe a possible model of sound moving through air that will explain your results.

Apply

1. What would an orchestra sound like if the higher frequencies traveled faster than the lower frequencies?

Practice Problems

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

6. The 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 He?

7. 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?

8. 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 in a bugle (ignoring end corrections).

b. Find the next two higher-resonant frequencies in the bugle.

9. A soprano saxophone is an open pipe. If all keys are closed, it is approximately 65 cm long. Using 343 m/s as the speed of sound, find the lowest frequency that can be played on this instrument (ignoring end corrections).

BIOLOGY CONNECTION

The Human Ear The human auditory canal acts as a closed-pipe resonator that increases the ear's sensitivity for frequencies between 2000 and 5000 Hz. In the middle ear, the three bones, or ossicles, act as a lever, a simple machine with a mechanical advantage of 1.5. By a feedback mechanism, the bones also help to protect the inner ear from loud sounds. Muscles, triggered by a loud noise, pull the third bone away from the oval window.

Detection of Pressure Waves

Sound detectors convert sound energy—the kinetic energy of the vibrating air molecules—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'll learn about this transformation process in Chapter 25, after your study of electricity.

The human ear The ear is an amazing sound detector. Not only can it detect sound waves over a very wide range of frequencies, but it also is sensitive to an enormous range of wave amplitudes. In addition, human hearing can distinguish many different qualities of sound. The ear is a complex sense organ. Knowledge of both physics and biology is required to understand it. The interpretation of sounds by the brain is even more complex, and it is not totally understood.

The human ear, shown in **Figure 15–14,** is a device that collects pressure waves and converts them to electrical impulses. Sound waves entering your auditory canal cause vibrations of the tympanic membrane. Three tiny bones then transfer this vibration to fluid in the cochlea. Tiny hairs lining the spiral-shaped cochlea pick up certain frequencies out of the fluid vibration. The hairs then stimulate nerve cells, which send an impulse to the brain, producing the sensation of sound.

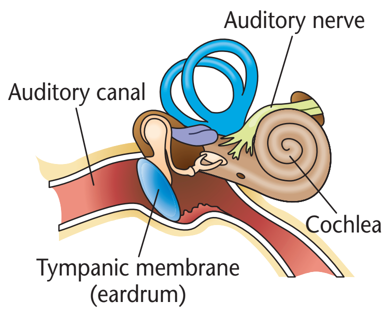


FIGURE 15–14 The human ear is a complex sense organ that translates sound vibrations into nerve impulses that are then sent to the brain for interpretation.

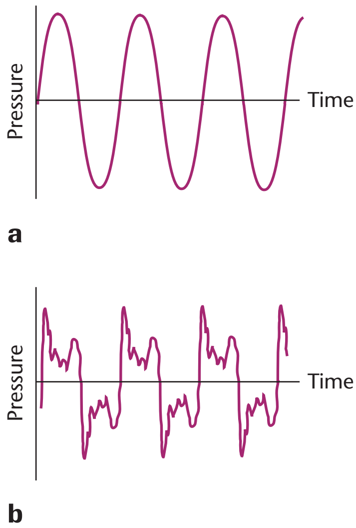


FIGURE 15–15 Graph of pure sound versus time **(a).** Graph of clarinet sound versus time **(b).**

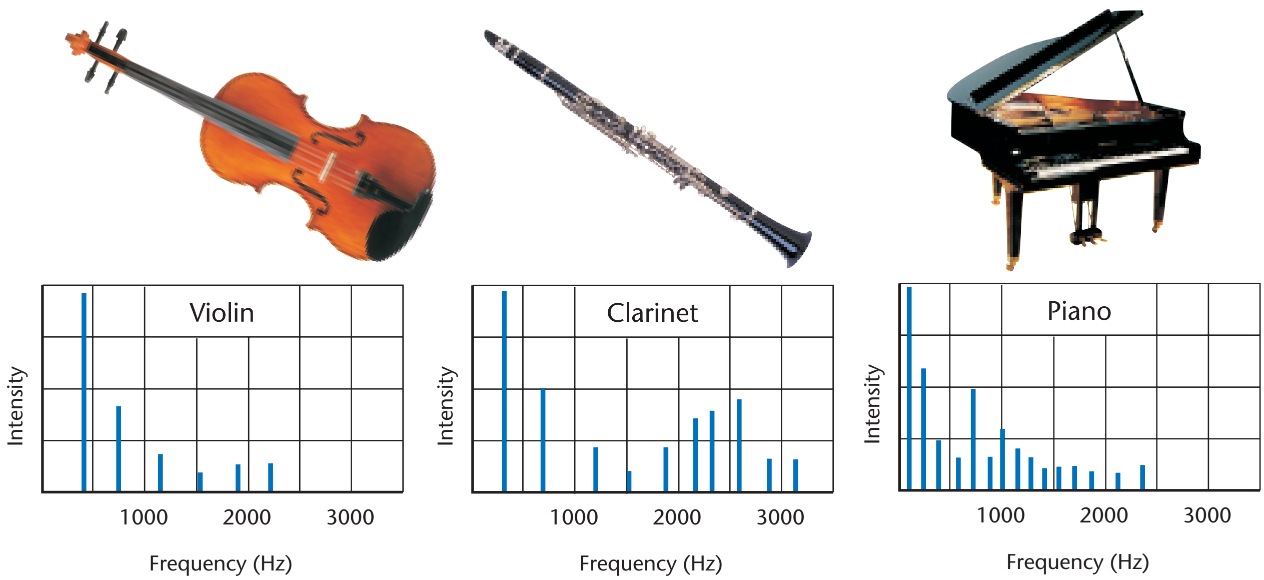
Sound Quality

A tuning fork produces a soft and uninteresting sound. That's because its tines vibrate like simple harmonic oscillators, producing the simple sine wave shown in **Figure 15–15a.** Sounds made by the human voice and musical instruments are much more complex, like the wave in **Figure 15–15b.** 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.

The sound spectrum: fundamental and harmonics The complex sound wave in **Figure 15–15b** was made by a clarinet. Why does an instrument such as a clarinet produce such a sound wave? The air column in a clarinet acts as a closed pipe. Look back at **Figure 15–11,** which shows three resonant frequencies for closed pipes. If the clarinet is of length L, then the lowest frequency, f_1, that will be resonant is $v/4L$. This lowest frequency is called the **fundamental.** But a closed pipe will also 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 is $f_1 = v/2L$ with harmonics at frequencies of $2f_1$, $3f_1$, $4f_1$ 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 the sound spectrum. The spectra of three instruments are shown in **Figure 15–16.** Each spectrum is as different as is the timbre of the instrument.

FIGURE 15–16 A violin, clarinet, and piano produce characteristic sound spectra.



Sounds good? 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. Musicians find that there are many such musical intervals that produce agreeable sounds.

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 an octave higher has a frequency of 880 Hz. A note one octave lower has a frequency of 220 Hz. The fundamental and its harmonics are related by octaves; the first harmonic is one octave higher, the second is two octaves higher, and so on. The sum of the fundamental and the first harmonic is shown in **Figure 15–17a.** It is important to recognize that it is the ratio of two frequencies, not the size of the interval between them, that determines the musical interval.

In other common 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 15–17.** More than two notes sounded together also can produce consonance. You are probably familiar with the major chord made up of the three notes called *do, mi,* and *sol.* 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.

F.Y.I.

A sonic boom will occur any time the speed of an aircraft goes above the speed of sound (Mach 1). Flying at supersonic speed causes the disturbed air to bunch together and collectively impact causing a thunder-like clap.

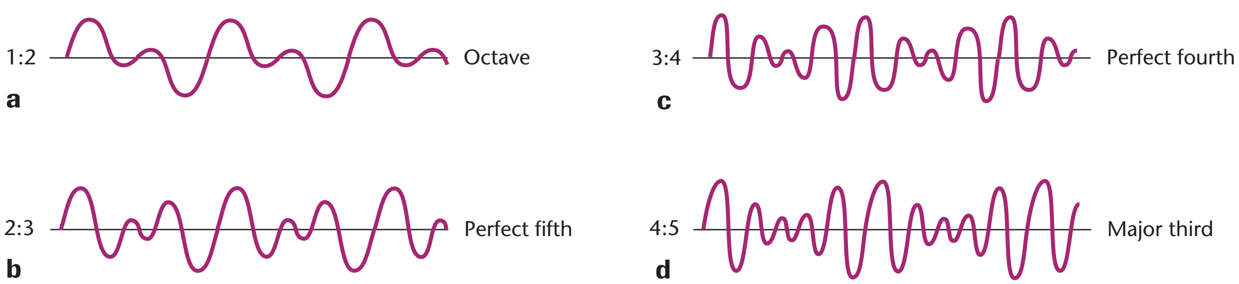
Pocket Lab

Ring, Ring

How good is your hearing? Here is a simple test to find out. Find a penny, a nickel, a dime, and a quarter. Ask a lab partner to drop them in any order and listen closely. Can you identify the sound of each coin with your eyes closed?

Analyze and Conclude Describe the differences in the sounds. What are the physical factors that cause the differences in the sounds? Can you suggest any patterns?

FIGURE 15–17 These time graphs show the superposition of two waves having the ratios of 1:2, 2:3, 3:4, and 4:5.



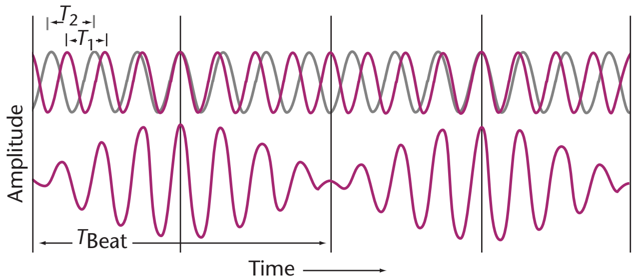


FIGURE 15–18 Beats occur as a result of the superposition of two sound waves of slightly different frequencies.

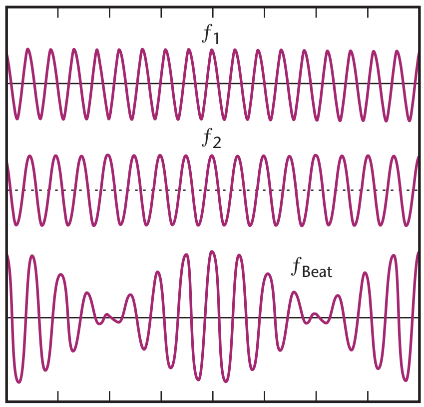
Beat Notes

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 15–18.** 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.

Example Problem

Finding the Beat

Two tuning forks, one with frequency of 442 Hz, the other with frequency of 444 Hz, are struck at the same time. What beat frequency will result?



Sketch the Problem

- In beat problems, making a sketch isn't necessary. However, it is instructive to take the time to produce at least one sketch depicting the interference of two waves, such as the sketch to the right.

Calculate Your Answer

Known:

$f_A = 442$ Hz

$f_B = 444$ Hz

Unknown:

$f_{beat} = ?$

Strategy:

The beat frequency is the magnitude of the difference between the two frequencies.

Calculations:

$$f_{beat} = |f_A - f_B|$$
$$f_{beat} = |442 \text{ Hz} - 444 \text{ Hz}|$$
$$f_{beat} = 2 \text{ Hz}$$

Check Your Answer

- Are the units correct? Frequencies are measured in Hz.
- Does the sign make sense? Frequencies are always positive.

Practice Problems

10. A 330.0-Hz and a 333.0-Hz tuning fork are struck simultaneously. What will the beat frequency be?

Sound Reproduction and Noise

How often do you listen to sound produced directly by a human voice or musical instrument? Most of the time the sound 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 15–19.** Many frequencies are present with approximately the same amplitude. While noise is not helpful in a telephone system, people claim that listening to noise has a calming effect, and some dentists use noise to help their patients relax.

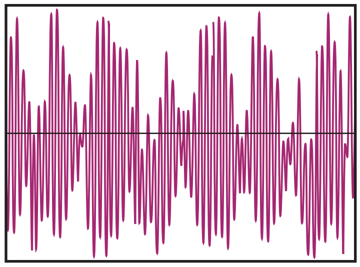


FIGURE 15–19 Noise is composed of several frequencies and involves random changes in frequency or amplitude.

15.2 Section Review

1. What is the vibrating object that produces sounds in
   a. the human voice?
   b. a clarinet?
   c. a tuba?
2. Hold one end of a ruler against your desktop, with one-quarter of it extending over the desk. Pluck the extended end of the ruler.
   a. Where does the noise you hear come from?
   b. Test your answer by placing a towel between the ruler and desk. What do you hear and what does the towel do?
   c. How does part **a** demonstrate sound production by a guitar?
3. The speech of a person with a head cold often sounds different from that person's normal speech. Explain.
4. **Critical Thinking** The end correction to a closed organ pipe increases the effective length by about 1.2 pipe diameters.
   a. Are the frequencies of the fundamental and higher harmonics still related by the numbers 1, 3, 5, and so on?
   b. Actually, the end correction depends slightly on wavelength. Does that change your answer to part **a?** Explain.

CHAPTER 15 REVIEW

Key Terms

15.1
- sound level
- decibel
- pitch
- Doppler shift

15.2
- closed-pipe resonator
- open-pipe resonator
- timbre
- fundamental
- harmonic
- dissonance
- consonance
- octave
- beat

Summary

15.1 Properties of Sound

- Sound is a pressure variation transmitted through matter as a longitudinal wave.
- Sound waves have frequency, wavelength, and speed. Sound waves reflect and interfere.
- The speed of sound in air at room temperature (20°C) is 343 m/s.
- The amplitude of a sound wave is measured in decibels (dB).
- The loudness of sound as perceived by the ear and brain depends mainly on its amplitude.
- The frequency of a sound wave is heard as its pitch.
- The Doppler shift is the change in frequency of sound caused by the motion of either the source or detector.

15.2 The Physics of Music

- Sound is produced by vibrating objects in matter.
- Most sounds are complex waves that are composed of more than one frequency.
- An air column can resonate with a sound source, increasing its amplitude.
- An open pipe resonates when its length is $\lambda/2$, $2\lambda/2$, $3\lambda/2$, and so on.
- A closed pipe resonates when its length is $\lambda/4$, $3\lambda/4$, $5\lambda/4$, and so on.
- Sound detectors convert the energy carried by a sound wave into another form of energy.
- 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.
- The shape of the throat and mouth cavity determines the timbre of the human voice.
- Notes on a musical scale differ in frequency by small, whole-number ratios.
- Two waves with almost the same frequency interfere to produce a beat note.

Reviewing Concepts

Section 15.1

1. What are the physical characteristics of sound waves?

2. A firecracker is set off near a set of hanging ribbons. Describe how they might vibrate.

3. 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?

4. 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?

5. Does the Doppler shift occur for only some types of waves or for all types of waves?

6. 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 wave changes to allow this measurement to work.

Section 15.2

7. How can a certain note sung by an opera singer cause a crystal glass to shatter?

8. 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.

9. What behaviors do sound waves exhibit? What behavior causes beats?
10. How must the length of an open tube compare to the wavelength of the sound to produce the strongest resonance?
11. Explain how the slide of a trombone changes the pitch of the sound in terms of a trombone being a resonance tube.
12. What property distinguishes notes played on both a trumpet and a clarinet if they have the same pitch and loudness?

Applying Concepts

13. A common method of estimating how far a lightning flash is from you is to count the seconds between the flash and the thunder, and then divide by 3. The result is the distance in kilometers. Explain how this rule works. Devise a similar rule for miles.
14. 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
    a. the frequency?
    b. the wavelength?
15. In a *Star Trek* episode, a space station orbiting Tanuga IV blows up. The crew of the *Enterprise* immediately hears and sees the explosion; they realize that there is no chance for rescue. If you had been hired as an advisor, what two physics errors would you have found and corrected?
16. Suppose the horns of all cars emitted sound at the same pitch or frequency. What would be the change in the frequency of the horn of a car moving
    a. toward you?
    b. away from you?
17. 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?
18. If the pitch of sound is increased, what are the changes in
    a. the frequency?
    b. the wavelength?
    c. the wave velocity?
    d. the amplitude of the wave?
19. 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?
20. 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.
21. How would resonance lengths be used in the production of a marimba? (A marimba is similar to a xylophone. Unlike a xylophone, a marimba has resonance tubes under each key.)
22. Two flutes are tuning up. If the conductor hears the beat frequency increasing, are the two flute frequencies getting closer together or farther apart?
23. 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?

Problems

Section 15.1

24. You hear the sound of the firing of a distant cannon 6.0 s after seeing the flash. How far are you from the cannon?
25. If you shout across a canyon and hear an echo 4.0 s later, how wide is the canyon?
26. A sound wave has a frequency of 9800 Hz and travels along a steel rod. If the distance between compressions, or regions of high pressure, is 0.580 m, what is the speed of the wave?
27. A rifle is fired in a valley with parallel vertical walls. The echo from one wall is heard 2.0 s after the rifle was fired. The echo from the other wall is heard 2.0 s after the first echo. How wide is the valley?
28. A certain instant camera determines 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 the camera if the subject were 3.00 m away?

29. Sound with a frequency of 261.6 Hz travels through water at a speed of 1435 m/s. Find the sound's wavelength in water. Don't confuse sound waves moving through water with surface waves moving through water.

30. If the wavelength of a 4.40×10^2 Hz sound in freshwater is 3.30 m, what is the speed of sound in water?

31. Sound with a frequency of 442 Hz travels through steel. A wavelength of 11.66 m is measured. Find the speed of the sound in steel.

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

33. 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 wavelength of the pressure wave in the body?

34. The equation for the Doppler shift of a sound wave of speed v reaching a moving detector, is $f_d = f_s(v + v_d)/(v - v_s)$, where v_d is the speed of the detector, v_s is the speed of the source, f_s is the frequency of the source, f_d is the frequency of the detector. If the detector moves toward the source, v_d is positive; if the source moves toward the detector, v_s is positive. A train moving toward a detector at 31 m/s blows a 305-Hz horn. What frequency is detected by a
  a. stationary train?
  b. train moving toward the first train at 21 m/s?

35. The train in problem 34 is moving away from the detector. Now what frequency is detected by
  a. a stationary train?
  b. a train moving away from the first train at a speed of 21 m/s?

36. 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 chain saw (110 dB), what decrease in dB will be required?
  b. If Adam now hears something that sounds like a whisper, what will a person not wearing the protectors hear?

37. A rock band plays at an 80-dB sound level. How many times greater is the sound pressure from another rock band playing at
  a. 100 dB? **b.** 120 dB?

38. If you drop a stone into a mine shaft 122.5 m deep, how soon after you drop the stone do you hear it hit the bottom of the shaft?

Section 15.2

39. A slide whistle has a length of 27 cm. If you want to play a note one octave higher, the whistle should be how long?

40. An open vertical tube 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?

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

42. If you hold a 1.0-m aluminum rod in the center and hit one end with a hammer, it will oscillate like an open pipe. Antinodes of air 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 lowest frequency of oscillation?

43. 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 would be the pitch if the same organ pipe were closed?

44. 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?

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

46. A clarinet sounds the same note, with a pitch of 370 Hz , as in problem 45. The clarinet, however, produces harmonics that are only odd multiples of the fundamental frequency. What are the frequencies of the lowest three harmonics produced by this instrument?

47. During normal conversation, the amplitude of a pressure wave is 0.020 Pa.

a. If the area of the eardrum is 0.52 cm^2, what is the force on the eardrum?

b. The mechanical advantage of the bones in the inner ear is 1.5. What force is exerted on the oval window?

c. The area of the oval window is 0.026 cm^2. What is the pressure increase transmitted to the liquid in the cochlea?

48. 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?

49. One organ pipe has a length of 836 mm. A second pipe should have a pitch one major third higher. The pipe should be how long?

50. In 1845, French scientist B. Ballot first tested the Doppler shift. He had a trumpet player sound an A, 440 Hz, while riding on a flatcar pulled by a locomotive. At the same time, a stationary trumpeter played the same note. Ballot heard 3.0 beats per second. How fast was the train moving toward him? (Refer to problem 34 for the Doppler shift equation.)

51. You try to repeat Ballot's experiment. 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 a major third above a stationary trumpet. (Refer to problem 34 for the Doppler shift equation.)

a. How fast would the car have to move?

b. Should you try the experiment?

Extra Practice For more practice solving problems, go to Extra Practice Problems, Appendix B.

Critical Thinking Problems

52. Suppose that the frequency of a car horn (when not moving) is 300 Hz. What would the graph of the frequency versus time look like as the car approached and then moved past you? Complete a rough sketch.

53. 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 were hitting their tee shots. Would your estimate of their velocities be too large or too small?

54. 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?

Going Further

Computer Application Here is a way to measure the speed of sound with Calculator Based Lab equipment or a microcomputer based lab setup such as a universal lab interface (ULI). If you are using a ULI, load the sound software and connect the microphone directly to the ULI. You will be able to see the pattern of the pressure changes in the air for different sounds. Record the sound when you snap your fingers. How much time does this sound take to die out? Now snap your fingers near the end of a hollow tube (10-cm or 15-cm diameter and 1 to 3 m long) and you will be able to see the original sound and also the echo. Use twice the length of the tube and the time delay to calculate the speed of sound. Try different lengths of tubes if you have them.

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