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CHAPTER 13

Sound

PHYSICS IN ACTION

Some marine mammals, such as dolphins, use sound waves to locate distant objects. In this process, called *echolocation,* a dolphin produces a rapid train of short sound pulses that travel through the water, bounce off distant objects, and reflect back to the dolphin. From these echoes, dolphins can determine the size, shape, speed, and distance of their potential prey.

A dolphin's echolocation is extremely sophisticated. Experiments have shown that at a distance of 114 m, a blindfolded dolphin can locate a stainless-steel sphere with a diameter of 7.5 cm and can distinguish between a sheet of aluminum and a sheet of copper. In this chapter you will study sound waves and see how dolphins echolocate.

- *How does dolphin echolocation work?*
- *How does a dolphin determine the direction a fish is moving?*

CONCEPT REVIEW

Longitudinal waves (Section 12-3)
Wave speed (Section 12-3)
Standing waves (Section 12-4)

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13-1
Sound waves

13-1 SECTION OBJECTIVES

- Explain how sound waves are produced.
- Relate frequency to pitch.
- Compare the speed of sound in various media.
- Relate plane waves to spherical waves.
- Recognize the Doppler effect, and determine the direction of a frequency shift when there is relative motion between a source and an observer.

THE PRODUCTION OF SOUND WAVES

Whether a sound wave conveys the shrill whine of a jet engine or the melodic whistling of a bird, it begins with a vibrating object. We will explore how sound waves are produced by considering a vibrating tuning fork, as shown in **Figure 13-1(a).**

The vibrating prong of a tuning fork, shown in **Figure 13-1(b),** sets the air molecules near it in motion. As the prong swings to the right, as shown in **Figure 13-1(c),** the air molecules in front of the movement are forced closer together. (This situation is exaggerated in the figure for clarity.) Such a region of high molecular density and high air pressure is called a **compression.** As the prong moves to the left, as in **Figure 13-1(d),** the molecules to the right spread apart, and the density and air pressure in this region become lower than normal. This region of lower density and pressure is called a **rarefaction.**

compression

the region of a longitudinal wave in which the density and pressure are greater than normal

rarefaction

the region of a longitudinal wave in which the density and pressure are less than normal

As the tuning fork continues to vibrate, a series of compressions and rarefactions form and spread away from each prong. These compressions and rarefactions expand and spread out in all directions, like ripple waves on a pond. When the tuning fork vibrates with simple harmonic motion, the air molecules also vibrate back and forth with simple harmonic motion.

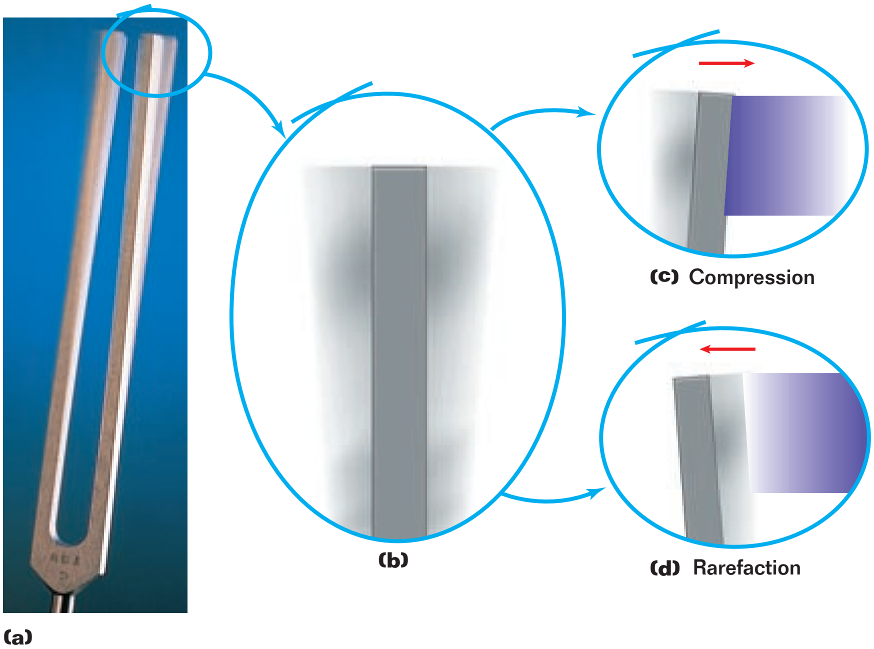

Figure 13-1
(a) The sound from a tuning fork is produced by **(b)** the vibrations of each of its prongs. **(c)** When a prong swings to the right, there is a region of high density and pressure. **(d)** When the prong swings back to the left, a region of lower density and pressure exists.

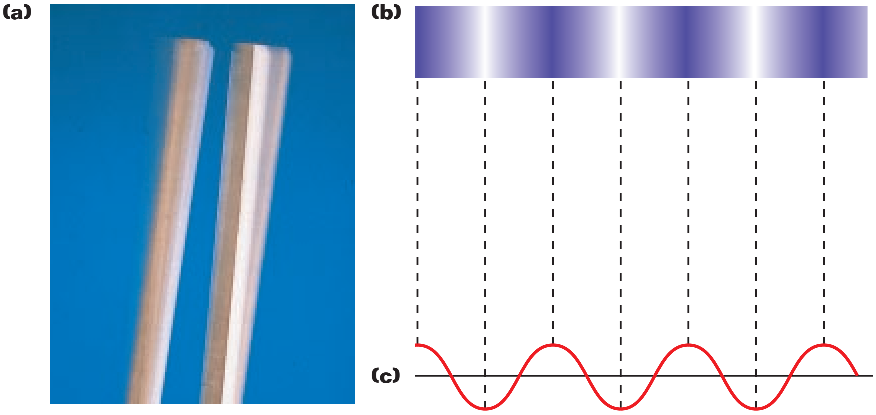

Figure 13-2
(a) As this tuning fork vibrates, **(b)** a series of compressions and rarefactions move away from each prong. **(c)** The crests of this sine wave correspond to compressions, and the troughs correspond to rarefactions.

Sound waves are longitudinal

In sound waves, the vibrations of air molecules are parallel to the direction of wave motion. Thus, sound waves are longitudinal. As you saw in Chapter 12, a longitudinal wave produced by a vibrating object can be represented by a sine curve. In **Figure 13-2** the crests of the sine curve correspond to compressions in the sound wave, and the troughs correspond to rarefactions. Because compressions are regions of higher pressure and rarefactions are regions of lower pressure, the sine curve represents the changes in air pressure due to the propagation of the sound waves.

CHARACTERISTICS OF SOUND WAVES

In Chapter 12, frequency was defined as the number of cycles per unit of time. Sound waves that the average human ear can hear, called *audible* sound waves, have frequencies between 20 and 20 000 Hz. (An individual's hearing depends on a variety of factors, including age and experiences with loud noises.) Sound waves with frequencies less than 20 Hz are called *infrasonic* waves, and those above 20 000 Hz are called *ultrasonic* waves.

It may seem confusing to use the term *sound waves* for infrasonic or ultrasonic waves since humans cannot hear these sounds, but ultrasonic and infrasonic waves consist of the same types of vibrations as the sounds that we can hear. The range of sound waves that are considered to be audible depends on the ability of the average human ear to detect their vibrations. Dogs can hear ultrasonic waves that humans cannot.

Did you know?

Elephants use infrasonic sound waves to communicate with one another. Their large ears enable them to detect these low-frequency sound waves, which have relatively long wavelengths. Elephants can effectively communicate in this way, even when they are separated by many kilometers.

Frequency determines pitch

The frequency of an audible sound wave determines how high or low we perceive the sound to be, which is known as **pitch.** As the frequency of a sound wave increases, the pitch rises. The frequency of a wave is an objective quantity that can be measured, while pitch refers to how different frequencies are perceived by the human ear.

pitch

the perceived highness or lowness of a sound, depending on the frequency of the sound waves

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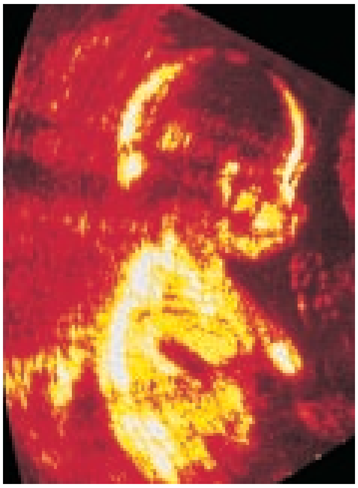

Figure 13-3
Ultrasound images, such as this one, are formed with reflected sound waves. This colorized image depicts a fetus after 21 weeks of development.

Ultrasonic waves can produce images

As discussed in Chapter 12, wavelength decreases as frequency increases. Thus, infrasonic waves have longer wavelengths than audible sound waves, and ultrasonic waves have shorter wavelengths. Because of their short wavelengths, ultrasonic waves have widespread medical applications.

For example, ultrasonic waves can be used to produce images of objects inside the body. Such imaging is possible because sound waves are partially reflected when they reach a boundary between two materials of different densities. The images produced by ultrasonic waves are clearer and more detailed than those that could be produced by lower-frequency sound waves because the short wavelengths of ultrasonic waves are easily reflected off small objects. Audible and infrasonic sound waves are not as effective because their longer wavelengths pass around small objects.

In order for ultrasonic waves to "see" an object inside the body, the wavelength of the waves used must be about the same size or smaller than the object. A typical frequency used in an ultrasonic device is about 10 Mhz. The speed of an ultrasonic wave in human tissue is about 1500 m/s, so the wavelength of 10 Mhz waves is $\lambda = v/f = 1.5$ mm. This device will not detect objects smaller than this size.

Physicians commonly use ultrasonic waves to observe fetuses. In this process, a crystal emits ultrasonic pulses. The same crystal acts as a receiver and detects the reflected sound waves. These reflected sound waves are converted to an electric signal, which forms an image on a fluorescent screen, as in **Figure 13-3.** By repeating this process for different portions of the mother's abdomen, a physician can obtain a complete picture of the fetus. **Figure 13-3** shows the ultrasound image of a fetus in the womb after 21 weeks of development. In this profile view, the head is at the upper right of the image, and an outline of the spine and upper arm can also be seen. At this stage, the nose, lips, and chin are fully developed, and the fetus weighs about 500 g. These images allow doctors to detect some types of fetal abnormalities.

Dolphin echolocation works in a similar manner. A dolphin sends out pulses of sound, which return in the form of reflected sound waves. These reflected waves allow the dolphin to form an image of the object that reflected the waves. Dolphins use high-frequency waves for echolocation because shorter wavelengths are most effective for detecting smaller objects.

Table 13-1 Speed of sound in various media

Medium	v (m/s)
Gases	
air (0°C)	331
air (25°C)	346
air (100°C)	366
helium (0°C)	972
hydrogen (0°C)	1290
oxygen (0°C)	317
Liquids at 25°C	
methyl alcohol	1140
sea water	1530
water	1490
Solids	
aluminum	5100
copper	3560
iron	5130
lead	1320
vulcanized rubber	54

Speed of sound depends on the medium

Sound waves can travel through solids, liquids, and gases. Because waves consist of particle vibrations, the speed of a wave depends on how quickly one particle can transfer its motion to another particle. For example, solid particles respond more rapidly to a disturbance than gas particles do because the molecules of a solid are closer together than those of a gas are. As a result, sound waves generally travel faster through solids than through gases. **Table 13-1** shows the speed of sound waves in various media.

The speed of sound also depends on the temperature of the medium. As temperature rises, the particles of a gas collide more frequently. Thus, in a gas,

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the disturbance can spread faster at higher temperatures than at lower temperatures. In liquids and solids, the particles are close enough together that the difference due to temperature changes is less noticeable.

Sound waves propagate in three dimensions

In Chapter 12, waves were shown as traveling in a single direction. But sound waves actually travel away from a vibrating source in all three dimensions. When a musician plays a saxophone in the middle of a room, the resulting sound can be heard throughout the room because the sound waves spread out in all directions. Such three-dimensional sound waves are approximately spherical. To simplify, we shall assume that sound waves are exactly spherical unless stated otherwise.

Spherical waves can be represented graphically in two dimensions with a series of circles surrounding the source, as shown in **Figure 13-4.** The circles represent the centers of compressions, called *wave fronts.* Because we are considering a three-dimensional phenomenon in two dimensions, each circle represents a spherical area.

Because each wave front corresponds to the center of a compression, the distance between adjacent wave fronts is equal to one wavelength, λ. The radial lines perpendicular to the wave fronts are called *rays.* Rays indicate the direction of the wave motion. The sine curve used in our previous representation of sound waves, also shown in **Figure 13-4,** corresponds to a single ray. Because crests of the sine curve represent compressions, each wave front crossed by this ray corresponds to a crest of the sine curve.

Now consider a small portion of a spherical wave front that is many wavelengths away from the source, as shown in **Figure 13-5.** In this case, the rays are nearly parallel lines, and the wave fronts are nearly parallel planes. Thus, at distances from the source that are great relative to the wavelength, we can approximate spherical wave fronts with parallel planes. Such waves are called *plane waves.* Any small portion of a spherical wave that is far from the source can be considered a plane wave. Plane waves can be treated as a series of identical one-dimensional waves, like those in Chapter 12, all traveling in the same direction.

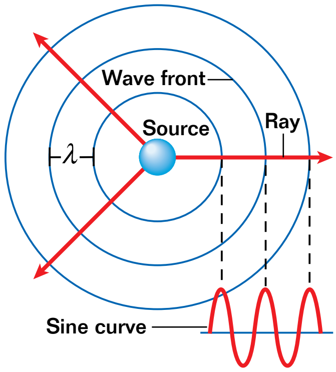

Figure 13-4
In this representation of a spherical wave, the wave fronts represent compressions and the rays show the direction of wave motion. Each wave front corresponds to a crest of the sine curve, which in turn corresponds to a single ray.

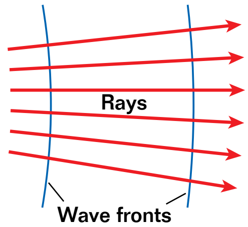

Figure 13-5
Spherical wave fronts that are a great distance from the source can be approximated with parallel planes known as plane waves.

Conceptual Challenge

1. Hydrogen and air Hydrogen atoms have a smaller mass than the primary components of air, so they are accelerated much more easily. How does this fact account for the great difference in the speed of sound waves traveling through air and hydrogen, as shown in **Table 13-1** on page 482?

2. Lightning and thunder Light waves travel nearly 1 million times faster than sound waves in air. With this in mind, explain how the distance to a lightning bolt can be determined by counting the seconds between the flash and the sound of the thunder.

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Tomorrow's Technology

Acoustic Bridge Inspection

When we drive over a bridge, we usually take its structural integrity for granted. Unfortunately, drivers should not always make that assumption. Many of the almost 600 000 bridges in the United States were built over 80 years ago, and most of the rest are 35 to 40 years old. As a bridge ages, cracks form in the steel that can weaken the bridge or even lead to eventual collapse. Inspectors search for those cracks visually, but that method is generally unreliable. David Prine, a senior research scientist at Northwestern University, thinks that the most reliable way to find damage in bridges is to listen to them.

"When a piece of steel cracks, high-frequency sound is emitted," explained Prine. These noises often sound like banging noises that echo throughout the bridge.

Prine has developed a way to inspect bridges using a system of acoustic-emissions sensors—sensitive microphones attached to the steel in a bridge—to capture audio signals from the structure. The signals are put into a computer, which filters out traffic and other noise and searches for sounds around 150 kHz, the frequency range of cracking steel. The computer locates where on the bridge each sound is coming from and then determines whether the recorded sounds match the pattern of a spreading crack. Damage can then be tracked down and repaired.

The device works best as a preventive measure. "The name of the game is to determine what the problems are at the earliest possible stage so you can do a minimal level of repair and not wait until it gets too bad," Prine said.

Still, the acoustic-emissions sensor comes in handy even after a bridge has been fixed. The sensor can monitor different repair methods after they have been tried to determine which methods best correct the problem. This is a much more efficient means of checking repairs than the old way—waiting until the bridge falls apart.

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THE DOPPLER EFFECT

If you stand on the street while someone drives by honking a car horn, you will notice the pitch of the horn change. The pitch will be higher as the car approaches and will be lower as the car moves away. As you read earlier in this section, the pitch of a sound depends on its frequency. But in this case, the car horn is not changing its frequency. How can we account for this change in pitch?

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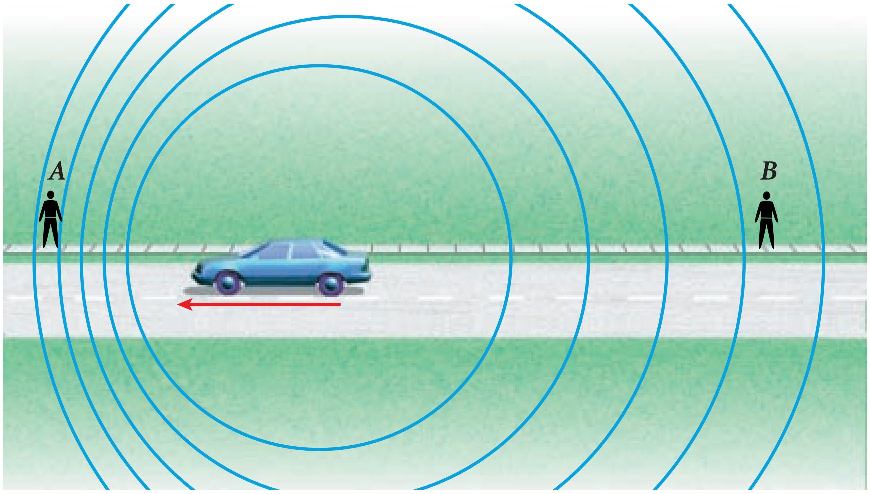

Figure 13-6
As this car moves to the left, an observer in front of the car, at point *A*, hears the car horn at a higher pitch than the driver, while an observer behind the car, at point *B*, hears a lower pitch.

Relative motion creates a change in frequency

In our earlier examples, we assumed that both the source of the sound waves and the listener were stationary. If a horn is honked in a parked car, an observer standing on the street hears the same pitch that the driver hears, as you would expect. For simplicity's sake, we will assume that the sound waves produced by the car horn are spherical.

When the car shown in **Figure 13-6** is moving, there is relative motion between the moving car and a stationary observer. This relative motion affects the way the wave fronts of the sound waves produced by the car's horn are perceived by an observer.

Although the frequency of the car horn (the source frequency) remains constant, the wave fronts reach an observer in front of the car, at point *A*, more often than they would if the car were stationary. This is because the source of the sound waves is moving toward the observer. Thus, the frequency heard by this observer is *greater* than the source frequency. (Note that the speed of the sound waves does not change.) For the same reason, the wave fronts reach an observer behind the car, at point *B*, less often than they would if the car were stationary. As a result, the frequency heard by this observer is *less* than the source frequency. This frequency shift is known as the **Doppler effect,** named for the Austrian physicist Christian Doppler (1803–1853), who first described it.

Did you know?

The Doppler effect occurs with all types of waves. In the radar systems used by police to monitor car speeds, a computer compares the frequency of radar waves emitted with those reflected from a moving car and then uses this comparison to calculate the speed of the car.

Doppler effect

a frequency shift that is the result of relative motion between the source of waves and an observer

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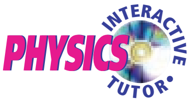

Module 13
"Doppler Effect"
provides an interactive lesson with guided problem-solving practice to teach you more about the Doppler effect.

Because frequency determines pitch, the Doppler effect affects the pitch heard by each listener on the street. The observer in front of the car hears a higher pitch, while the observer behind the car hears a lower pitch.

We have considered a moving source with respect to a stationary observer, but the Doppler effect also occurs when the observer is moving with respect to a stationary source or when both are moving at different speeds. In other words, the Doppler effect occurs whenever there is *relative motion* between the source of waves and an observer. Although the Doppler effect is most commonly experienced with sound waves, it is a phenomenon common to all waves, including electromagnetic waves, such as visible light.

Section Review

1. If you hear a higher pitch from a trumpet than from a saxophone, how do the frequencies of the sound waves from the trumpet compare with those from the saxophone?
2. Could a small portion of the innermost wave front shown in **Figure 13-7** be approximated by a plane wave? Why or why not?

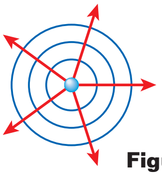

Figure 13-7

3. **Figure 13-8** is a diagram of the Doppler effect in a ripple tank. In which direction is the source of these ripple waves moving?
4. If the source of the waves in **Figure 13-8** is stationary, which way must the ripple tank be moving?

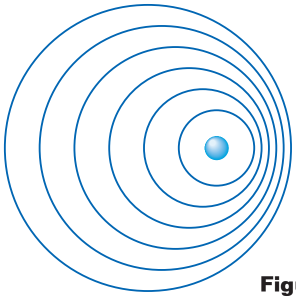

Figure 13-8

5. **Physics in Action** Dolphins can produce sound waves with frequencies ranging from 0.25 kHz to 220 kHz, but only those at the upper end of this spectrum are used in echolocation. Explain why high-frequency waves work better than low-frequency waves.
6. **Physics in Action** Sound pulses emitted by a dolphin travel through 20°C ocean water at a rate of 1450 m/s. In 20°C air, these pulses would travel 342.9 m/s. How can you account for this difference in speed?
7. **Physics in Action** As a dolphin swims toward a fish, it sends out sound waves to determine the direction the fish is moving. If the frequency of the reflected waves is increased, is the dolphin catching up to the fish or falling behind?

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13-2
Sound intensity and resonance

SOUND INTENSITY

When a piano player strikes a piano key, a hammer inside the piano strikes a wire and causes it to vibrate, as shown in **Figure 13-9.** The wire's vibrations are then transferred to the piano's soundboard. As the soundboard vibrates, it exerts a force on air molecules around it, causing air molecules to move. Because this force is exerted through displacement of the soundboard, the soundboard does work on the air. Thus, as the soundboard vibrates back and forth, its kinetic energy is converted into sound waves. This is one reason that the vibration of the soundboard gradually dies out.

Intensity is the rate of energy flow through a given area

As described in Section 13-1, sound waves traveling in air are longitudinal waves. As the sound waves travel outward from the source, energy is transferred from one air molecule to the next. The rate at which this energy is transferred through a unit area of the plane wave is called the **intensity** of the wave. Because power, P, is defined as the rate of energy transfer, intensity can also be described in terms of power.

$$\text{intensity} = \frac{\Delta E/\Delta t}{\text{area}} = \frac{P}{\text{area}}$$

As seen in Chapter 5, the SI unit for power is the watt. Thus, intensity has units of watts per square meter (W/m^2). In a spherical wave, energy propagates equally in all directions; no one direction is preferred over any other. In this case, the power emitted by the source (P) is distributed over a spherical surface (area $= 4\pi r^2$), assuming that there is no absorption in the medium.

INTENSITY OF A SPHERICAL WAVE

$$\text{intensity} = \frac{P}{4\pi r^2}$$

$$\textbf{intensity} = \frac{\textbf{(power)}}{(4\pi)(\textbf{distance from the source})^2}$$

This equation shows that the intensity of a sound wave decreases as the distance from the source (r) increases. This occurs because the same amount of energy is spread over a larger area.

13-2 SECTION OBJECTIVES

- **Calculate the intensity of sound waves.**
- **Relate intensity, decibel level, and perceived loudness.**
- **Explain why resonance occurs.**

intensity

the rate at which energy flows through a unit area perpendicular to the direction of wave motion

Figure 13-9
As this piano wire vibrates, it transfers energy to the piano's soundboard, which in turn transfers energy into the air in the form of sound.

SAMPLE PROBLEM 13A

Intensity of sound waves

PROBLEM

What is the intensity of the sound waves produced by a trumpet at a distance of 3.2 m when the power output of the trumpet is 0.20 W? Assume that the sound waves are spherical.

SOLUTION

Given: $P = 0.20$ W $\quad r = 3.2$ m

Unknown: Intensity = ?

Use the equation for the intensity of a spherical wave, given on page 487.

$$\text{Intensity} = \frac{P}{4\pi r^2}$$

$$\text{Intensity} = \frac{0.20\ \text{W}}{4\pi(3.2\ \text{m})^2}$$

$$\boxed{\text{Intensity} = 1.6 \times 10^{-3}\ \text{W/m}^2}$$

CALCULATOR SOLUTION

The calculator answer for intensity is 0.0015542. This is rounded to 1.6×10^{-3} because each of the given quantities has two significant figures.

PRACTICE 13A

Intensity of sound waves

1. Calculate the intensity of the sound waves from an electric guitar's amplifier at a distance of 5.0 m when its power output is equal to each of the following values:

a. 0.25 W
b. 0.50 W
c. 2.0 W

2. At a maximum level of loudness, the power output of a 75-piece orchestra radiated as sound is 70.0 W. What is the intensity of these sound waves to a listener who is sitting 25.0 m from the orchestra?

3. If the intensity of a person's voice is 4.6×10^{-7} W/m^2 at a distance of 2.0 m, how much sound power does that person generate?

4. How much power is radiated as sound from a band whose intensity is 1.6×10^{-3} W/m^2 at a distance of 15 m?

5. The power output of a tuba is 0.35 W. At what distance is the sound intensity of the tuba 1.2×10^{-3} W/m^2?

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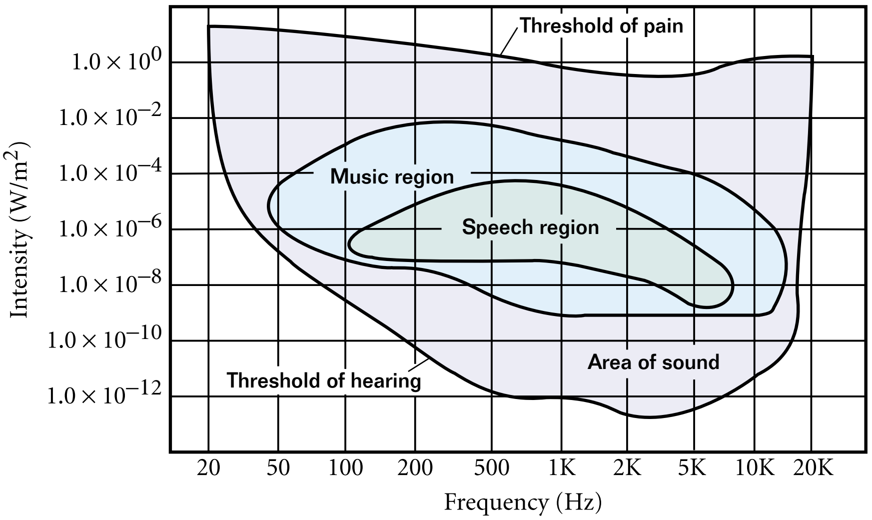

Figure 13-10
Human hearing depends on both the frequency and the intensity of sound waves. Sounds in the middle of the spectrum of frequencies can be heard more easily (at lower intensities) than those at lower and higher frequencies.

Intensity and frequency determine which sounds are audible

As you saw in Section 13-1, the frequency of sound waves heard by the average human ranges from 20 to 20 000 Hz. Intensity is also a factor in determining which sound waves are audible. **Figure 13-10** shows how the range of audibility of the average human ear depends on both frequency and intensity. As you can see in this graph, sounds at low frequencies (those below 50 Hz) or high frequencies (those above 12 000 Hz) must be relatively intense to be heard, whereas sounds in the middle of the spectrum are audible at lower intensities.

The softest sounds that can be heard by the average human ear occur at a frequency of about 1000 Hz and an intensity of 1.0×10^{-12} W/m^2. Such a sound is said to be at the *threshold of hearing*. (Note that some humans can hear slightly softer sounds, at a frequency of about 3300 Hz.) The threshold of hearing at each frequency is represented by the lowest curve in **Figure 13-10.** At the threshold of hearing, the changes in pressure due to compressions and rarefactions are about three ten-billionths of atmospheric pressure.

The maximum displacement of an air molecule at the threshold of hearing is approximately 1×10^{-11} m. Comparing this number to the diameter of a typical air molecule (about 1×10^{-10} m) reveals that the ear is an extremely sensitive detector of sound waves.

The loudest sounds that the human ear can tolerate have an intensity of about 1.0 W/m^2. This is known as the *threshold of pain* because sounds with greater intensities can produce pain in addition to hearing. The highest curve in **Figure 13-10** represents the threshold of pain at each frequency. Exposure to sounds above the threshold of pain can cause immediate damage to the ear, even if no pain is felt. Prolonged exposure to sounds of lower intensities can also damage the ear. For this reason, many rock musicians wear earplugs during their performances, and some rock stars must wear hearing aids. Note that the threshold of hearing and the threshold of pain merge at both high and low ends of the spectrum.

Did you know?

A 75-piece orchestra produces about 75 W at its loudest. This is comparable to the power required to keep one medium-sized electric light bulb burning. Speech has even less power. It would take the conversation of about 2 million people to provide the amount of power required to keep a 50 W light bulb burning.

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Relative intensity is measured in decibels

Just as the frequency of a sound wave determines its pitch, the intensity of a wave determines its loudness, or volume. However, volume is not directly proportional to intensity. For example, a sound twice the intensity of the faintest audible sound is not perceived as being twice as loud. This is because the sensation of loudness is approximately logarithmic in the human ear.

Relative intensity, which is found by relating the intensity of a given sound wave to the intensity at the threshold of hearing, corresponds more closely to human perceptions of loudness. Relative intensity is also referred to as **decibel level** because relative intensity is measured in units called *decibels* (dB). The decibel is a dimensionless unit because it relates one intensity to another.

decibel level

relative intensity, determined by relating the intensity of a sound wave to the intensity at the threshold of hearing

The conversion of intensity to decibel level is shown in **Table 13-2.** Notice in **Table 13-2** that when the intensity is multiplied by 10, 10 dB are added to the decibel level. A difference in 10 dB means the sound is approximately twice as loud. Although much more intensity (0.9 W/m^2) is added between 110 and 120 dB than between 10 and 20 dB (9×10^{-11} W/m^2), in each case the volume doubles. Because the volume doubles each time the decibel level increases by 10, sounds at the threshold of pain are 4096 times as loud as sounds at the threshold of hearing.

Did you know?

The original unit of decibel level is the *bel,* named in honor of Alexander Graham Bell, the inventor of the telephone. The decibel is equivalent to 0.1 bel.

Table 13-2 Conversion of intensity to decibel level

Intensity (W/m^2)	Decibel level (dB)	Examples
1.0×10^{-12}	0	threshold of hearing
1.0×10^{-11}	10	rustling leaves
1.0×10^{-10}	20	quiet whisper
1.0×10^{-9}	30	whisper
1.0×10^{-8}	40	mosquito buzzing
1.0×10^{-7}	50	normal conversation
1.0×10^{-6}	60	air conditioning at 6 m
1.0×10^{-5}	70	vacuum cleaner
1.0×10^{-4}	80	busy traffic, alarm clock
1.0×10^{-3}	90	lawn mower
1.0×10^{-2}	100	subway, power motor
1.0×10^{-1}	110	auto horn at 1 m
1.0×10^{0}	120	threshold of pain
1.0×10^{1}	130	thunderclap, machine gun
1.0×10^{3}	150	nearby jet airplane

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FORCED VIBRATIONS AND RESONANCE

When an isolated guitar string is held taut and plucked, hardly any sound is heard. When the same string is placed on a guitar and plucked, the intensity of the sound increases dramatically. What is responsible for this difference? To find the answer to this question, consider a set of pendulums suspended from a beam and bound by a loose rubber band, as shown in **Figure 13-11.** If one of the pendulums is set in motion, its vibrations are transferred by the rubber band to the other pendulums, which will also begin vibrating. This is called a *forced vibration.*

The vibrating strings of a guitar force the bridge of the guitar to vibrate, and the bridge in turn transfers its vibrations to the guitar body. These forced vibrations are called *sympathetic vibrations.* The guitar body enables the strings' vibrations to be transferred to the air much more quickly because it has a larger area than the strings. As a result, the intensity of the sound is increased, and the strings' vibrations die out faster than they would if they were not attached to the body of the guitar. In other words, the guitar body allows the energy exchange between the strings and the air to happen more efficiently, thereby increasing the intensity of the sound produced.

In an electric guitar, string vibrations are translated into electrical impulses, which can be amplified as much as desired. An electric guitar can produce sounds that are much more intense than those of an unamplified acoustic guitar, which uses only the forced vibrations of the guitar's body to increase the intensity of the sound from the vibrating strings.

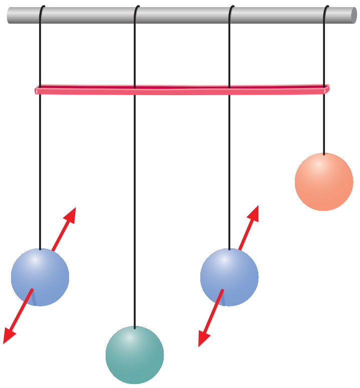

Figure 13-11
If one blue pendulum is set in motion, only the other blue pendulum, whose length is the same, will eventually oscillate with a large amplitude, or resonate.

Vibration at the natural frequency produces resonance

As you saw in Chapter 12, the frequency of a pendulum depends on its string length. Thus, every pendulum will vibrate at a certain frequency, known as its *natural frequency.* In **Figure 13-11,** the two blue pendulums have the same natural frequency, while the red and green pendulums have different natural frequencies. When the first blue pendulum is set in motion, the red and green pendulums will vibrate only slightly, but the second blue pendulum will oscillate with a much larger amplitude because its natural frequency matches the

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Quick Lab

Resonance

MATERIALS LIST

✔ swing set

Go to a playground, and swing on one of the swings. Try pumping (or being pushed) at different rates—faster than, slower than, and equal to the natural frequency of the swing. Observe whether the rate at which you pump (or are pushed) affects how easily the amplitude of the vibration increases. Are some rates more effective at building your amplitude than others? You should find that the pushes are most effective when they match the swing's natural frequency. Explain how your results support the statement that resonance works best when the frequency of the applied force matches the system's natural frequency.

resonance

a condition that exists when the frequency of a force applied to a system matches the natural frequency of vibration of the system

frequency of the pendulum that was initially set in motion. This system is said to be in **resonance.** Since energy is transferred from one pendulum to the other, the amplitude of vibration of the first blue pendulum will decrease as the second blue pendulum's amplitude increases.

A striking example of structural resonance occurred in 1940, when the Tacoma Narrows bridge, in Washington, shown in **Figure 13-12,** was set in motion by the wind. High winds set up standing waves in the bridge, causing the bridge to oscillate at one of its natural frequencies. The amplitude of the vibrations increased until the bridge collapsed. A more recent example of structural resonance occurred during the Loma Prieta earthquake near Oakland, California, in 1989, when part of the upper deck of a freeway collapsed. The collapse of this particular section of roadway has been traced to the fact that the earthquake waves had a frequency of 1.5 Hz, very close to the natural frequency of that section of the roadway.

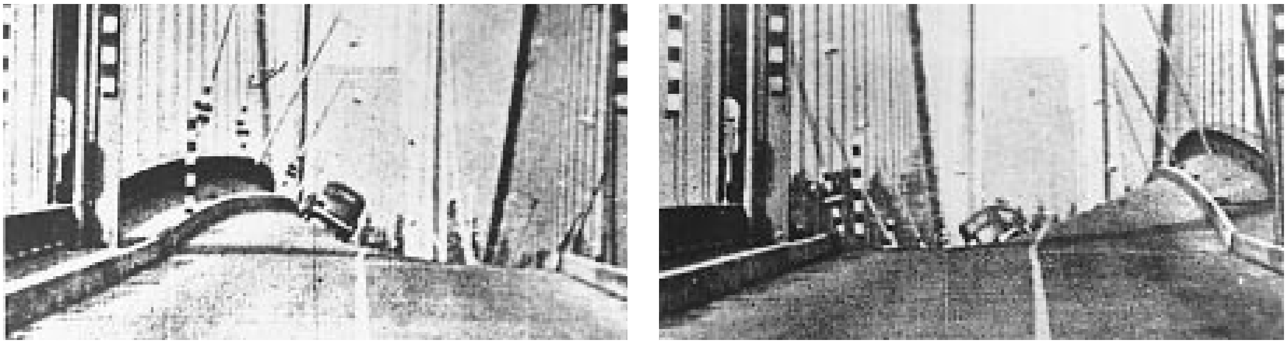


Figure 13-12
On November 7, 1940, the Tacoma Narrows suspension bridge collapsed, just four months after it opened. Standing waves caused by strong winds set the bridge in motion and led to its collapse.

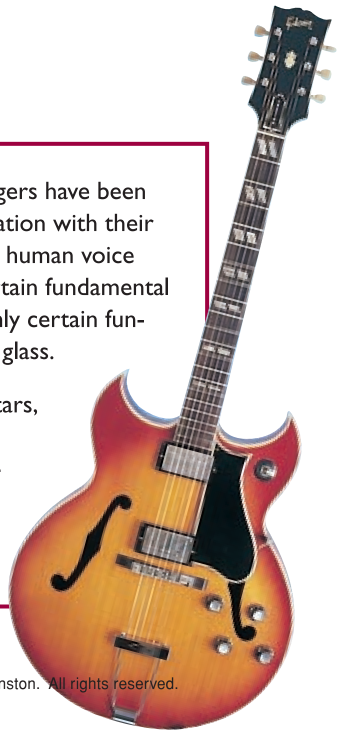
Conceptual Challenge

1. Concert If a 15-person musical ensemble gains 15 new members, so that its size doubles, will a listener perceive the music created by the ensemble to be twice as loud? Why or why not?

2. A noisy factory Federal regulations require that no office or factory worker be exposed to noise levels that average above 90 dB over an 8 h day. Thus, a factory that currently averages 100 dB must reduce its noise level by 10 dB. Assuming that each piece of machinery produces the same amount of noise, what percentage of equipment must be removed? Explain your answer.

3. Broken crystal Opera singers have been known to set crystal goblets in vibration with their powerful voices. In fact, an amplified human voice can shatter the glass, but only at certain fundamental frequencies. Speculate about why only certain fundamental frequencies will break the glass.

4. Electric guitars Electric guitars, which use electric amplifiers to magnify their sound, can have a variety of shapes, but acoustic guitars must have an hourglass shape. Explain why.



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The human ear transmits vibrations that cause nerve impulses

The human ear is divided into three sections—outer, middle, and inner—as shown in **Figure 13-13.** Sound waves from the atmosphere travel down the ear canal of the outer ear. The ear canal terminates at a thin, flat piece of tissue called the eardrum.

The eardrum vibrates with the sound waves and transfers these vibrations to the three small bones of the middle ear, known as the hammer, the anvil, and the stirrup. These bones in turn transmit the vibrations to the inner ear, which contains a snail-shaped tube about 2 cm long called the cochlea.

The cochlea is divided along its length by the basilar membrane, which consists of small hairs and nerve fibers. This membrane has different natural frequencies at different positions. Sound waves of varying frequencies resonate at different spots along the basilar membrane, creating impulses in different nerve fibers. These impulses are then sent to the brain, which interprets them as sounds of varying frequencies.

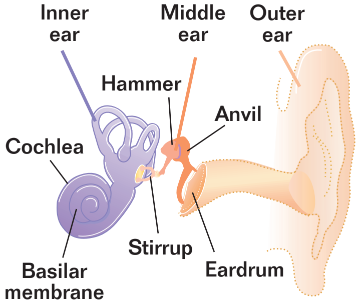


Figure 13-13
Sound waves travel through the three regions of the ear and are then transmitted to the brain as impulses through nerve endings on the basilar membrane.

Section Review

1. When the decibel level of traffic in the street goes from 40 to 60 dB, how much louder does the traffic noise seem? How much greater is the intensity?

2. If two flutists play their instruments together at the same intensity, is the sound twice as loud as that of either flutist playing alone at that intensity? Why or why not?

3. Which of the following factors change when a sound gets louder? Which change when a pitch gets higher?

a. intensity
b. speed of the sound waves
c. frequency
d. decibel level
e. wavelength
f. amplitude

4. A tuning fork consists of two metal prongs that vibrate at a single frequency when struck lightly. What will happen if a vibrating tuning fork is placed near another tuning fork of the same frequency? Explain.

5. **Physics in Action** A certain microphone placed in the ocean is sensitive to sounds emitted by dolphins. To produce a usable signal, sound waves striking the microphone must have a decibel level of 10 dB. If dolphins emit sound waves with a power of 0.050 W, how far can a dolphin be from the microphone and still be heard? (Assume the sound waves propagate spherically, and disregard absorption of the sound waves.)

13-3
Harmonics

13-3 SECTION OBJECTIVES

- **Differentiate between the harmonic series of open and closed pipes.**
- **Calculate the harmonics of a vibrating string and of open and closed pipes.**
- **Relate harmonics and timbre.**
- **Relate the frequency difference between two waves to the number of beats heard per second.**

STANDING WAVES ON A VIBRATING STRING

As discussed in Chapter 12, a variety of standing waves can occur when a string is fixed at one end and set into vibration at the other by a tuning fork or your moving hand. The vibrations on the string of a musical instrument, such as the violin in **Figure 13-14,** usually consist of many standing waves together at the same time, each of which has a different wavelength and frequency. So the sounds you hear from a stringed instrument, even those that sound like a single pitch, actually consist of multiple frequencies.

Table 13-3, on page 495, shows several possible vibrations on an idealized string. The ends of the string, which cannot vibrate, must always be nodes. The simplest vibration that can occur is shown in the first row of **Table 13-3.** In this case, the center of the string experiences the most displacement, and so it is an antinode. Because the distance from one node to the next is always half a wavelength, the string length must equal $\lambda_1/2$. Thus, the wavelength is twice the string length ($\lambda_1 = 2L$).

As described in Chapter 12, the speed of a wave equals the frequency times the wavelength, which can be rearranged as shown.

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

By substituting the value for wavelength found above into this equation for frequency, we see that the frequency of this vibration is equal to the speed of the wave divided by twice the string length.

$$\text{fundamental frequency} = f_1 = \frac{v}{\lambda_1} = \frac{v}{2L}$$

This frequency of vibration is called the **fundamental frequency** of the vibrating string. Because frequency is inversely proportional to wavelength and because we are considering the greatest possible wavelength, the fundamental frequency is the lowest possible frequency of a standing wave.

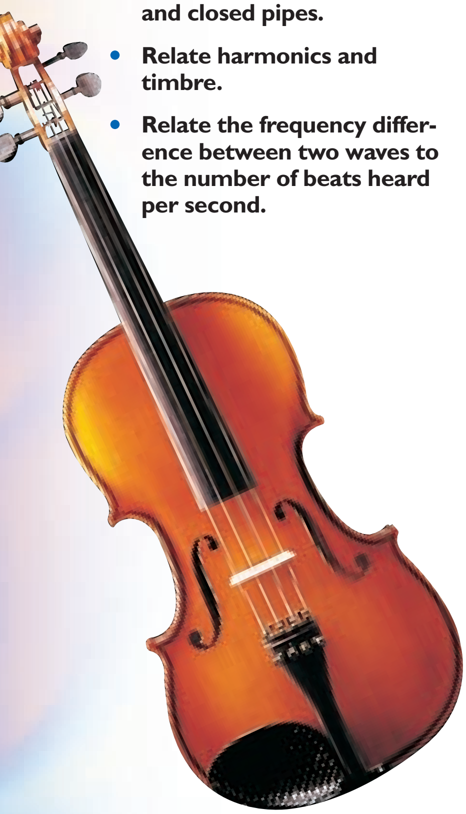


Figure 13-14
The vibrating strings of a violin produce standing waves whose frequencies depend on the string lengths.

fundamental frequency

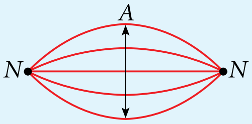
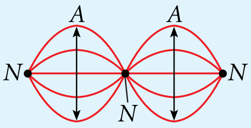
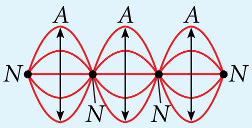
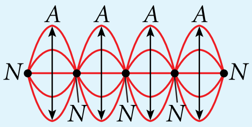
the lowest frequency of vibration of a standing wave

Harmonics are integral multiples of the fundamental frequency

The next possible standing wave for a string is shown in the second row of **Table 13-3.** In this case, there are three nodes instead of two, so the string length is equal to one wavelength. Because this wavelength is half the previous wavelength, the frequency of this wave is twice as much.

$$f_2 = 2f_1$$

Table 13-3 The harmonic series

	$\lambda_1 = 2L$	f_1	fundamental frequency, or first harmonic
	$\lambda_2 = L$	$f_2 = 2f_1$	second harmonic
	$\lambda_3 = \frac{2}{3}L$	$f_3 = 3f_1$	third harmonic
	$\lambda_4 = \frac{1}{2}L$	$f_4 = 4f_1$	fourth harmonic

This pattern continues, and the frequency of the standing wave shown in the third row of **Table 13-3** is three times the fundamental frequency. Hence, the frequencies of the standing wave patterns are all integral multiples of the fundamental frequency. These frequencies form what is called a **harmonic series.** The fundamental frequency (f_1) corresponds to the first harmonic, the next frequency (f_2) corresponds to the second harmonic, and so on.

Because each harmonic is an integral multiple of the fundamental frequency, the equation for the fundamental frequency can be generalized to include the entire harmonic series. Thus, $f_n = nf_1$, where f_1 is the fundamental frequency ($f_1 = \frac{v}{2L}$) and f_n is the frequency of the nth harmonic. Note that v is the speed of waves on the vibrating string and not the speed of the resultant sound waves in air.

harmonic series

a series of frequencies that includes the fundamental frequency and integral multiples of the fundamental frequency

HARMONIC SERIES OF STANDING WAVES ON A VIBRATING STRING

$$f_n = n\frac{v}{2L} \qquad n = 1, 2, 3, \ldots$$

$$\textbf{frequency} = \textbf{harmonic number} \times \frac{\textbf{(speed of waves on the string)}}{\textbf{(2)(length of vibrating string)}}$$

When a guitar player presses down on a guitar string at any point, that point becomes a node and only a portion of the string vibrates. As a result, a single string can be used to create a variety of fundamental frequencies. In the previous equation, L refers to the portion of the string that is vibrating.

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Figure 13-15
The harmonic series present in each of these organ pipes depends on whether the end of the pipe is open or closed.

STANDING WAVES IN AN AIR COLUMN

Standing waves can also be set up in a tube of air, such as the inside of a trumpet, the column of a saxophone, or the pipes of an organ like those shown in **Figure 13-15.** While some waves travel down the tube, others are reflected back upward. These waves traveling in opposite directions combine to produce standing waves. Many brass instruments and woodwinds produce sound by means of these vibrating air columns.

If both ends of a pipe are open, all harmonics are present

The harmonic series present in an organ pipe depends on whether the reflecting end of the pipe is open or closed. When the reflecting end of the pipe is open, as is illustrated in **Figure 13-16,** the air molecules have complete freedom of motion, so an antinode exists at this end. If a pipe is open at both ends, each end is an antinode. This is the exact opposite of a string fixed at both ends, where both ends are nodes.

Because the distance from one node to the next ($\frac{1}{2}\lambda$) equals the distance from one antinode to the next, the pattern of standing waves that can occur in a pipe open at both ends is the same as that of a vibrating string. Thus, the entire harmonic series is present in this case, as shown in **Figure 13-16,** and our earlier equation for the harmonic series of a vibrating string can be used.

HARMONIC SERIES OF A PIPE OPEN AT BOTH ENDS

$$f_n = n\frac{v}{2L} \qquad n = 1, 2, 3, \ldots$$

$$\textbf{frequency} = \textbf{harmonic number} \times \frac{\textbf{(speed of sound in the pipe)}}{\textbf{(2)(length of vibrating air column)}}$$

In this equation, L represents the length of the vibrating air column. Just as the fundamental frequency of a string instrument can be varied by changing the string length, the fundamental frequency of many woodwind and brass instruments can be varied by changing the length of the vibrating air column.

Did you know?

A flute is similar to a pipe open at both ends. When all keys of a flute are closed, the length of the vibrating air column is approximately equal to the length of the flute. As the keys are opened one by one, the length of the vibrating air column decreases, and the fundamental frequency increases.

Harmonics in an open-ended pipe

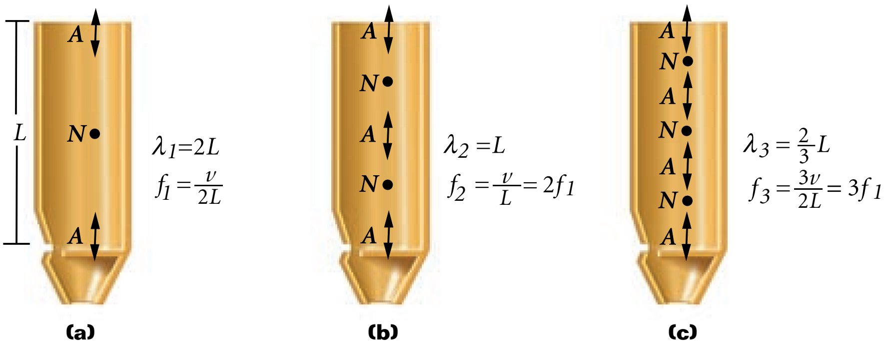

Figure 13-16
In a pipe open at both ends, each end is an antinode, and all harmonics are present. Shown here are the **(a)** first, **(b)** second, and **(c)** third harmonics.

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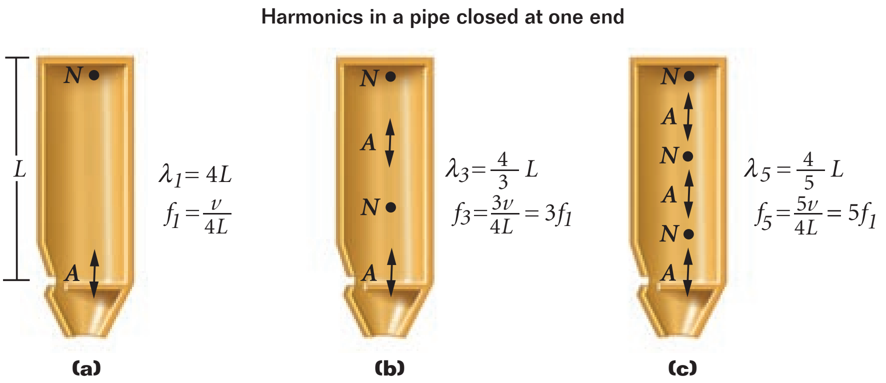

Figure 13-17
In a pipe closed at one end, the closed end is a node and the open end is an antinode. In this case, only the odd harmonics are present. The **(a)** first, **(b)** third, and **(c)** fifth harmonics are shown here.

If one end of a pipe is closed, only odd harmonics are present

When one end of an organ pipe is closed, as is illustrated in **Figure 13-17,** the movement of air molecules is restricted at this end, making this end a node. In this case, one end of the pipe is a node and the other is an antinode. As a result, a different set of standing waves can occur.

As shown in **Figure 13-17(a),** the simplest possible standing wave that can exist in this pipe is equal to one-fourth of a wavelength. The wavelength of this standing wave equals four times the length of the pipe. Thus, in this case, the fundamental frequency equals the velocity divided by four times the pipe length.

$$f_1 = \frac{v}{\lambda_1} = \frac{v}{4L}$$

For the case shown in **Figure 13-17(b),** there is three-fourths of a wavelength in the pipe, so the wavelength is four-thirds the length of the pipe ($\lambda_3 = \frac{4}{3}L$). Substituting this value into the equation for frequency gives the frequency of this harmonic.

$$f_3 = \frac{v}{\lambda_3} = \frac{v}{\frac{4}{3}L} = \frac{3v}{4L} = 3f_1$$

Notice that the frequency of this harmonic is *three* times the fundamental frequency. Repeating this calculation for the case shown in **Figure 13-17(c)** gives a frequency equal to *five* times the fundamental frequency. Thus, only the odd-numbered harmonics vibrate in a pipe closed at one end.

As with the vibrating string, we can generalize the equation for the harmonic series of a pipe closed at one end.

HARMONIC SERIES OF A PIPE CLOSED AT ONE END

$$f_n = n\frac{v}{4L} \qquad n = 1, 3, 5, \ldots$$

$$\textbf{frequency} = \textbf{harmonic number} \times \frac{\textbf{(speed of sound in the pipe)}}{\textbf{(4)(length of vibrating air column)}}$$

Quick Lab

A Pipe Closed at One End

MATERIALS LIST

- ✔ straw
- ✔ scissors

SAFETY CAUTION

Always use caution when working with scissors.

Snip off the corners of one end of the straw so that the end tapers to a point, as shown above. Chew on this end to flatten it, and you create a double-reed instrument! Put your lips around the tapered end of the straw, press them together tightly, and blow through the straw. When you hear a steady tone, slowly snip off pieces of the straw at the other end. Be careful to keep about the same amount of pressure with your lips. How does the pitch change as the straw becomes shorter? How can you account for this change in pitch? You may be able to produce more than one tone for any given length of the straw. How is this possible?

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Trumpets, saxophones, and clarinets are similar to a pipe closed at one end. Although a trumpet has two open ends, the player's mouth effectively closes one end of the instrument. In a saxophone or a clarinet, the reed closes one end.

Despite the similarity between these instruments and a pipe closed at one end, our equation for the harmonic series of pipes does not directly apply to such instruments because any deviation from the cylindrical shape of a pipe affects the harmonic series of an instrument. For example, a clarinet is primarily cylindrical, but because the open end of the instrument is bell-shaped, there are some even harmonics in a clarinet's tone at relatively small intensities. The shape of a saxophone is such that the harmonic series in a saxophone is similar to a cylindrical pipe open at both ends even though only one end of the saxophone is open. These deviations are in part responsible for the variety of sounds that can be produced by different instruments.

SAMPLE PROBLEM 13B

Harmonics

PROBLEM

What are the first three harmonics in a 2.45 m long pipe that is open at both ends? What are the first three harmonics of this pipe when one end of the pipe is closed? Assume that the speed of sound in air is 345 m/s for both of these situations.

SOLUTION

1. DEFINE

Given: $L = 2.45$ m $\quad v = 345$ m/s

Unknown: Pipe open at both ends: $f_1 \quad f_2 \quad f_3$

Pipe closed at one end: $f_1 \quad f_3 \quad f_5$

2. PLAN

Choose an equation(s) or situation:

When the pipe is open, all harmonics are present. Thus, the fundamental frequency can be found by using the equation for the entire harmonic series, given on page 496:

$$f_n = n\frac{v}{2L},\ n = 1, 2, 3, \ldots$$

When the pipe is closed at one end, only odd harmonics are present. In this case, the fundamental frequency is found by using the equation for the odd harmonic series, given on page 497:

$$f_n = n\frac{v}{4L},\ n = 1, 3, 5, \ldots$$

In both cases, the second two harmonics can be found by multiplying the harmonic numbers by the fundamental frequency.

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3. CALCULATE For a pipe open at both ends:

$$f_1 = n\frac{v}{2L} = (1)\left(\frac{345 \text{ m/s}}{(2)(2.45 \text{ m})}\right) = \boxed{70.4 \text{ Hz}}$$

Because all harmonics are present in this case, the next two harmonics are the second and the third:

$$f_2 = 2f_1 = (2)(70.4 \text{ Hz}) = \boxed{141 \text{ Hz}}$$

$$f_3 = 3f_1 = (3)(70.4 \text{ Hz}) = \boxed{211 \text{ Hz}}$$

For a pipe closed at one end:

$$f_1 = n\frac{v}{4L} = (1)\left(\frac{345 \text{ m/s}}{(4)(2.45 \text{ m})}\right) = \boxed{35.2 \text{ Hz}}$$

Only the odd harmonics are present in this case, so the next possible harmonics are the third and the fifth:

$$f_3 = 3f_1 = (3)(35.2 \text{ Hz}) = \boxed{106 \text{ Hz}}$$

$$f_5 = 5f_1 = (5)(35.2 \text{ Hz}) = \boxed{176 \text{ Hz}}$$

4. EVALUATE In a pipe open at both ends, the first possible wavelength is $2L$; in a pipe closed at one end, the first possible wavelength is $4L$. Because frequency and wavelength are inversely proportional, the fundamental frequency of the open pipe should be twice that of the closed pipe, that is, $70.4 = (2)(35.2)$.

PRACTICE 13B

Harmonics

1. What is the fundamental frequency of a 0.20 m long organ pipe that is closed at one end, when the speed of sound in the pipe is 352 m/s?

2. A flute is essentially a pipe open at both ends. The length of a flute is approximately 66.0 cm. What are the first three harmonics of a flute when all keys are closed, making the vibrating air column approximately equal to the length of the flute? The speed of sound in the flute is 340 m/s.

3. What is the fundamental frequency of a guitar string when the speed of waves on the string is 115 m/s and the effective string lengths are as follows:

a. 70.0 cm **b.** 50.0 cm **c.** 40.0 cm

4. A violin string that is 50.0 cm long has a fundamental frequency of 440 Hz. What is the speed of the waves on this string?

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Harmonics account for sound quality, or timbre

Table 13-4, on page 501, shows the harmonics present in a tuning fork, a clarinet, and a viola when each sounds the musical note A-natural. Each instrument has its own characteristic mixture of harmonics at varying intensities.

The harmonics shown in the second column of **Table 13-4** add together according to the principle of superposition to give the resultant waveform shown in the third column. Since a tuning fork vibrates at only its fundamental frequency, its waveform is simply a sine wave. (Some tuning forks also vibrate at higher frequencies when they are struck hard enough.) The waveforms of the other instruments are more complex because they consist of many harmonics, each at different intensities. Each individual harmonic waveform is a sine wave, but the resultant wave is more complex than a sine wave because each individual waveform has a different frequency.

The different waveforms shown in the third column of **Table 13-4** explain why a clarinet sounds different from a viola, even when both instruments are sounding the same note at the same volume. In music, the mixture of harmonics that produces the characteristic sound of an instrument is referred to as the spectrum of the sound, which results in a response in the listener called sound quality, or **timbre.** The rich harmonics of most instruments provide a much fuller sound than that of a tuning fork.

timbre

the quality of a steady musical sound that is the result of a mixture of harmonics present at different intensities

Consumer Focus *Reverberation*

Auditoriums, churches, concert halls, libraries, and music rooms are designed with specific functions in mind. One auditorium may be made for rock concerts, while another is constructed for use as a lecture hall. Your school's auditorium, for instance, may allow you to hear a speaker well but make a band sound damped and muffled.

Rooms are often constructed so that sounds made by a speaker or a musical instrument bounce back and forth against the ceiling, walls, floor, and other surfaces. This repetitive echo is called *reverberation.* The reverberation time is the amount of time it takes for a sound's intensity to decrease by 60 dB.

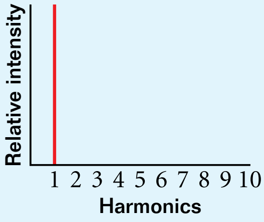
For speech, the auditorium should be designed so that the reverberation time is relatively short. A repeated echo of each word could become confusing to listeners.

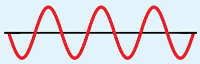
Music halls may also differ in construction depending on the type of music usually played there. For example, rock music is generally less pleasing with a large amount of reverberation, but more reverberation is sometimes desired for orchestral and choral music.

For these reasons, you may notice a difference in the way ceilings, walls, and furnishings are designed in different rooms. Ceilings designed for a lot of reverberation are flat and hard. Ceilings in libraries and other quiet places are often made of soft or textured material to muffle sounds. Padded furnishings and plants can also be strategically arranged to absorb sound. All of these different factors are considered and combined to accomodate the auditory function of a room.

Table 13-4 **Harmonics of a tuning fork, a clarinet, and a viola at the same pitch**

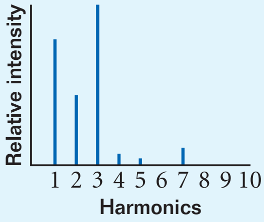
Tuning fork

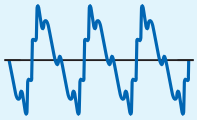




Resultant waveform

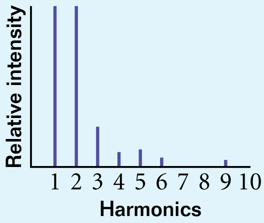
Clarinet

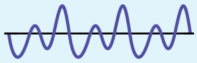




Resultant waveform

Viola





Resultant waveform

The intensity of each harmonic varies within a particular instrument, depending on frequency, amplitude of vibration, and a variety of other factors. With a violin, for example, the intensity of each harmonic depends on where the string is bowed, the speed of the bow on the string, and the force the bow exerts on the string. Because there are so many factors involved, most instruments can produce a wide variety of tones.

Even though the waveforms of a clarinet and a viola are more complex than those of a tuning fork, note that each consists of repeating patterns. Such waveforms are said to be *periodic*. These repeating patterns occur because each frequency is an integral multiple of the fundamental frequency.

Fundamental frequency determines pitch

As you saw in Section 13-1, the frequency of a sound determines its pitch. In musical instruments, the fundamental frequency of a vibration typically determines pitch. Other harmonics are sometimes referred to as overtones. In the chromatic (half-step) musical scale, there are 12 notes, each of which has a characteristic frequency. The frequency of the thirteenth note is exactly twice that of the first note, and together the 13 notes constitute an *octave*. For stringed instruments and open-ended wind instruments, the frequency of the second harmonic of a note corresponds to the frequency of the octave above that note.

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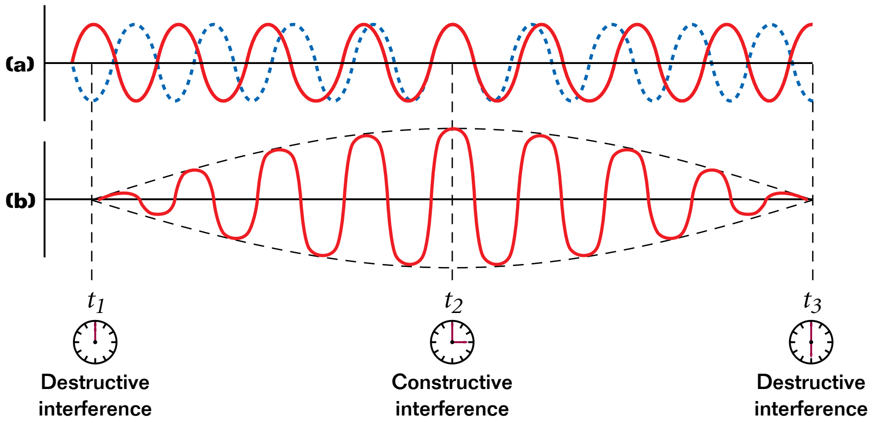


Figure 13-18
Beats are formed by the interference of two waves of slightly different frequencies traveling in the same direction. In this case, one beat occurs at t_2, where constructive interference is greatest.

BEATS

beat

interference of waves of slightly different frequencies traveling in the same direction, perceived as a variation in loudness

So far, we have considered the superposition of waves in a harmonic series, where each frequency is an integral multiple of the fundamental frequency. When two waves of *slightly* different frequencies interfere, the interference pattern varies in such a way that a listener hears an alternation between loudness and softness. The variation from soft to loud and back to soft is called a **beat.**

Sound waves at slightly different frequencies produce beats

Figure 13-18 shows how beats occur. In **Figure 13-18(a),** the waves produced by two tuning forks of different frequencies start exactly opposite one another. These waves combine according to the superposition principle, as shown in **Figure 13-18(b).** When the two waves are exactly opposite one another, they are said to be *out of phase,* and complete destructive interference occurs. For this reason, no sound is heard at t_1.

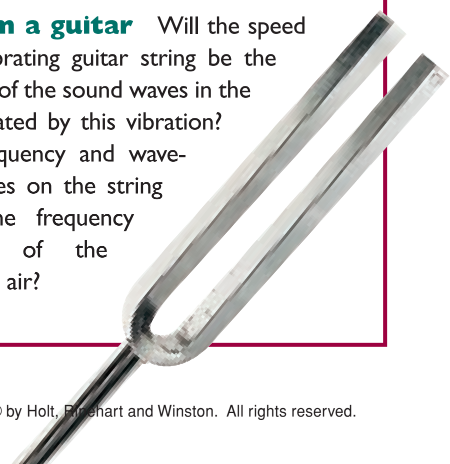
Because these waves have different frequencies, after a few more cycles, the crest of the blue wave matches up with the crest of the red wave, as at t_2. At this

Conceptual Challenge

1. Piano tuning How does a piano tuner use a tuning fork to adjust a piano wire to a certain fundamental frequency?

2. Concert violins Before a performance, musicians tune their instruments to match their fundamental frequencies. If a conductor hears the number of beats decreasing as two violin players are tuning, are the fundamental frequencies of these violins becoming closer together or farther apart? Explain.

3. Sounds from a guitar Will the speed of waves on a vibrating guitar string be the same as the speed of the sound waves in the air that are generated by this vibration? How will the frequency and wavelength of the waves on the string compare with the frequency and wavelength of the sound waves in the air?



point, the waves are said to be *in phase.* Now constructive interference occurs, and the sound is louder. Because the blue wave has a higher frequency than the red wave, the waves are out of phase again at t_3, and no sound is heard.

As time passes, the waves continue to be in and out of phase, the interference constantly shifts between constructive interference and destructive interference, and the listener hears the sound getting softer and louder and then softer again. You may have noticed a similar phenomenon on a playground swing set. If two people are swinging next to one another at different frequencies, the two swings may alternate between being in phase and being out of phase.

Did you know?

The ability to detect beats depends on an individual's hearing and musical training. The average human ear can distinguish beats up to a frequency of approximately 10 beats per second.

The number of beats per second corresponds to the difference between frequencies

In our previous example, there is one beat, which occurs at t_2. One beat corresponds to the blue wave gaining one entire cycle on the red wave. This is because to go from one destructive interference to the next, the red wave must lag one entire cycle behind the blue wave. If the time that lapses from t_1 to t_3 is one second, then the blue wave completes one more cycle per second than the red wave. In other words, its frequency is greater by 1 Hz. By generalizing this, you can see that the frequency difference between two sounds can be found by the number of beats heard per second.

Section Review

1. On a piano, the note middle C has a fundamental frequency of 264 Hz. What is the second harmonic of this note?
2. If the piano wire in item 1 is 66.0 cm long, what is the speed of waves on this wire?
3. A piano tuner using a 392 Hz tuning fork to tune the wire for G-natural hears four beats per second. What are the two possible frequencies of vibration of this piano wire?
4. In a clarinet, the reed end of the instrument acts as a node and the first open hole acts as an antinode. Because the shape of the clarinet is nearly cylindrical, its harmonic series approximately follows that of a pipe closed at one end. What harmonic series is predominant in a clarinet?
5. Which of the following must be different for a trumpet and a banjo when notes are being played by both at the same fundamental frequency?
   a. wavelength in air of the first harmonic
   b. number of harmonics present
   c. intensity of each harmonic
   d. speed of sound in air

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PHYSICS ON THE EDGE

The Doppler Effect and the BIG BANG

Earlier in this chapter, you learned that relative motion between the source of sound waves and an observer creates a frequency shift known as the Doppler effect. For visible light, the Doppler effect is observed as a change in color because the frequency of light waves determines color.

Frequency shifts

Of the colors of the visible spectrum, red light has the lowest frequency and violet light has the highest. When the source of electromagnetic waves is moving toward an observer, the frequency detected is higher than the source frequency. This corresponds to a shift toward the blue end of the spectrum, which is called a *blue shift*. When the source of electromagnetic waves is moving away from an observer, the observer detects a lower frequency, which corresponds to a shift toward the red end of the spectrum, called a *red shift*. These two types of frequency shifts are known as *blue shift* and *red shift*, respectively, even though this shift occurs for any type of radiation, not just visible light.

In astronomy, the light from distant stars or galaxies is analyzed by a process called *spectroscopy*. In this process, starlight is passed through a prism or diffraction grating to produce a spectrum. Dark lines appear in the spectrum at specific frequencies determined by the elements present in the atmospheres of stars. When these lines are shifted toward the red end of the spectrum, astronomers know the star is moving away from Earth; when the lines are shifted toward the blue end, the star is moving toward Earth.

Table 13-5 The Doppler effect for light

stationary source	$v = 0$	no shift
approaching source	v	blue shift
receding source	v	red shift

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The expansion of the universe

As scientists began to study other galaxies with spectroscopy, the results were astonishing: nearly all of the galaxies that were observed exhibited a red shift, which suggested that they were moving away from Earth. If all galaxies are moving away from Earth, the universe must be expanding. This does not suggest that Earth is at the center of the expansion; from any other point in the universe, the same phenomenon would be observed.

The expansion of the universe suggests that at some point in the past the universe must have been confined to a point of infinite density. The eruption of the universe is often referred to as the *big bang,* which is generally considered to have occurred between 10 billion and 20 billion years ago. Current models indicate that the big bang involved such great amounts of energy in such a small space that matter could not form clumps or even individual atoms. It took about 700 000 years for the universe to cool from around 10^{32} K to around 3000 K, a temperature cool enough for atoms to begin forming.

Figure 13-19
Penzias and Wilson detected microwave background radiation, presumably left over from the big bang, with the horn antenna (in background) at Bell Telephone Laboratories, in New Jersey.

Experimental verification

In the 1960s, a group of scientists at Princeton predicted that the explosion of the big bang was so momentous that a small amount of radiation—the leftover glow from the big bang—should still be found in the universe. Around this time, Arno Penzias and Robert Wilson, of Bell Labs, noticed a faint background hiss interfering with satellite-communications experiments they were conducting. This signal, which was detected in equal amounts in all directions, remained despite all attempts to remove it. Penzias and Wilson learned of the Princeton group's work and realized that the interference they were experiencing matched the characteristics of the radiation expected from the big bang. Subsequent experiments have confirmed the existence of this radiation, known as *cosmic microwave background radiation.* This background radiation is considered to be the most conclusive evidence for the big bang theory.

The big bang theory is generally accepted by scientists today. Research now focuses on more-detailed issues. However, there are certain phenomena that the standard big bang model cannot account for, such as the uniform distribution of matter on a large scale and the large-scale clustering of galaxies. As a result, some scientists are currently working on modifications and refinements to the standard big bang theory.

In December 1995, the Hubble Space Telescope obtained an image that reveals galaxies so far away from Earth that their light must have left them 10 billion to 20 billion years ago. This image shows the galaxies as they existed 10 billion to 20 billion years in the past, when the universe was less than a billion years old. As technology improves, scientists can see galaxies even farther away and, hence, even farther back in time. Such observations may resolve many of the current questions regarding the origin of the universe.

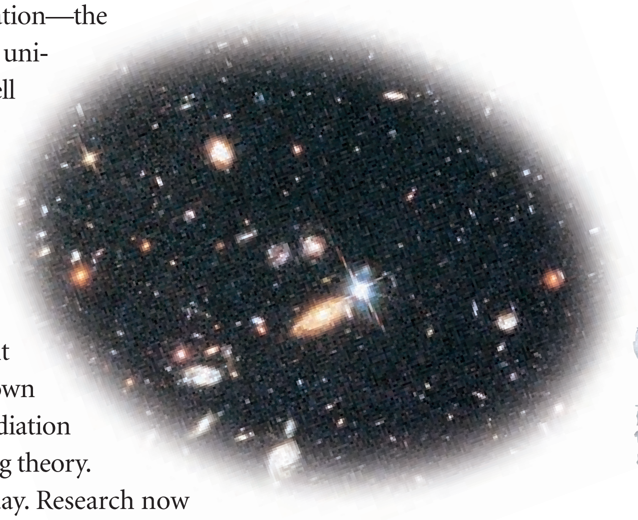

Figure 13-20
This image, called the Hubble Deep Field, is a composite of 342 separate exposures taken by NASA's Hubble Space Telescope during 10 consecutive days. Most of the objects are galaxies, each containing billions of stars. The full image contains over 1500 galaxies, some perhaps dating back to when galaxies first began forming.

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CHAPTER 13
Summary

KEY TERMS

beat (p. 502)

compression (p. 480)

decibel level (p. 490)

Doppler effect (p. 485)

fundamental frequency (p. 494)

harmonic series (p. 495)

intensity (p. 487)

pitch (p. 481)

rarefaction (p. 480)

resonance (p. 492)

timbre (p. 500)

KEY IDEAS

Section 13-1 Sound waves

- The frequency of a sound wave determines its pitch.
- The speed of sound depends on the medium.
- The relative motion between the source of waves and an observer creates an apparent frequency shift known as the Doppler effect.

Section 13-2 Sound intensity and resonance

- The sound intensity of a spherical wave is the power per area, as follows:

$$\boxed{\text{Intensity} = \frac{P}{4\pi r^2}}$$

- Decibel level is a measure of relative intensity on a logarithmic scale.
- A forced vibration at the natural frequency produces resonance.

Section 13-3 Harmonics

- Harmonics of a vibrating string or a pipe open at both ends can be found with the following equation:

$$\boxed{f_n = n\frac{v}{2L},\ n = 1, 2, 3, \ldots}$$

- Harmonics of a pipe closed at one end can be found with the following equation:

$$\boxed{f_n = n\frac{v}{4L},\ n = 1, 3, 5, \ldots}$$

- The number and intensity of harmonics account for the sound quality of an instrument, also known as timbre.

Variable symbols

	Quantities	Units	
	sound intensity	W/m^2	watts/meters squared
	decibel level	dB	decibels
f_n	frequency of the *n*th harmonic	Hz	Hertz = s^{-1}
L	length of a vibrating string or an air column	m	meters

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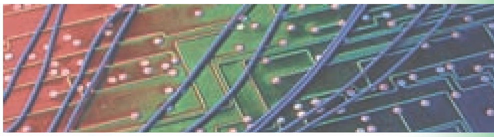
CHAPTER 13
Review and Assess



SOUND WAVES

Review questions

1. Why are sound waves in air characterized as longitudinal?

2. Draw the sine curve that corresponds to the sound wave depicted in **Figure 13-21.**

Figure 13-21

3. What is the difference between frequency and pitch?

4. Why can a dog hear a sound produced by a dog whistle, while his owner cannot?

5. What are the differences between infrasonic, audible, and ultrasonic sound waves?

6. Explain why the speed of sound depends on the temperature of the medium. Why is this temperature dependence more noticeable in a gas than in a solid or a liquid?

7. The Doppler effect occurs when
   a. a source of sound moves toward a listener.
   b. a listener moves toward a source of sound.
   c. a listener and a source of sound move away from each other.
   d. a listener and a source of sound move toward each other.
   e. All of the above

8. You are at a street corner and hear an ambulance siren. Without looking, how can you tell when the ambulance passes by?

9. Ultrasound waves are often used to produce images of objects inside the body. Why are ultrasound waves effective for this purpose?

Conceptual questions

10. If the wavelength of a sound source is reduced by a factor of 2, what happens to the wave's frequency? What happens to its speed?

11. As a result of a distant explosion, an observer first senses a ground tremor, then hears the explosion. What accounts for this time lag?

12. By listening to a band or an orchestra, how can you determine that the speed of sound is the same for all frequencies?

13. A sound wave travels in air at a frequency of 500 Hz. If part of the wave travels from air into water, does its frequency change? Does its wavelength change? Note that the speed of sound in air is about 340 m/s, whereas the speed of sound in water is about 1500 m/s.

14. A fire engine is moving at 40 m/s and sounding its horn. A car in front of the fire engine is moving at 30 m/s, and a van in front of the car is stationary. Which observer hears the fire engine's horn at a higher pitch, the driver of the car or the driver of the van?

15. A bat flying toward a wall emits a chirp at 40 kHz. Is the frequency of the echo received by the bat greater than, less than, or equal to 40 kHz?

SOUND INTENSITY AND RESONANCE

Review questions

16. If a sound seems to be getting louder, which of the following is probably increasing?
   a. intensity
   b. frequency
   c. speed of sound
   d. wavelength

Back

17. What is the difference between intensity, decibel level, and volume?

18. Using **Table 13-2** (page 490) as a guide, estimate the decibel levels of the following sounds: a cheering crowd at a football game, background noise in a church, the pages of this textbook being turned, and light traffic.

19. Why is the threshold of hearing represented as a curve in **Figure 13-10** (page 489) rather than as a single point?

20. Under what conditions does resonance occur?

Conceptual questions

21. If the distance from a point source of sound is tripled, by what factor does the sound intensity decrease? Assume there are no reflections from nearby objects to affect your results.

22. Why is the intensity of an echo less than that of the original sound?

23. The decibel level of an orchestra is 90 dB, and a single violin achieves a level of 70 dB. How do the intensity and volume of the sound of the full orchestra compare with those of the violin's sound?

24. A noisy machine in a factory produces a decibel rating of 80 dB. How many identical machines could you add to the factory without exceeding the 90 dB limit set by federal regulations?

25. Why are pushes given to a playground swing more effective if they are given at certain, regular intervals than if they are given at random positions in the swing's cycle?

26. Although soldiers are usually required to march together in step, they must break their march when crossing a bridge. Explain the possible danger of crossing a rickety bridge without taking this precaution.

Practice problems

27. A baseball coach shouts loudly at an umpire standing 5.0 meters away. If the sound power produced by the coach is 3.1×10^{-3} W, what is the decibel level of the sound when it reaches the umpire? (Hint: See Sample Problem 13A, then use **Table 13-2** on page 490.)

28. A stereo speaker represented by P in **Figure 13-22** emits sound waves with a power output of 100.0 W. What is the intensity of the sound waves at point x when $r = 10.0$ m? (See Sample Problem 13A.)

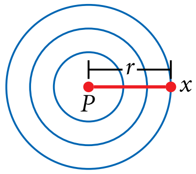


Figure 13-22

HARMONICS

Review questions

29. What is fundamental frequency? How are harmonics related to the fundamental frequency?

30. **Figure 13-23** shows a stretched string vibrating in several of its modes. If the length of the string is 2.0 m, what is the wavelength of the wave on the string in **(a)**, **(b)**, **(c)**, and **(d)**?

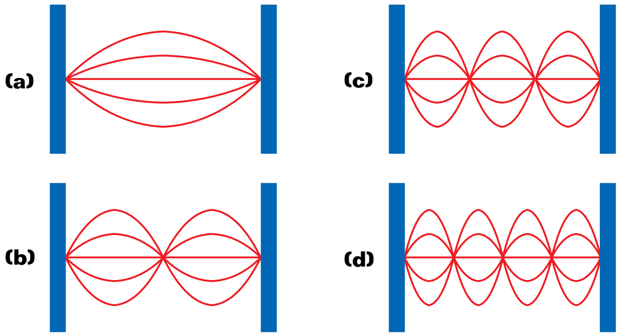


Figure 13-23

31. Why does a pipe closed at one end have a different harmonic series than an open pipe?

32. Explain why a saxophone sounds different from a clarinet, even when they sound the same fundamental frequency at the same decibel level.

Conceptual questions

33. Why does a vibrating guitar string sound louder when it is on the instrument than it does when it is stretched on a work bench?

34. Two violin players tuning their instruments together hear six beats in 2 s. What is the frequency difference between the two violins?

35. What is the purpose of the slide on a trombone and the valves on a trumpet?

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36. A student records the first 10 harmonics for a pipe. Is it possible to determine whether the pipe is open or closed by comparing the difference in frequencies between the adjacent harmonics with the fundamental frequency? Explain.

37. A flute is similar to a pipe open at both ends, while a clarinet is similar to a pipe closed at one end. Explain why the fundamental frequency of a flute is about twice that of the clarinet, even though the length of these two instruments is approximately the same.

38. The fundamental frequency of any note produced by a flute will vary slightly with temperature changes in the air. For any given note, will an increase in temperature produce a slightly higher fundamental frequency or a slightly lower one?

Practice problems

39. What are the first three harmonics of a note produced on a 31.0 cm long violin string if waves on this string have a speed of 274.4 m/s?
(See Sample Problem 13B.)

40. The human ear canal is about 2.8 cm long and can be regarded as a tube open at one end and closed at the eardrum. What is the fundamental frequency around which we would expect hearing to be best when the speed of sound in air is 340 m/s?
(See Sample Problem 13B.)

MIXED REVIEW

41. A pipe that is open at both ends has a fundamental frequency of 320 Hz when the speed of sound in air is 331 m/s.
   - **a.** What is the length of this pipe?
   - **b.** What are the next two harmonics?
   - **c.** What is the fundamental frequency of this pipe when the speed of sound in air is increased to 367 m/s due to a rise in the temperature of the air?

42. The area of a typical eardrum is approximately 5.0×10^{-5} m^2. Calculate the sound power (the energy per second) incident on the eardrum at
   - **a.** the threshold of hearing.
   - **b.** the threshold of pain.

43. The frequency of a tuning fork can be found by the method shown in **Figure 13-24.** A long tube open at both ends is submerged in a beaker of water, and the vibrating tuning fork is placed near the top of the tube. The length of the air column, *L*, is adjusted by moving the tube vertically. The sound waves generated by the fork are reinforced when the length of the air column corresponds to one of the resonant frequencies of the tube. The largest value for *L* for which a peak occurs in sound intensity is 9.00 cm. (Use 345 m/s as the speed of sound in air.)
   - **a.** What is the frequency of the tuning fork?
   - **b.** What is the value of *L* for the next two harmonics?

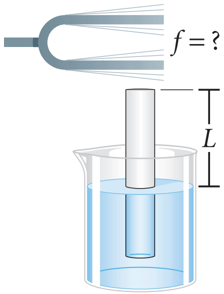

Figure 13-24

44. When two tuning forks of 132 Hz and 137 Hz, respectively, are sounded simultaneously, how many beats per second are heard?

45. The range of human hearing extends from approximately 20 Hz to 20 000 Hz. Find the wavelengths of these extremes when the speed of sound in air is equal to 343 m/s.

46. A dolphin in 25°C sea water emits a sound directed toward the bottom of the ocean 150 m below. How much time passes before it hears an echo? (See **Table 13-1** on page 482 for the speed of the sound.)

47. An open organ pipe is 2.46 m long, and the speed of the air in the pipe is 345 m/s.
   - **a.** What is the fundamental frequency of this pipe?
   - **b.** How many harmonics are possible in the normal hearing range, 20 Hz to 20 000 Hz?

48. The greatest value ever achieved for the speed of sound in air is about 1.0×10^4 m/s, and the highest frequency ever produced is about 2.0×10^{10} Hz. Find the wavelength of this wave.

49. If you blow across the open end of a soda bottle and produce a tone of 250 Hz, what will be the frequency of the next harmonic heard if you blow much harder?

50. A rock group is playing in a club. Sound emerging outdoors from an open door spreads uniformly in all directions. If the decibel level is 70 dB at a distance of 1.0 m from the door, at what distance is the music just barely audible to a person with a normal threshold of hearing? Disregard absorption.

51. The fundamental frequency of an open organ pipe corresponds to the note middle C ($f = 261.6$ Hz on the chromatic musical scale). The third harmonic (f_3) of another organ pipe that is closed at one end has the same frequency. Compare the lengths of these two pipes.

52. A typical decibel level for a buzzing mosquito is 40 dB, and normal conversation is approximately 50 dB. How many buzzing mosquitoes will produce a sound intensity equal to that of normal conversation?

53. Some studies indicate that the upper frequency limit of hearing is determined by the diameter of the eardrum. The wavelength of the sound wave and the diameter of the eardrum are approximately equal at this upper limit. If this is so, what is the diameter of the eardrum of a person capable of hearing 2.0×10^4 Hz? Assume 378 m/s is the speed of sound in the ear.

54. The decibel level of the noise from a jet aircraft is 130 dB when measured 20.0 m from the aircraft.

a. How much sound power does the jet aircraft emit?

b. How much sound power would strike the eardrum of an airport worker 20.0 m from the aircraft? (Use the diameter found in item 53 to calculate the area of the eardrum.)

Alternative Assessment

Performance assessment

1. A new airport is being built 750 m from your school. The noise level 50 m from planes that will land at the airport is 130 dB. In open spaces, such as the fields between the school and the airport, the level decreases by 20 dB each time the distance increases tenfold. Work in a cooperative group to research the options for keeping the noise level tolerable at the school. How far away would the school have to be moved to make the sound manageable? Research the cost of land near your school. What options are available for soundproofing the school's buildings? How expensive are these options? Have each member in the group present the advantages and disadvantages of such options.

2. Use soft-drink bottles and water to make a musical instrument. Adjust the amount of water in different bottles to create musical notes. Play them as percussion instruments (by tapping the bottles) or as wind instruments (by blowing over the mouths of individual bottles). What media are vibrating in each case? What affects the fundamental frequency? Use a microphone and an oscilloscope to analyze your performance and to demonstrate the effects of tuning your instrument.

Portfolio projects

3. Interview members of the medical profession to learn about human hearing. What are some types of hearing disabilities? How are hearing disabilities related to disease, age, and occupational or environmental hazards? What procedures and instruments are used to test hearing? How do hearing aids help? What are the limitations of hearing aids? Present your findings to the class.

4. Do research on the types of architectural acoustics that would affect a restaurant. What are some of the acoustics problems in places where many people gather? How do odd-shaped ceilings, decorative panels, draperies, and glass windows affect echo and noise? Find the shortest wavelengths of sounds that should be absorbed, considering that conversation sounds range from 500 to 5000 Hz. Prepare a plan or a model of your school cafeteria showing what approaches you would use to keep the level of noise to a minimum.

Technology & Learning

Graphing calculators

Refer to Appendix B for instructions on downloading programs for your calculator. The program "Chap13" allows you to analyze a graph of the frequency of a sound versus its apparent frequency to a stationary observer.

As you learned earlier in this chapter, a Doppler effect is experienced whenever there is relative motion between a source of sound and an observer. The frequencies heard by the observer can be described by the following two equations in which f' represents the apparent frequency and f represents the actual frequency.

$$f' = f\left(\frac{v_{sound}}{v_{sound} - v_{source}}\right)$$

$$f' = f\left(\frac{v_{sound}}{v_{sound} + v_{source}}\right)$$

The program "Chap13" stored on your graphing calculator makes use of the Doppler effect equations. Once the "Chap13" program is executed, your calculator will ask for the speed of sound and the speed of the source.

The graphing calculator will use the following equations to create two graphs: the apparent frequency (Y_1) versus the actual frequency (X) as the source approaches the observer, and the apparent frequency (Y_2) versus the actual frequency (X) as the source moves away from the observer. The relationships in these equations are the same as those in the Doppler effect equations shown above.

$$Y_1 = SX/(S-V)$$

$$Y_2 = SX/(S+V)$$

a. Which frequency is higher: Y_1 or Y_2?

Execute "Chap13" on the [PRGM] menu, and press [ENTER] to begin the program. Enter the magnitudes of the speed of sound and the speed of the source (shown below), pressing [ENTER] after each value.

The calculator will provide graphs of the actual frequency versus the apparent frequencies. (If the graphs are not visible, press [WINDOW] and change the settings for the graph window, then press [GRAPH].)

Press [TRACE], and use the arrow keys to trace along the curves. The *x*-value corresponds to the source's actual frequency in hertz. The *y*-value in the upper graph corresponds to the frequency of the source as heard by the observer as the source approaches the observer. The *y*-value in the lower graph corresponds to the frequency of the source as heard by the observer as the source moves away from the observer. Use the [▲] and [▼] keys to toggle between the two graphs.

Determine the apparent frequencies in the following cases (b–e) if the speed of sound is 346 m/s:

b. a car horn tuned to middle C (264 Hz) passing the listener at a speed of 25 m/s

c. a car horn tuned to G (392 Hz) passing the listener at a speed of 25 m/s

d. a trumpet player playing middle C (264 Hz) on a parade float that passes the listener at a speed of 5.0 m/s

e. a trumpet player playing G (392 Hz) on a parade float that passes the listener at a speed of 5.0 m/s

f. Two police cars are in pursuit of a criminal. Car 54 drives past you at 25 m/s, then car 42 passes you at 30 m/s. Both cars have the same siren set to play a constant frequency. Which car's siren will sound the most different when moving toward you versus moving away from you?

Press [2nd] [QUIT] to stop graphing. Press [ENTER] to input new values or [CLEAR] to end the program.

CHAPTER 13
Laboratory Exercise

OBJECTIVES

- Find the speed of sound in air.

MATERIALS LIST

✔ Check list for appropriate procedure.

PROCEDURE

CBL AND SENSORS

✔ cardboard tube
✔ CBL
✔ CBL microphone
✔ graphing calculator with link cable
✔ masking tape
✔ meterstick
✔ support stand with clamp
✔ CBL temperature sensor

RESONANCE APPARATUS

✔ 4 tuning forks of different frequencies
✔ Erlenmeyer flask, 1000 mL
✔ resonance apparatus with clamp
✔ thermometer
✔ tuning-fork hammer
✔ water

SPEED OF SOUND

Sound waves can travel through solids, liquids, and gases. The speed of sound in a medium depends on the density of the particles that make up the medium. The speed also depends on the temperature, especially in a gas like air. In air, sound travels faster at higher temperatures and slower at lower temperatures. In this experiment, you will measure the speed of sound in air using one of the methods described below.

- **CBL and sensors** The speed of sound will be determined using a CBL microphone placed directly above the opening of a large tube. A short, sharp noise will be recorded by the microphone at the top of the tube and again after the sound travels down the tube and reflects back to the microphone. You can use the time between recordings and distance traveled by the sound to determine the speed of sound in air.

- **Resonance apparatus** The speed of sound will be determined using a tuning fork to produce resonance in a closed tube. The wavelength of the sound may be calculated from the resonant length of the tube, and the speed of the sound can be calculated from the equation $v = f\lambda$, where v is the speed of sound, f is the frequency of the sound produced by the tuning fork, and λ is the wavelength of the sound.

SAFETY

- **Never put broken glass or ceramics in a regular waste container. Use a dustpan, brush, and heavy gloves to carefully pick up broken pieces and dispose of them in a container specifically provided for this purpose.**
- **If a thermometer breaks, notify the teacher immediately.**

PREPARATION

1. Determine whether you will be using the CBL and sensors procedure or the resonance apparatus procedure. Read the entire lab for the appropriate procedure, and plan what steps you will take.

Resonance apparatus procedure begins on page 514.

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PROCEDURE

CBL AND SENSORS

Finding the speed of sound

2. Prepare a data table in your lab notebook with four columns and five rows. In the first row, label the first through fourth columns *Trial, Distance from microphone to bottom of tube (m), Temperature (°C),* and *Time interval (s).* In the first column, label the second through fifth rows *1, 2, 3,* and *4.*

3. Set up the temperature probe, CBL microphone, ring stand, tube, CBL, and calculator, as shown in **Figure 13-25.** Tape or clamp the tube securely in place. Clamp the CBL microphone to the edge of the table or to a ring stand so that the microphone points down and is directly above the open end of the tube. Connect the CBL to the graphing calculator. Connect the CBL microphone to the CH1 port and the temperature probe to the CH2 port on the CBL unit. Hang the temperature probe inside the tube to measure the air temperature.

4. Turn on the CBL unit and the calculator. Start the program PHYSICS on the calculator.

   a. Select the *SET UP PROBES* option from the MAIN MENU. Enter 1 for the number of probes. Select the *TEMPERATURE* probe. Enter 2 for the channel number.

   b. Select the *MONITOR INPUT* option from the MAIN MENU. Record the temperature reading in your data table. Press "+" to return to the MAIN MENU.

5. From the MAIN MENU, select the *SET UP PROBES* option. Enter 1 for the number of probes. Select the *MICROPHONE*. Your teacher will tell you what type of microphone you are using. Select the appropriate description from the list on the calculator. From the COLLECTION MODE menu, select *WAVEFORM/TRIGR*. Press ENTER on the graphing calculator.

6. Make a loud, short noise—such as a snap of the fingers—directly above the tube. This will trigger the CBL to collect the sound data.

7. When the CBL unit displays DONE, press ENTER on the calculator.

8. Use the metric ruler to measure the length from the bottom of the CBL microphone to the bottom of the tube. Record this length to the nearest millimeter in the data table.

9. Look at the graph on the graphing calculator, which shows the sound plotted against time in seconds. There should be two peaks on the graph, one near the beginning and one a little later. The first peak is the sound and the second peak is the echo of the sound. Use the arrow keys to trace the graph.

Figure 13-25
Step 6: The CBL will begin collecting sound data as soon as you make a sound, so work quietly until you are ready to begin the experiment. Remain quiet until the CBL displays DONE. Background noise may affect your results.
Step 9: On the graph, the first and second peaks may not be the same height, but they should both be noticeably higher than the other points on the graph. If the sound was too loud, the graph will show many high and low points. Repeat with a softer sound for better results.

10. Find the difference between the *x*-values of the two peaks to find the time interval between them. Record the time interval in your data table. Sketch the graph in your lab notebook. Press ENTER on the calculator.

11. Repeat the procedure for several trials. Try different sounds, such as a soft noise, a loud noise, a high-pitched sound, or a low-pitched sound. Record all data in your data table.

12. Clean up your work area. Put equipment away safely so that it is ready to be used again. Recycle or dispose of used materials as directed by your teacher.

Analysis and Interpretation begins on page 515.

PROCEDURE

RESONANCE APPARATUS

Finding the speed of sound

2. Prepare a data table in your lab notebook with four columns and five rows. In the first row, label the first through fourth columns *Trial, Length of tube (m), Frequency (Hz),* and *Temperature (°C).* In the first column, label the second through fifth rows *1, 2, 3,* and *4.*

3. Set up the resonance apparatus as shown in **Figure 13-26.**

4. Raise the reservoir so that the top is level with the top of the tube. Fill the reservoir with water until the level in the tube is at the 5 cm mark.

Figure 13-26
Step 7: From the position of greatest resonance, move the reservoir up 2 cm and down again until you find the exact position.

5. Measure and record the temperature of the air inside the tube. Select a tuning fork, and record the frequency of the fork in the data table.

6. Securely clamp the tuning fork in place as shown in the figure, with the lower tine about 1 cm above the end of the tube. Strike the tuning fork sharply, but not too hard, with the tuning-fork hammer to create a vibration. A few practice strikes may be helpful to distinguish the tonal sound of the tuning fork from the unwanted metallic "ringing" sound that may result from striking the fork too hard. ***Do not strike the fork with anything other than a hard rubber mallet.***

7. While the tuning fork is vibrating directly above the tube, slowly lower the reservoir about 20 cm or until you locate the position of the reservoir where the resonance is loudest. (Note: To locate the exact position of the resonance, you may need to strike the tuning fork again while the water level is falling.) Raise the reservoir to about 2 cm above the approximate level where you think the resonance is loudest. Strike the tuning fork with the tuning fork hammer and carefully lower the reservoir about 5 cm until you find the exact position of resonance.

8. Using the scale marked on the tube, record the level of the water in the tube when the resonance is loudest. Record this level to the nearest millimeter in your data table.

9. Repeat the procedure for several trials, using tuning forks of different frequencies.

10. Clean up your work area. Put equipment away safely so that it is ready to be used again. Recycle or dispose of used materials as directed by your teacher.

Back

ANALYSIS AND INTERPRETATION

Calculations and data analysis

1. Organizing data

a. CBL and sensors For each trial, calculate the total distance the sound traveled by multiplying the distance measured by 2.

b. Resonance apparatus For each trial, calculate the wavelength of the sound by using the equation for the fundamental wavelength, $\lambda = 4L$, where L is the length of the tube.

2. Analyzing data For each trial, find the speed of sound.

a. CBL and sensors Use the values for distance traveled and the time interval from your data table to find the speed for each trial.

b. Resonance apparatus Use the equation $v = f\lambda$, where f is the frequency of the tuning fork.

3. Evaluating data Find the *accepted* value for the speed of sound in air at room temperature (see page 482, **Table 13-1**). Find the average of your results for the speed of sound, and use the average as the experimental value.

a. Compute the absolute error using the following equation:

$$\text{absolute error} = |\text{experimental} - \text{accepted}|$$

b. Compute the relative error using the following equation:

$$\text{relative error} = \frac{(\text{experimental} - \text{accepted})}{\text{accepted}}$$

Conclusions

4. Applying conclusions Based on your results, is the speed of sound in air at a given temperature the same for all sounds, or do some sounds move more quickly or more slowly than other sounds? Explain.

5. Applying ideas How could you find the speed of sound in air at different temperatures?

Extensions

6. Evaluating methods How could you modify the experiment to find the length of an open pipe? If there is time and your teacher approves your plan, carry out the experiment.

7. Research and communications Many musical instruments operate by resonating air in open or closed tubes. In a pipe organ, for example, both open and closed tubes are used to create music. Research a pipe instrument, and find out how different notes are produced.

Science • Technology • Society

Suppose you are spending some quiet time alone–reading, studying, or just daydreaming. Suddenly your peaceful mood is shattered by the sound of a lawn mower, loud music, or an airplane taking off. If this has happened to you, then you have experienced noise pollution.

Noise is defined as any loud, discordant, or disagreeable sound, so classifying sounds as noise is often a matter of personal opinion. When you are at a party, you might enjoy listening to loud music, but when you are at home trying to sleep, you may find the same music very disturbing.

There are two kinds of noise pollution, both of which can result in long-term hearing problems and even physical damage to the ear. Chapter 13 explains how we receive and interpret sound.

How can noise damage hearing?

The small bones and hairlike cells of the inner ear are delicate and very sensitive to the compression waves we interpret as sounds. The first type of noise pollution involves noises that are so loud they endanger the sensitive parts of the ear. Prolonged exposure to sounds of about 85 dB can begin to damage hearing irreversibly. Certain sounds above 120 dB can cause immediate damage. The sound level produced by a food blender or by diesel truck traffic is about 85 dB. A jet engine heard from a few meters away is about 140 dB.

Have you ever noticed the "headphones" worn by ground crew at an airport or by workers using chain saws or jackhammers? In most cases, these are ear protectors worn to prevent the hearing loss brought on by damage to the inner ear.

Whose noise annoys?

The second kind of noise pollution is more controversial because it involves noises that are considered annoyances. No one knows for sure how to measure levels of annoyance, but sometimes annoying noise becomes intolerable. Lack of

sleep due to noise causes people to have slow reaction times and poor judgment, which can result in mistakes at work or school and accidents on the job or on the road. Scientists have found that continuous, irritating noise often produces high blood pressure, which leads to other health problems.

A major debate involves noise made by aircraft. Airport traffic in the United States nearly doubled from 1980 to 1990 and continues to grow at a rapid pace. People who live near airports once found aircraft noise an occasional annoyance, but because of increased traffic and runways added to accommodate growth, they now suffer sleep disruptions and other health effects.

Many people have organized groups to oppose airport expansion. Their primary concerns are the increase in noise and the decrease in property values associated with airport expansion.

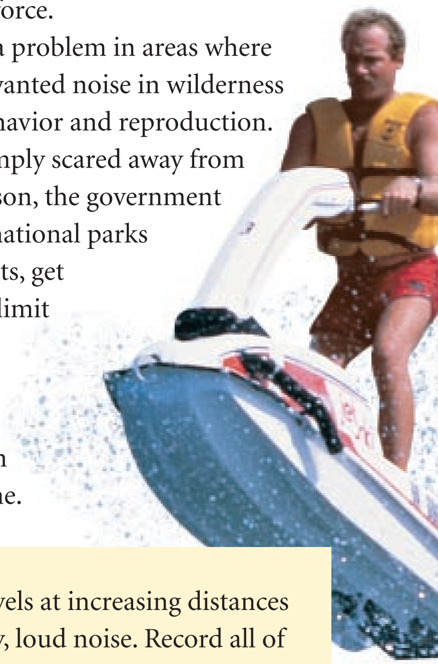
But, city governments argue that an airport benefits the entire community both socially and economically and that airports must expand to meet the needs of increased populations. Officials have also argued that people knew they were taking chances by building or buying near an airport and that the community cannot compensate for their losses. Airlines contend that attempts to reduce noise by using less power during takeoffs or by veering away from populated areas can pose a serious threat to passenger safety.

Other annoyances

Besides airports, people currently complain most about noise pollution from nearby construction sites, jet skis, loud stereos in homes and cars, all-terrain vehicles, snowmobiles, and power lawn equipment, such as mowers and leaf blowers. Many people want to control such noise by passing laws to limit the use of this equipment to certain times of the day or by requiring that sound-muffling devices be used.

Opponents to these measures argue that much of this activity takes place on private property and that, in the case of building sites and industries, noise limitation would increase costs. Some public officials would like to control annoying noise but point out that laws to do so fall under the category of nuisance laws, which are notoriously difficult to enforce.

Noise pollution is also a problem in areas where few or no people live. Unwanted noise in wilderness areas can affect animal behavior and reproduction. Sometimes animals are simply scared away from their habitats. For this reason, the government has taken action in some national parks to reduce sightseeing flights, get rid of noisy campers, and limit or eliminate certain noisy vehicles. Some parks have drastically limited the number of people who can be in a park at any one time.



Researching the Issue

1. Obtain a sound-level meter, and measure the noise level at places where you and your friends might be during an average week. Also make some measurements at locations where sound is annoyingly loud. Be sure to hold the meter at head level and read the meter for 30 seconds to obtain an average. Present your findings to the class in a graphic display.

2. Measure the sound levels at increasing distances from two sources of steady, loud noise. Record all of your locations and measurements. Graph your data, and write an interpretation describing how sound level varies with distance from the source.

3. Is there a source of noise in your community that most people recognize to be a problem? If so, find out what causes the noise and what people want to do to relieve the problem. Hold a panel discussion to analyze the opinions of each side, and propose your own solution.