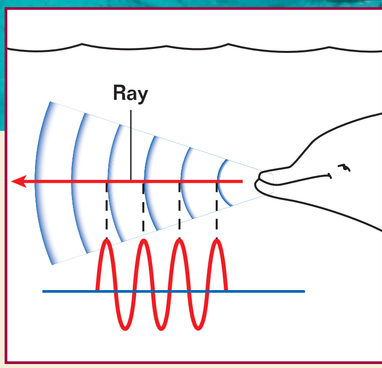
# CHAPTER 12

# *Sound*




Some marine mammals, such as dolphins, use sound waves to locate distant objects. In this process, called *echo-location,* 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.

## WHAT TO EXPECT

In this chapter, you will study many physical aspects of sound, including the nature of sound waves, frequency, intensity, resonance, and harmonics.

## WHY IT MATTERS

Some animals, including dolphins and bats, use sound waves to learn about their prey. Musical instruments create a variety of pleasing sounds through different harmonics.

## CHAPTER PREVIEW

SECTION 1

# Sound Waves

### 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 1(a).**

The vibrating prong of a tuning fork, shown in **Figure 1(b),** sets the air molecules near it in motion. As the prong swings to the right, as in **Figure 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 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.**

As the tuning fork continues to vibrate, a series of compressions and rarefactions forms and spreads away from each prong. These compressions and rarefactions 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.

**compression**

*the region of a longitudinal wave in which the density and pressure are at a maximum*

**rarefaction**

*the region of a longitudinal wave in which the density and pressure are at a minimum*

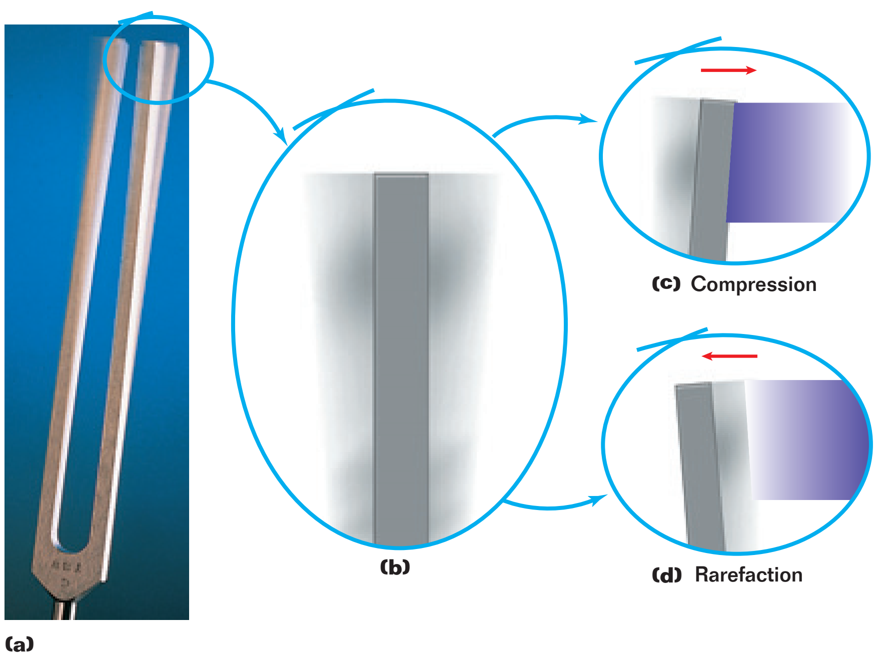



**Figure 1**
**(a)** The sound from a tuning fork is produced by **(b)** the vibrations of each of its prongs. **(c)** When a prong swings to the right, there is a region of high density and pressure. **(d)** When the prong swings back to the left, a region of lower density and pressure exists.

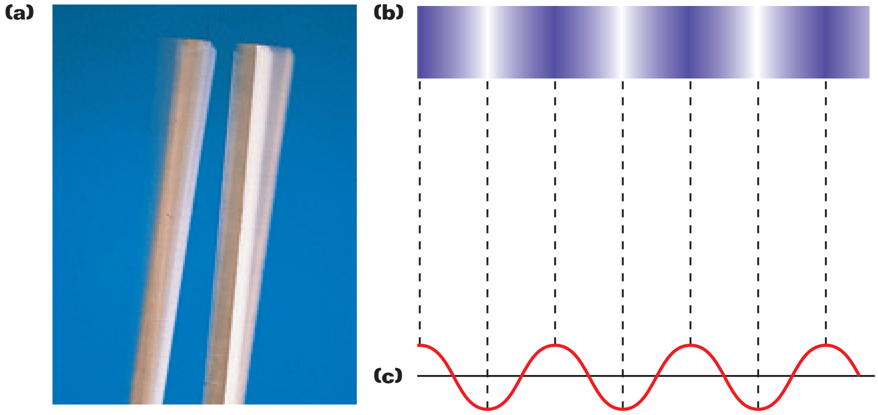



**Figure 2**
**(a)** As this tuning fork vibrates, **(b)** a series of compressions and rarefactions moves away from each prong. **(c)** The crests of this sine wave correspond to compressions, and the troughs correspond to rarefactions.

### 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. The simplest longitudinal wave produced by a vibrating object can be represented by a sine curve. In **Figure 2,** the crests correspond to compressions (regions of higher pressure), and the troughs correspond to rarefactions (regions of lower pressure). Thus, the sine curve represents the changes in air pressure due to the propagation of the sound waves. Note that **Figure 2** shows an idealized case. This example disregards energy losses that would decrease the wave amplitude.



## CHARACTERISTICS OF SOUND WAVES

As discussed earlier, *frequency* is 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 because humans cannot hear these sounds, but these waves consist of the same types of vibrations as the sounds that we can hear. The range of audible sound waves 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.

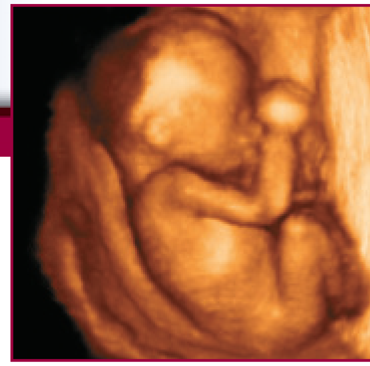
### Frequency determines pitch

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 depends not only on frequency but also on other factors, such as background noise and loudness.

**pitch**

*a measure of how high or low a sound is perceived to be, depending on the frequency of the sound wave*

# The Inside Story on Ultrasound Images



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 can 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 as 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 $\lambda = v/f = 0.15$ mm. A 10 MHz ultrasonic 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 electrical signal, which forms an image on a fluorescent screen. By repeating this process for different portions of the mother's abdomen, a physician can obtain a complete picture of the fetus, as shown above. These images allow doctors to detect some types of fetal abnormalities.

**Table 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 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, 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 the chapter "Vibrations and Waves," 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. The wave fronts of sound waves spreading in three dimensions are approximately spherical. To simplify, we shall assume that the wave fronts are exactly spherical unless stated otherwise.

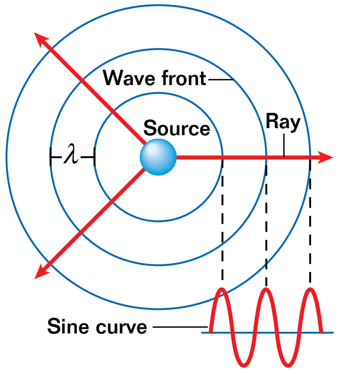



**Figure 3**
In this representation of a spherical wave, the wave fronts represent compressions, and the rays show the direction of wave motion. Each wave front corresponds to a crest of the sine curve. In turn, the sine curve corresponds to a single ray.

Spherical waves can be represented graphically in two dimensions with a series of circles surrounding the source, as shown in **Figure 3.** 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 locates the center of a compression, the distance between adjacent wave fronts is equal to one wavelength, $\lambda$. 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 3,** 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 4.** 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 one-dimensional waves all traveling in the same direction, as in the chapter "Vibrations and Waves."

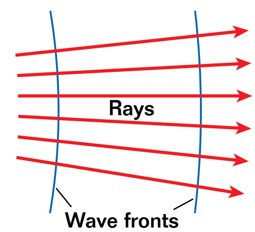
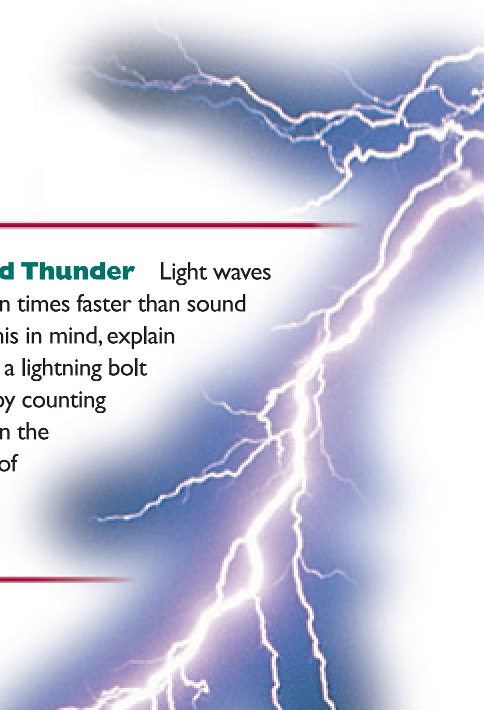



**Figure 4**
Spherical wave fronts that are a great distance from the source can be approximated with parallel planes known as *plane waves.*

## Conceptual Challenge



**1. Music from a Trumpet** Suppose you hear music being played from a trumpet that is across the room from you. Compressions and rarefactions from the sound wave reach your ear, and you interpret these vibrations as sound. Were the air particles that are vibrating near your ear carried across the room by the sound wave? How do you know?

**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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For a variety of links related to this chapter, go to www.scilinks.org

**Topic:** Doppler Effect
**SciLinks Code:** HF60424

## THE DOPPLER EFFECT

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


**Figure 5**
As this ambulance moves to the left, Observer *A* hears the siren at a higher frequency than the driver does, while Observer *B* hears a lower frequency.

### Relative motion creates a change in frequency

If a siren sounds in a parked ambulance, an observer standing on the street hears the same frequency that the driver hears, as you would expect. When an ambulance is moving, as shown in **Figure 5,** there is relative motion between the moving ambulance and a stationary observer. This relative motion affects the way the wave fronts of the sound waves produced by the siren are perceived by an observer. (For simplicity's sake, we will assume that the sound waves produced by the siren are spherical.)

Although the frequency of the siren remains constant, the wave fronts reach an observer in front of the ambulance (Observer *A*) more often than they would if the ambulance were stationary. The reason is that the source of the sound waves is moving toward the observer. The speed of sound in the air does not change, because the speed depends only on the temperature of the air. Thus, the product of wavelength and frequency remains constant. Because the wavelength is less, the frequency heard by Observer *A* is *greater* than the source frequency.

For the same reason, the wave fronts reach an observer behind the ambulance (Observer *B*) less often than they would if the ambulance were stationary. As a result, the frequency heard by Observer *B* is *less* than the source frequency. This frequency shift is known as the **Doppler effect.** The Doppler effect is named for the Austrian physicist Christian Doppler (1803–1853), who first described it.

INTERACTIVE PHYSICS TUTOR

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

**Doppler effect**

*an observed change in frequency when there is relative motion between the source of waves and an observer*

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

**ADVANCED TOPICS**

See "The Doppler Effect and the Big Bang" in **Appendix J: Advanced Topics** to learn how observations of the Doppler effect with light waves have provided evidence for the expansion of the universe.

## SECTION REVIEW

1. What is the relationship between frequency and pitch?

2. Dolphin echolocation is similar to ultrasound. Reflected sound waves allow a dolphin to form an image of the object that reflected the waves. 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.

3. 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?

4. **Interpreting Graphics** Could a portion of the innermost wave front shown in **Figure 6** be approximated by a plane wave? Why or why not?

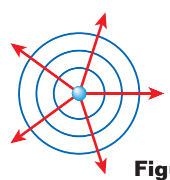

**Figure 6**

5. **Interpreting Graphics** **Figure 7** is a diagram of the Doppler effect in a ripple tank. In which direction is the source of these ripple waves moving?

6. **Interpreting Graphics** If the source of the waves in **Figure 7** is stationary, which way must the ripple tank be moving?

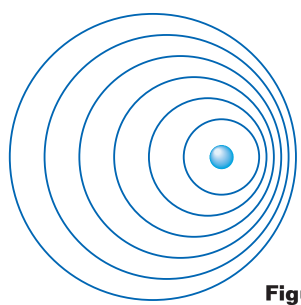

**Figure 7**

7. **Critical Thinking** As a dolphin swims toward a fish, the dolphin sends out sound waves to determine the direction the fish is moving. If the frequency of the reflected waves is higher than that of the emitted waves, is the dolphin catching up to the fish or falling behind?

# SECTION 2

# *Sound Intensity and Resonance*

**SECTION OBJECTIVES**

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

## 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 8.** 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 the 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 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.

**intensity**

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

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

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.

**Figure 8**
As a piano wire vibrates, it transfers energy to the piano's soundboard, which in turn transfers energy into the air in the form of sound.

**INTENSITY OF A SPHERICAL WAVE**

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

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

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.

## SAMPLE PROBLEM A

### 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:** $P = 0.20\ \text{W}$ $\quad r = 3.2\ \text{m}$

**Unknown:** Intensity = ?

Use the equation for the intensity of a spherical wave.

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

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

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

**CALCULATOR SOLUTION**

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

## PRACTICE A

### 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 $4.6 \times 10^{-7}\ \text{W/m}^2$ 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 $1.6 \times 10^{-3}\ \text{W/m}^2$ 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 $1.2 \times 10^{-3}\ \text{W/m}^2$?

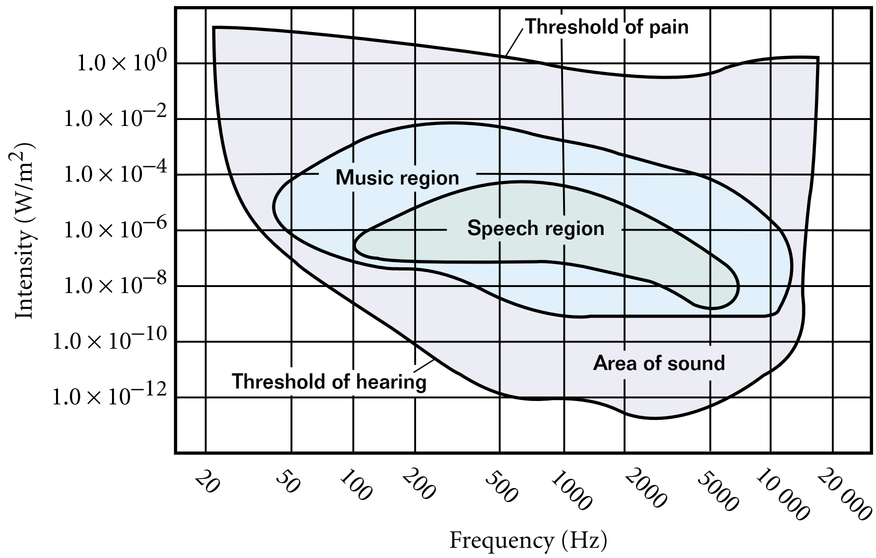


**Figure 9**

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 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 9** 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 $1.0 \times 10^{-12}$ $W/m^2$. 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 9.**

For frequencies near 1000 Hz and 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 $1 \times 10^{-11}$ m. Comparing this number to the diameter of a typical air molecule (about $1 \times 10^{-10}$ 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 9** 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 musicians wear earplugs during their performances. 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.

## Relative intensity is measured in decibels

Just as the frequency of a sound wave determines its pitch, the intensity of a wave approximately determines its perceived loudness. However, loudness is not directly proportional to intensity. The reason is that the sensation of loudness is approximately logarithmic in the human ear.

*Relative intensity* is the ratio of the intensity of a given sound wave to the intensity at the threshold of hearing. Because of the logarithmic dependence of perceived loudness on intensity, using a number equal to 10 times the logarithm of the relative intensity provides a good indicator for human perceptions of loudness. This measure of loudness is referred to as the *decibel level.* The decibel level is dimensionless because it is proportional to the logarithm of a ratio. A dimensionless unit called the **decibel** (dB) is used for values on this scale.

The conversion of intensity to decibel level is shown in **Table 2.** Notice in **Table 2** that when the intensity is multiplied by 10, 10 dB are added to the decibel level. A given difference in decibels corresponds to a fixed difference in perceived loudness. Although much more intensity (0.9 $W/m^2$) is added between 110 and 120 dB than between 10 and 20 dB ($9 \times 10^{-11}$ $W/m^2$), in each case the perceived loudness increases by the same amount.

**decibel**

*a dimensionless unit that describes the ratio of two intensities of sound; the threshold of hearing is commonly used as the reference intensity*

**Table 2 Conversion of Intensity to Decibel Level**

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

### 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.

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## FORCED VIBRATIONS AND RESONANCE

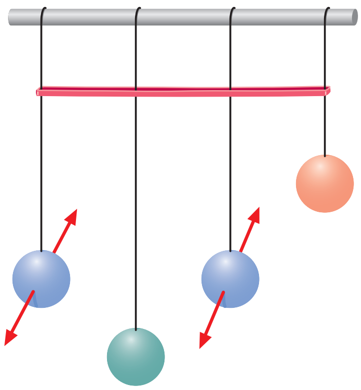

**Figure 10**
If one blue pendulum is set in motion, only the other blue pendulum, whose length is the same, will eventually oscillate with a large amplitude, or resonate.

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 10.** 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.* Because the guitar body has a larger area than the strings do, it enables the strings' vibrations to be transferred to the air more efficiently. 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.

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**Topic:** Resonance
**SciLinks Code:** HF61303

### Vibration at the natural frequency produces resonance

As you saw in the chapter on waves, 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 10,** 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

**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.

matches the frequency of the pendulum that was initially set in motion. This system is said to be in **resonance.** Because 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.

**resonance**

*a phenomenon that occurs when the frequency of a force applied to a system matches the natural frequency of vibration of the system, resulting in a large amplitude of vibration*

A striking example of structural resonance occurred in 1940, when the Tacoma Narrows bridge, in Washington, shown in **Figure 11,** 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.

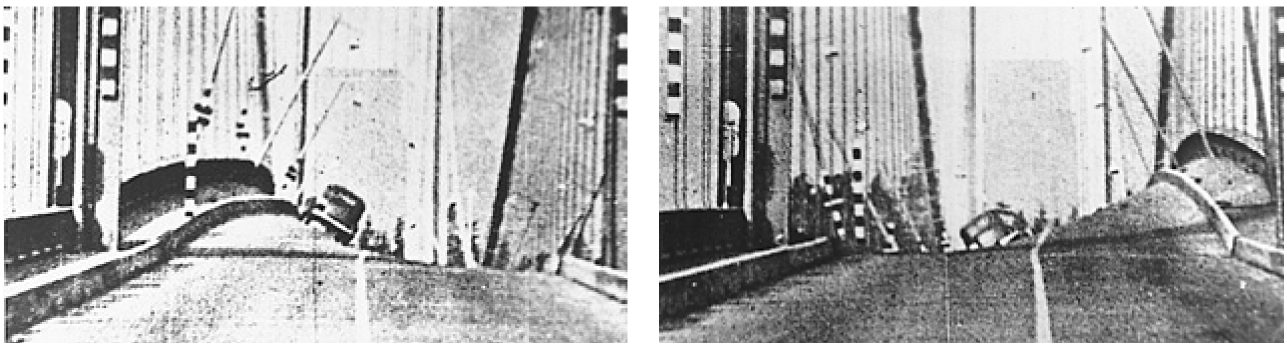


**Figure 11**
On November 7, 1940, the Tacoma Narrows suspension bridge collapsed, just four months after it opened. Standing waves caused by strong winds set the bridge in motion and led to its collapse.

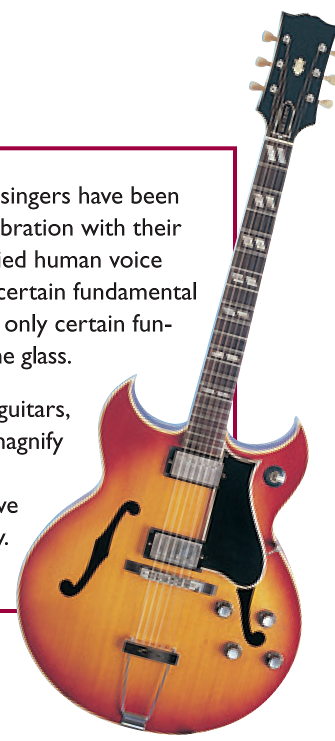
## Conceptual Challenge

**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 all have the same basic shape. Explain why.



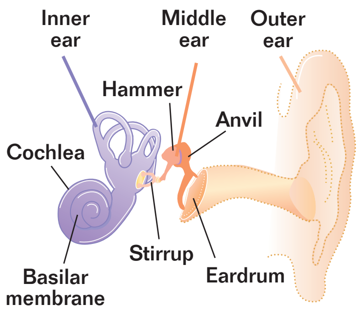



**Figure 12**
Sound waves travel through the three regions of the ear and are then transmitted to the brain as impulses through nerve endings on the basilar membrane.

### 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 12.** Sound waves 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 *basilar membrane* runs through the coiled cochlea, dividing it roughly in half. The basilar membrane has different natural frequencies at different positions along its length, according to the width and thickness of the membrane at that point. Sound waves of varying frequencies resonate at different spots along the basilar membrane, creating impulses in hair cells—specialized nerve cells—embedded in the membrane. These impulses are then sent to the brain, which interprets them as sounds of varying frequencies.

## SECTION REVIEW

1. When the decibel level of traffic in the street goes from 40 to 60 dB, how much greater is the intensity of the noise?
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. 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.
4. 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.)
5. **Critical Thinking** 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

# The Inside Story on Hearing Loss

To prevent damage to their ears, people should wear ear protection when working with power tools.

About 10 percent of all Americans have some degree of hearing loss. There are three basic types of hearing loss. *Conductive hearing loss* is an impairment of the transmission of sound waves in the outer ear or transmission of vibrations in the middle ear. Conductive hearing loss is most often caused by improper development of the parts of the outer or middle ear or by damage to these parts of the ear by physical trauma or disease. Conductive hearing loss can often be corrected with medicine or surgery. *Neural hearing loss* is caused by problems with the auditory nerve, which carries signals from the inner ear to the brain. One common cause of neural hearing loss is a tumor pressing against the auditory nerve. *Sensory hearing loss* is caused by damage to the inner ear, particularly the microscopic hair cells in the cochlea.

Sensory hearing loss can be present at birth and may be genetic or due to disease or developmental disorders. However, the most common source of damage to hair cells is exposure to loud noise. Short-term exposure to loud noise can cause ringing in the ears and temporary hearing impairment. Frequent or long-term exposure to noise above 70 dB—including noise from familiar sources such as hair dryers or lawn mowers—can damage the hair cells permanently.

The hair cells in the cochlea are not like the hair on your head or skin. They are highly specialized nerve cells that cannot be repaired or replaced by the body when they are severely damaged or destroyed. Cochlear hair cells can recover from minor damage, but if the source of the damage recurs frequently, even if it is only moderately loud noise, the hair cells may not have time to recover and can become permanently damaged. It is therefore important to protect yourself from sensory hearing loss by reducing your exposure to loud noise or by using a noise-dampening headset or earplugs that fully block the ear canal when you must be exposed to loud noise.

Permanent sensory hearing loss usually occurs gradually, sometimes over 20 years or more. Because the hair cells that respond to higher-pitched sounds are smaller and more delicate, sensitivity to sounds with frequencies around 20 kHz is usually the first to be lost. Loss of sensitivity to sounds with frequencies around 4 kHz is often the first to be noticed because these frequencies are in the upper range of human speech. People who are starting to lose their hearing often have trouble hearing higher-pitched voices or hearing consonant sounds such as *s, t, p, d,* and *f*. As the hearing loss advances, loss of sensitivity to a wider range of sounds follows.

Although there is currently no true "cure" for sensory hearing loss, some remedies are available. *Hearing aids* act like tiny amplifiers, making any sounds that reach the ear louder. *Assistive listening devices* serve to amplify a specific small range of frequencies for people who have only partial hearing loss in that range. *Cochlear implants* use an electrode that is surgically implanted into the cochlea through a hole behind the outer ear. Electrical signals to the electrode stimulate the auditory nerve directly, in effect bypassing the hair cells altogether.

SECTION 3

# Harmonics

## 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 the chapter "Vibrations and Waves," a variety of standing waves can occur when a string is fixed at both ends and set into vibration. The vibrations on the string of a musical instrument, such as the violin in **Figure 13,** 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 3,** on the next page, shows several possible vibrations on an idealized string. The ends of the string, which cannot vibrate, must always be nodes ($N$). The simplest vibration that can occur is shown in the first row of **Table 3.** In this case, the center of the string experiences the most displacement, and so it is an antinode ($A$). Because the distance from one node to the next is always half a wavelength, the string length ($L$) must equal $\lambda_1/2$. Thus, the wavelength is twice the string length ($\lambda_1 = 2L$).

As described in the chapter on waves, 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.

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

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

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 on this string.

**fundamental frequency**

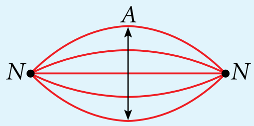
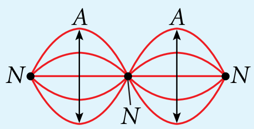
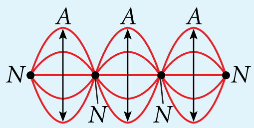
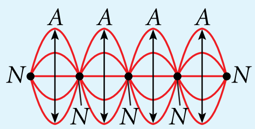
*the lowest frequency of vibration of a standing wave*

### Harmonics are integral multiples of the fundamental frequency

The next possible standing wave for a string is shown in the second row of **Table 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 that of the fundamental frequency.

$$f_2 = 2f_1$$

**Table 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 |

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**SciLinks Code:** HF60715

This pattern continues, and the frequency of the standing wave shown in the third row of **Table 3** is three times the fundamental frequency. More generally, 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 $n$th harmonic. The general form of the equation is written as follows:

**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**

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

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

Note that $v$ in this equation is the speed of waves on the vibrating string and not the speed of the resultant sound waves in air. If the string vibrates at one of these frequencies, the sound waves produced in the surrounding air will have the same frequency. However, the speed of these waves will be the speed of sound waves in air, and the wavelength of these waves will be that speed divided by the frequency.

## Did you know?

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 equation on this page, $L$ refers to the portion of the string that is vibrating.

**Figure 14**
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 14.** 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 15,** the air molecules have complete freedom of motion, so an antinode (of displacement) exists at this end. If a pipe is open at both ends, each end is an antinode. This situation 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 15,** and our earlier equation for the harmonic series of a vibrating string can be used.

**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.

**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.

**Harmonics in an open-ended pipe**

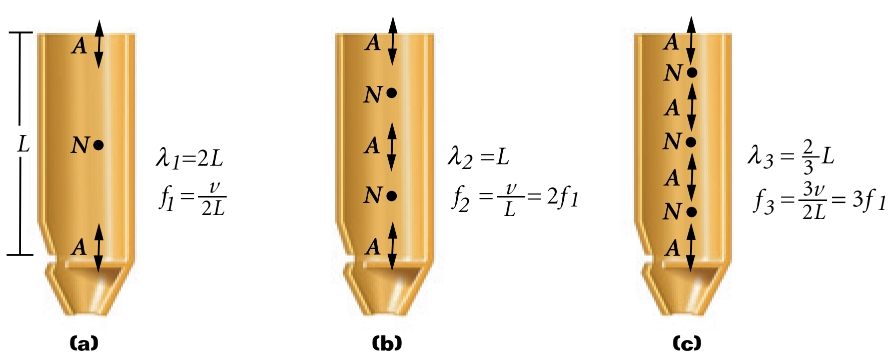


**Figure 15**
In a pipe open at both ends, each end is an antinode of displacement, and all harmonics are present. Shown here are the **(a)** first, **(b)** second, and **(c)** third harmonics.

Harmonics in a pipe closed at one end

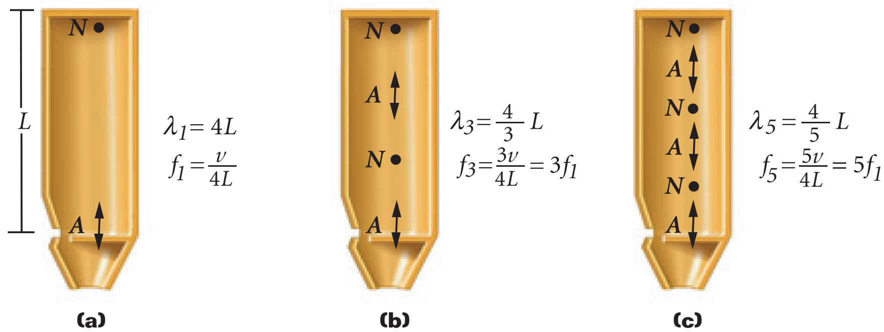


**Figure 16**
In a pipe closed at one end, the closed end is a node of displacement and the open end is an antinode of displacement. In this case, only the odd harmonics are present. The **(a)** first, **(b)** third, and **(c)** fifth harmonics are shown here.

### 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 16,** 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 16(a),** the simplest possible standing wave that can exist in this pipe is one for which the length of the pipe is equal to one-fourth of a wavelength. Hence, 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 16(b),** the length of the pipe is equal to three-fourths of a wavelength, 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.

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

The frequency of this harmonic is *three* times the fundamental frequency. Repeating this calculation for the case shown in **Figure 16(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. We can generalize the equation for the harmonic series of a pipe closed at one end as follows:

**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?

## SAMPLE PROBLEM B

### 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.**

**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 or situation:**

When the pipe is open at both ends, the fundamental frequency can be found by using the equation for the entire harmonic series:

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

When the pipe is closed at one end, use the following equation:

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

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

**3. CALCULATE**

**Substitute the values into the equations and solve:**

For a pipe open at both ends:

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

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:

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

The next possible harmonics are the third and the fifth:

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

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

**TIP** *Be sure to use the correct harmonic numbers for each situation. For a pipe open at both ends, $n = 1, 2, 3$, etc. For a pipe closed at one end, only odd harmonics are present, so $n = 1, 3, 5$, etc.*

**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 B

### 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?

Trumpets, saxophones, and clarinets are similar to a pipe closed at one end. For example, although the trumpet shown in **Figure 17** 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. One reason the equation does not apply is that any deviation from the cylindrical shape of a pipe affects the harmonic series of an instrument. Another reason is that the open holes in many instruments affect the harmonics. For example, a clarinet is primarily cylindrical, but 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 that in 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.

**Figure 17**
Variations in shape give each instrument a different harmonic series.

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## Harmonics account for sound quality, or timbre

**Table 4** 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 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.

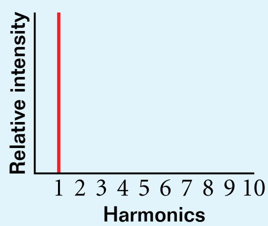
In music, the mixture of harmonics that produces the characteristic sound of an instrument is referred to as the *spectrum of the sound.* From the perspective of the listener, this spectrum results in *sound quality,* or **timbre.** A clarinet sounds different from a viola because of differences in timbre, even when both instruments are sounding the same note at the same volume. The rich harmonics of most instruments provide a much fuller sound than that of a tuning fork.

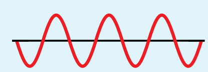
**timbre**

*the musical quality of a tone resulting from the combination of harmonics present at different intensities*

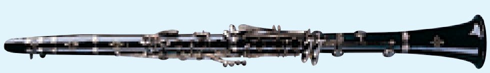
**Table 4 Harmonics of a Tuning Fork, a Clarinet, and a Viola at the Same Pitch**

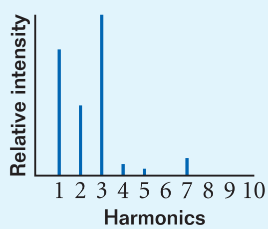
**Tuning fork**

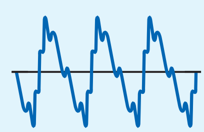




Resultant waveform

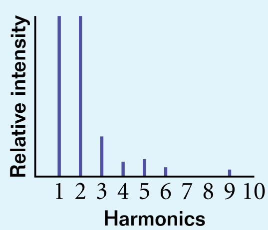
**Clarinet**

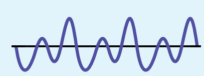






Resultant waveform

**Viola**





Resultant waveform

## The Inside Story on 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 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 accommodate the auditory function of a room.

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 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.

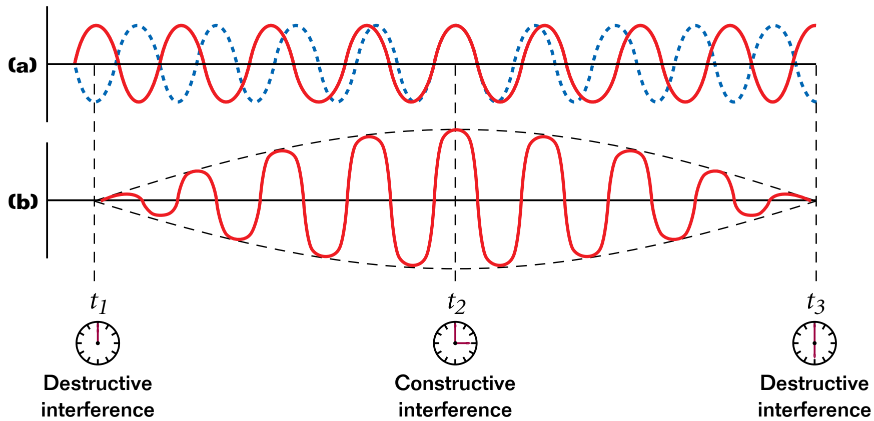



**Figure 18**
Beats are formed by the interference of two waves of slightly different frequencies traveling in the same direction. In this case, constructive interference is greatest at $t_2$, when the two waves are in phase.

## BEATS

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.**

**beat**

*the periodic variation in the amplitude of a wave that is the superposition of two waves of slightly different frequencies*

### Sound waves at slightly different frequencies produce beats

**Figure 18** shows how beats occur. In **Figure 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 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 $t_1$.

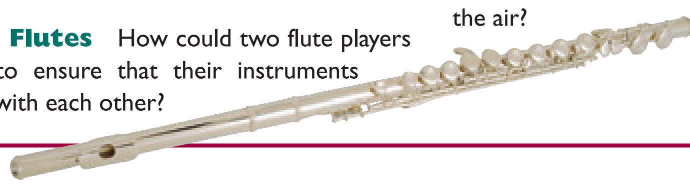
Because these waves have different frequencies, after a few more cycles, the crest of the blue wave matches up with the crest of the red wave, as at $t_2$. At this

## Conceptual Challenge

**1. 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.

**2. Tuning Flutes** How could two flute players use beats to ensure that their instruments are in tune with each other?

**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.

### 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 262 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. **Critical Thinking** Which of the following are different for a trumpet and a banjo when both play notes at the same fundamental frequency?
   - **a.** wavelength in air of the first harmonic
   - **b.** which harmonics are present
   - **c.** intensity of each harmonic
   - **d.** speed of sound in air

# PHYSICS CAREERS

## Piano Tuner

**Piano tuners apply their knowledge of one aspect of physics—sound—to their everyday work. To learn more about piano tuning as a career, read the interview with Ramón Ramírez.**

### *What schooling did you receive in order to become a registered piano technician (RPT)?*

I started off as a music education major and completed that degree. Then, I became the first person in the United States to receive a master's degree in applied music with piano technology as the major.

### *Did you receive encouragement from a teacher or some other person?*

Yes. First, my parents and siblings, who helped me decide to major in music, encouraged me. Later, I was instructed by acoustician Owen Jorgensen, who authored three of the most influential books on historical tuning. Also an accomplished performer, Owen Jorgensen is a phenomenal piano tuner and technician. His work with experimental tuning has opened a new direction for music of the future.

### *What sort of equipment do you use?*

The three most basic tools are a type of wrench called a *tuning hammer,* mutes to silence strings that should not be sounding at a given moment, and a tuning fork, which is used to establish precise pitch. Additionally, a metronome and a watch or clock are useful for timing beats. A calculator can be used for operations such as converting beats per second to beats per minute.

### *What is your favorite thing about your job?*

This question is difficult because there are so many details about my work that I like. Possibly, it is the

Each piano string is wrapped around a tuning pin. Rotating the pins with a tuning hammer alters the string tension, which changes the pitch.

people I work with on a daily basis. Piano owners tend to be interesting and often enjoyable people.

### *How does physics influence your work?*

Physics is the vehicle by which the complex mathematics of tuning moves from theory to audible reality. The harmonic series might seem only theoretical on paper, but modern tuners have to clearly hear individual pitches up to the sixth harmonic, and historical systems required a working ability to hear to the seventh. (A few tuners can hear to the twelfth harmonic.)

### *What advice would you give to students who are interested in piano tuning?*

Obtain a used piano, some basic tools, and a copy of Owen Jorgensen's 1992 book, *Tuning.* Begin by tuning the simplest historical systems and gradually work your way through more complex systems. Because attending one of the very few schools that teach piano technology will probably require relocating, you can find out if you have talent and/or interest before making a larger investment.

# CHAPTER 12 Highlights

## KEY IDEAS

**Section 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 2 Sound Intensity and Resonance**

- The sound intensity of a spherical wave is the power per area.
- Sound intensity is inversely proportional to the square of the distance from the source because the same energy is spread over a larger area.
- Intensity and frequency determine which sounds are audible.
- Decibel level is a measure of relative intensity on a logarithmic scale.
- A given difference in decibels corresponds to a fixed difference in perceived loudness.
- A forced vibration at the natural frequency produces resonance.
- The human ear transmits vibrations that cause nerve impulses. The brain interprets these impulses as sounds of varying frequencies.

**Section 3 Harmonics**

- Harmonics are integral multiples of the fundamental frequency.
- A vibrating string or a pipe open at both ends produces all harmonics.
- A pipe closed at one end produces only odd harmonics.
- 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 |

## KEY TERMS

**compression (p. 408)**

**rarefaction (p. 408)**

**pitch (p. 409)**

**Doppler effect (p. 412)**

**intensity (p. 414)**

**decibel (p. 417)**

**resonance (p. 419)**

**fundamental frequency (p. 422)**

**harmonic series (p. 423)**

**timbre (p. 428)**

**beat (p. 430)**

**PROBLEM SOLVING**

See **Appendix D: Equations** for a summary of the equations introduced in this chapter. If you need more problem-solving practice, see **Appendix I: Additional Problems.**

# CHAPTER 12 Review

## 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 below.

3. What is the difference between frequency and pitch?
4. What are the differences between infrasonic, audible, and ultrasonic sound waves?
5. 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?
6. You are at a street corner and hear an ambulance siren. Without looking, how can you tell when the ambulance passes by?
7. Why do ultrasound waves produce images of objects inside the body more effectively than audible sound waves do?

### Conceptual Questions

8. 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?
9. As a result of a distant explosion, an observer first senses a ground tremor, then hears the explosion. What accounts for this time lag?
10. By listening to a band or an orchestra, how can you determine that the speed of sound is the same for all frequencies?
11. 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?
12. 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

13. What is the difference between intensity and decibel level?
14. Using **Table 2** (Section 2) 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.
15. Why is the threshold of hearing represented as a curve in **Figure 9** (Section 2) rather than as a single point?
16. Under what conditions does resonance occur?

### Conceptual Questions

17. The decibel level of an orchestra is 90 dB, and a single violin achieves a level of 70 dB. How does the sound intensity from the full orchestra compare with that from the violin alone?
18. 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?
19. Why is the intensity of an echo less than that of the original sound?

**20.** 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?

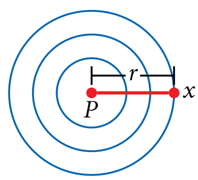
**21.** Although soldiers are usually required to march together in step, they must break their march when crossing a bridge. Explain the possible danger of crossing a rickety bridge without taking this precaution.

## Practice Problems

***For problems 22–23, see Sample Problem A.***

**22.** A baseball coach shouts loudly at an umpire standing 5.0 meters away. If the sound power produced by the coach is $3.1 \times 10^{-3}$ W, what is the decibel level of the sound when it reaches the umpire? (Hint: Use **Table 2** in this chapter.)

**23.** A stereo speaker represented by $P$ in the figure on the right 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?

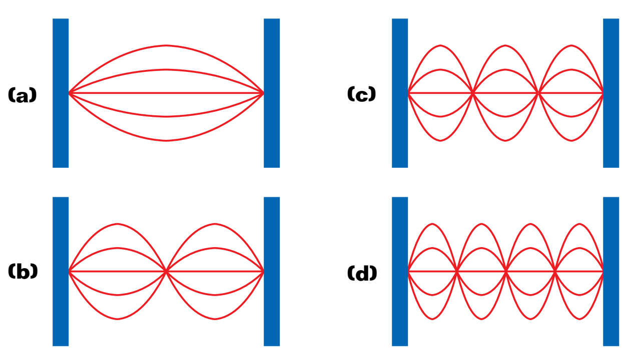



# HARMONICS

## Review Questions

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

**25.** The figures below show 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)**?




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

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

## Conceptual Questions

**28.** 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?

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

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

**31.** 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.

**32.** 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.

**33.** 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

***For problems 34–35, see Sample Problem B.***

**34.** 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?

**35.** 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 frequency around which we would expect hearing to be best when the speed of sound in air is 340 m/s? (Hint: Find the fundamental frequency for the ear canal.)

## MIXED REVIEW

**36.** 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?

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

**38.** 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.

## Graphing Calculator Practice

**Doppler Effect**

As you learned earlier in this chapter, relative motion between a source of sound and an observer can create changes in the observed frequency. This frequency shift is known as the *Doppler effect*. The frequencies heard by the observer can be described by the following two equations, where $f'$ 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 first equation applies when the source of sound is approaching the observer, and the second equation applies when the source of sound is moving away from the observer.

In this graphing calculator activity, you will graph these two equations and will analyze the graphs to determine the apparent frequencies for various situations.

Visit go.hrw.com and type in the keyword **HF6SNDX** to find this graphing calculator activity. Refer to **Appendix B** for instructions on downloading the program for this activity.

**39.** 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 1** in this chapter for the speed of the sound.)

**40.** 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?

**41.** 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.

**42.** 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 $2.0 \times 10^4$ Hz? Assume 378 m/s is the speed of sound in the ear.

**43.** 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 42 to calculate the area of the eardrum.)

## *Alternative 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.

**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, and show what approaches you would use to keep the level of noise to a minimum.

# Standardized Test Prep

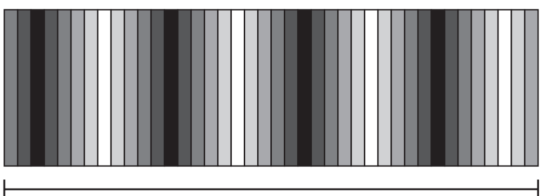
## MULTIPLE CHOICE

**1.** When a part of a sound wave travels from air into water, which property of the wave remains unchanged?

**A.** speed
**B.** frequency
**C.** wavelength
**D.** amplitude

**2.** What is the wavelength of the sound wave shown in the figure below?

**F.** 1.00 m
**G.** 0.75 m
**H.** 0.50 m
**J.** 0.25 m




**3.** If a sound seems to be getting louder, which of the following is probably increasing?

**A.** speed of sound
**B.** frequency
**C.** wavelength
**D.** intensity

**4.** The intensity of a sound wave increases by 1000 W/m$^2$. What is this increase equal to in decibels?

**F.** 10
**G.** 20
**H.** 30
**J.** 40

**5.** The Doppler effect occurs in all but which of the following situations?

**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 remain at rest with respect to each other.
**D.** A listener and a source of sound move toward or away from each other.

**6.** If the distance from a point source of sound is tripled, by what factor is the sound intensity changed?

**F.** $\frac{1}{9}$
**G.** $\frac{1}{3}$
**H.** 3
**J.** 9

**7.** Why can a dog hear a sound produced by a dog whistle, but its owner cannot?

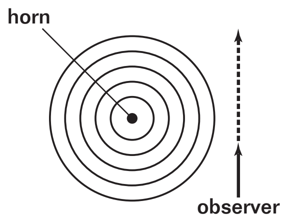
**A.** Dogs detect sounds of less intensity than do humans.
**B.** Dogs detect sounds of higher frequency than do humans.
**C.** Dogs detect sounds of lower frequency than do humans.
**D.** Dogs detect sounds of higher speed than do humans.

**8.** The greatest value ever achieved for the speed of sound in air is about $1.0 \times 10^4$ m/s, and the highest frequency ever produced is about $2.0 \times 10^{10}$ Hz. If a single sound wave with this speed and frequency were produced, what would its wavelength be?

**F.** $5.0 \times 10^{-6}$ m
**G.** $5.0 \times 10^{-7}$ m
**H.** $2.0 \times 10^{6}$ m
**J.** $2.0 \times 10^{14}$ m

9. The horn of a parked automobile is stuck. If you are in a vehicle that passes the automobile, as shown below, what is the nature of the sound that you hear?

**A.** The original sound of the horn rises in pitch.
**B.** The original sound of the horn drops in pitch.
**C.** A lower pitch is heard rising to a higher pitch.
**D.** A higher pitch is heard dropping to a lower pitch.




10. The second harmonic of a guitar string has a frequency of 165 Hz. If the speed of waves on the string is 120 m/s, what is the string's length?

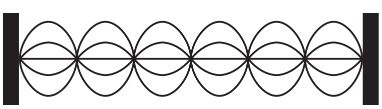
**F.** 0.36 m
**G.** 0.73 m
**H.** 1.1 m
**J.** 1.4 m

## SHORT RESPONSE

11. Two wind instruments produce sound waves with frequencies of 440 Hz and 447 Hz, respectively. How many beats per second are heard from the superposition of the two waves?

12. 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?

13. The figure below shows a string vibrating in the sixth harmonic. The length of the string is 1.0 m. What is the wavelength of the wave on the string?



14. The power output of a certain loudspeaker is 250.0 W. If a person listening to the sound produced by the speaker is sitting 6.5 m away, what is the intensity of the sound?

## EXTENDED RESPONSE

***Use the following information to solve problems 15–16. Be sure to show all of your work.***

The area of a typical eardrum is approximately equal to $5.0 \times 10^{-5}$ m$^2$.

15. What is the sound power (the energy per second) incident on the eardrum at the threshold of pain (1.0 W/m$^2$)?

16. What is the sound power (the energy per second) incident on the eardrum at the threshold of hearing ($1.0 \times 10^{-12}$ W/m$^2$)?

***Use the following information to solve problems 17–19. Be sure to show all of your work.***

A pipe that is open at both ends has a fundamental frequency of 456 Hz when the speed of sound in air is 331 m/s.

17. How long is the pipe?

18. What is the frequency of the pipe's second harmonic?

19. What is the fundamental frequency of this pipe when the speed of sound in air is increased to 367 m/s as a result of a rise in the temperature of the air?

**Test TIP** Be certain that the equations used in harmonic calculations are for the right kind of sound source (vibrating string, pipe open at both ends, or pipe closed at one end).

CHAPTER 12

# Skills Practice Lab

# Speed of Sound

## OBJECTIVES

- **Measure** the speed of sound in air using a resonance apparatus.

## MATERIALS LIST

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

The speed of sound can be determined using a tuning fork to produce resonance in a tube that is closed at the bottom but open on top. The wavelength of the sound may be calculated from the resonant length of the tube. In this experiment, you will use a resonance apparatus to measure the speed of sound.

### SAFETY

- **Put on goggles.**
- **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.**

## PROCEDURE

### Preparation

1. Read the entire lab, and plan what steps you will take.
2. If you are not using a datasheet provided by your teacher, 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.*

### Finding the Speed of Sound

3. Set up the resonance apparatus as shown in **Figure 1.**
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.
5. Measure and record the temperature of the air inside the tube. Select a tuning fork, and record the frequency of the fork in your 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.

**Figure 1**
**Step 7:** From the position of greatest resonance, move the reservoir up 2 cm and down again until you find the exact position.

## ANALYSIS

1. **Organizing Data** 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. **Organizing Data** For each trial, find the speed of sound. Use the equation $v = f\lambda$, where $f$ is the frequency of the tuning fork.

## CONCLUSIONS

3. **Evaluating Results** Find the accepted value for the speed of sound in air at room temperature (see **Appendix F**). 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:
   $$\text{relative error} = \frac{(\text{experimental} - \text{accepted})}{\text{accepted}}$$
4. **Analyzing Results** 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?

## Science • Technology • Society

# Noise Pollution

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. The chapter "Sound" explains how we receive and interpret sound.

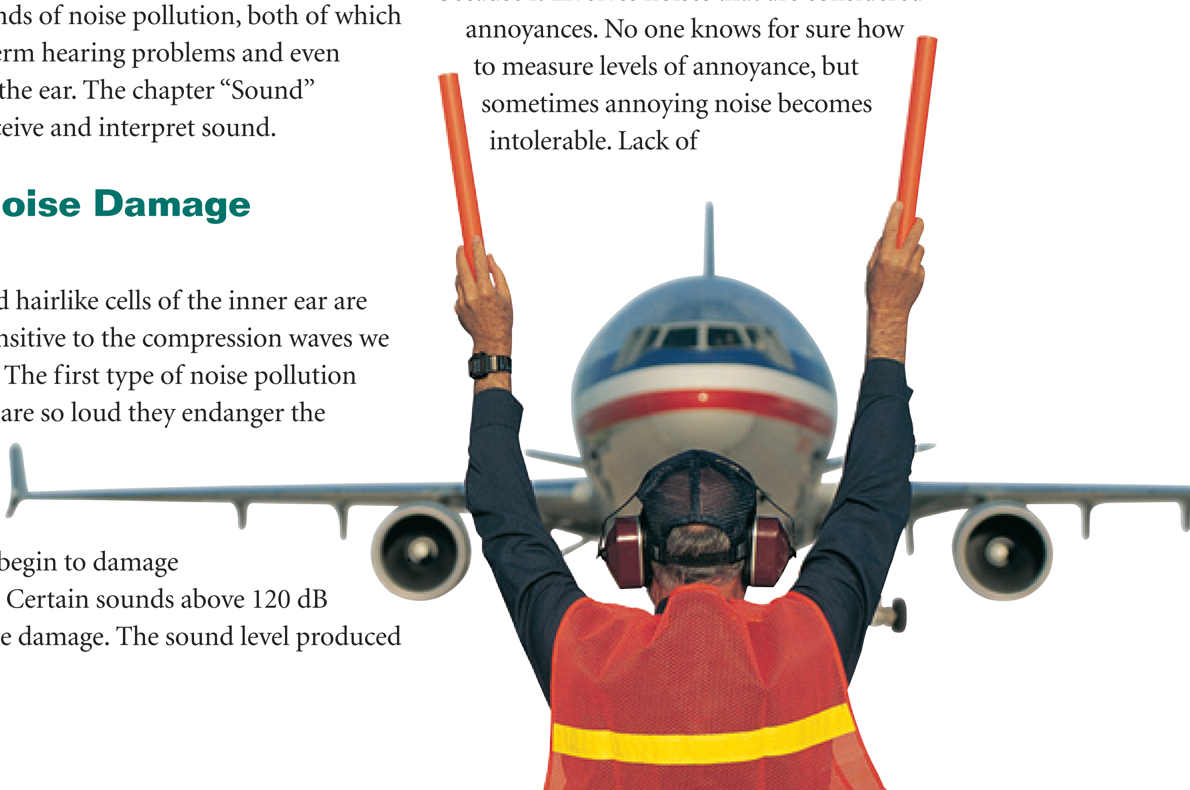
## How Can Noise Damage Hearing?

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 can raise 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.

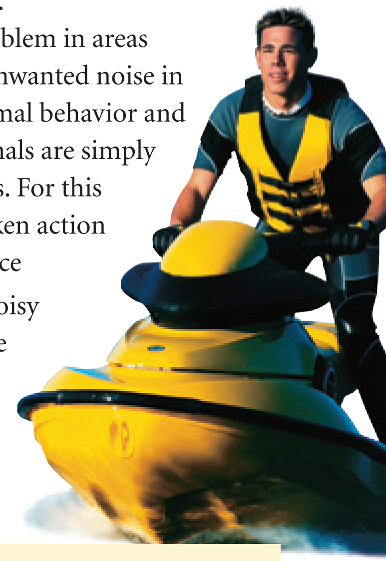
But, city governments argue that an airport benefits the entire community both socially and economically and that airports must expand to meet the needs of increased populations. Officials have also argued that people knew they were taking chances by building or buying near an airport and that the community 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, personal watercraft, 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.