26 SOUND

Objectives

- State what the source of sound is. (26.1)
- Describe the movement of sound through air. (26.2)
- Compare the transmission of sound through air with that through solids, liquids, and a vacuum. (26.3)
- Describe factors that affect the speed of sound. (26.4)
- Describe loudness and sound intensity. (26.5)
- Describe natural frequency. (26.6)
- Describe the purpose of a sounding board in a stringed musical instrument. (26.7)
- Describe resonance. (26.8)
- Describe how sound waves interfere with one another. (26.9)
- Describe beats. (26.10)

discover!

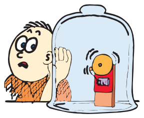
MATERIALS tuning forks

EXPECTED OUTCOME Students will hear a change in sound intensity as they rotate a vibrating tuning fork.

ANALYZE AND CONCLUDE

1. The intensity of the sound varies.
2. Alternating loud and soft sounds occur more frequently with a tuning fork with a higher frequency.
3. Each of the tuning fork's tines has a front and a back surface. Sounds from these surfaces interfere with each other in the area surrounding the tines, producing an audible interference pattern.

26 SOUND

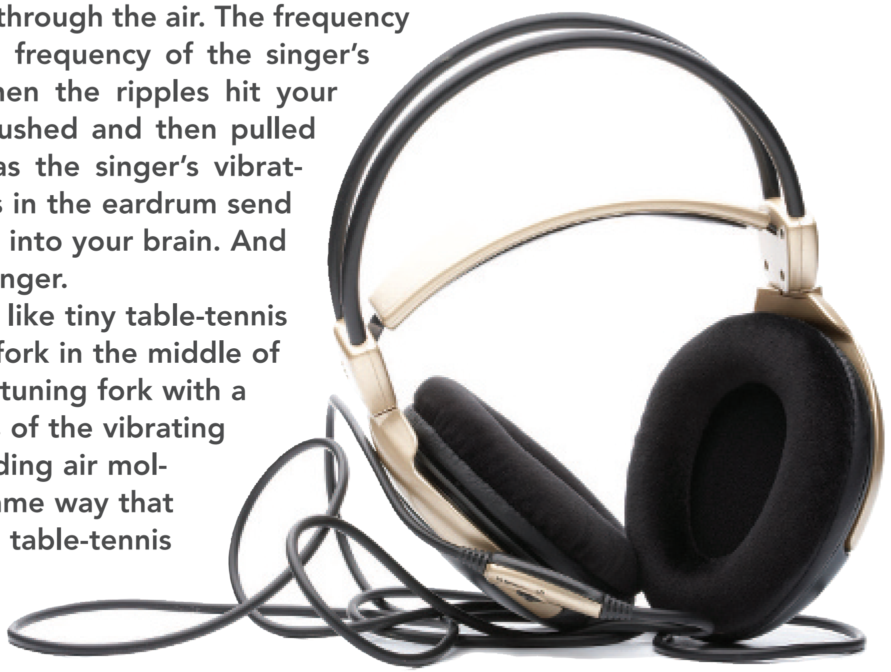


THE BIG IDEA

Sound is a form of energy that spreads out through space.

When a singer sings, the vocal chords in the singer's throat vibrate to and fro, causing adjacent air molecules to vibrate. This air, in turn, vibrates against neighboring air molecules. A series of ripples in the form of a longitudinal wave travels through the air. The frequency of the ripples matches the frequency of the singer's vibrating vocal chords. When the ripples hit your eardrum, the eardrum is pushed and then pulled with the same frequency as the singer's vibrating vocal chords. Vibrations in the eardrum send rhythmic electrical impulses into your brain. And you hear the voice of the singer.

Molecules of air behave like tiny table-tennis balls. If you place a tuning fork in the middle of a room and then strike the tuning fork with a rubber hammer, the prongs of the vibrating tuning fork set the surrounding air molecules into motion in the same way that the moving paddle sets the table-tennis balls into motion.



discover!

What Is Acoustical Interference?

1. Strike a tuning fork with a rubber hammer or on the heel of your shoe. (Do not strike the tuning fork on the edge of the table.)
2. Place the vibrating tuning fork near your ear.
3. Slowly rotate the vibrating tuning fork. Make certain that you rotate the tuning fork through 360 degrees.

Analyze and Conclude

1. **Observing** What do you hear as you rotate the tuning fork?
2. **Predicting** What do you think you would hear if you were to use a tuning fork with a higher pitch? A lower pitch?
3. **Making Generalizations** What causes the changes in sound intensity produced by rotating a tuning fork?

26.1 The Origin of Sound

All sounds originate in the vibrations of material objects. In a piano, violin, or guitar, a sound wave is produced by vibrating strings; in a saxophone, by a vibrating reed; in a flute, by a fluttering column of air at the mouthpiece. The prongs of the tuning fork in Figure 26.1 vibrate when the fork is struck. Your voice results from the vibration of your vocal chords.

In each of these cases, the original vibration stimulates the vibration of something larger or more massive—the sounding board of a stringed instrument, the air column within a reed or wind instrument, or the air in the throat and mouth of a singer. This vibrating material then sends a disturbance through a surrounding medium, usually air, in the form of longitudinal waves. Under ordinary conditions, the frequency of the sound waves produced equals the frequency of the vibrating source.

We describe our subjective impression about the frequency of sound by the word **pitch.** A high-pitched sound like that from a piccolo has a high vibration frequency, while a low-pitched sound like that from a foghorn has a low vibration frequency.

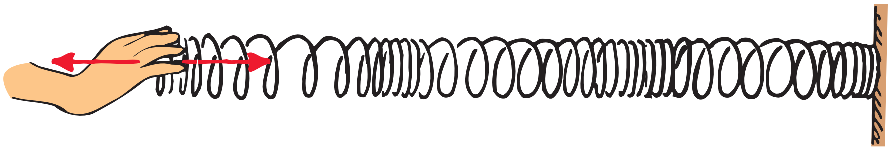
A young person can normally hear pitches with frequencies from about 20 to 20,000 hertz. As we grow older, our hearing range shrinks, especially at the high-frequency end. Sound waves with frequencies below 20 hertz are called **infrasonic,** and those with frequencies above 20,000 hertz are called **ultrasonic.** We cannot hear infrasonic or ultrasonic sound waves. Dogs can hear frequencies of 40,000 Hz or more. Bats can hear sounds at over 100,000 Hz.

CONCEPT CHECK What is the source of all sound?

FIGURE 26.1 ▲
The source of all sound waves is vibration.

26.2 Sound in Air

Clap your hands and you produce a sound pulse that goes out in all directions. The pulse vibrates the air somewhat as a similar pulse would vibrate the coiled spring shown in Figure 26.2. Each particle moves back and forth along the direction of motion of the expanding wave.



◀ FIGURE 26.2
A compression travels along the spring.

26.1 The Origin of Sound

Key Terms
pitch, infrasonic, ultrasonic

▶ **Teaching Tip** State that sound is the only thing that the ear can hear. Then state that the source of sound or any wave motion is a vibrating object.

Demonstrations

Tap a large tuning fork and show that it is vibrating by dipping the vibrating prongs in a cup of water. The splashing water shows that the prongs are moving. (Small forks do not work well because the frequency is too high for the eyes to see.)

Show a large radio speaker without its cover. Play low frequencies with an audio oscillator (or other source) so students gathered around can see the diaphragm vibrating.

Rub some pine pitch or rosin on your fingers and stroke an aluminum rod. If you do it properly, it will "sing" quite loudly. Do this while holding the rod at its midpoint, and then at different places to show harmonics. (Of course you have practiced this first!)

CONCEPT CHECK All sounds originate in the vibrations of material objects.

Teaching Resources

Conceptual Physics Alive!
DVDs
Vibrations and Sound I, II

26.2 Sound in Air

Key Terms
compression, rarefaction

▶ **Teaching Tip** Vibrate a Slinky transversely to show a transverse wave. Then vibrate it longitudinally to show a longitudinal wave. Call attention to the compressions and rarefactions of the longitudinal wave and relate them to the compressions and rarefactions that occur in air as sound passes through it.

CONCEPT CHECK As a source of sound vibrates, a series of compressions and rarefactions travels outward from the source.

Teaching Resources

- Reading and Study Workbook
- Presentation*EXPRESS*
- Interactive Textbook

For a clearer picture of this process, consider the long room shown in Figure 26.3. At one end is an open window with a curtain over it. At the other end is a door.

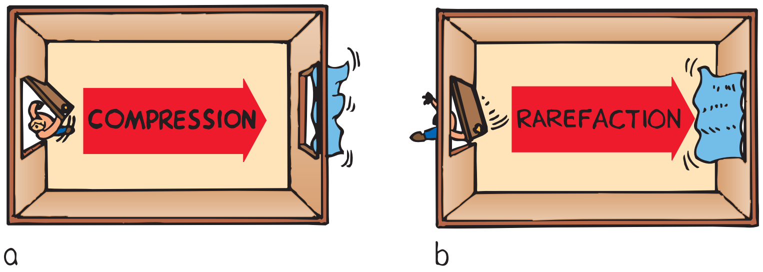


FIGURE 26.3 ▶
Opening and closing a door produces compressions and rarefactions. **a.** When the door is opened, a compression travels across the room. **b.** When the door is closed, a rarefaction travels across the room.

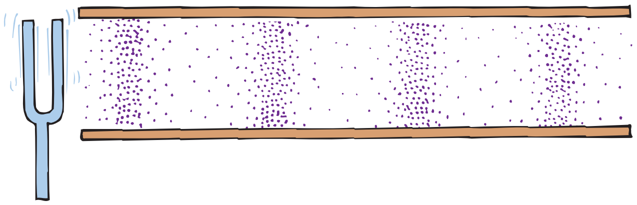
When you quickly open the door as in Figure 26.3a, you can imagine the door pushing the molecules next to it away from their initial positions, and into their neighbors. Neighboring molecules, in turn, push into their neighbors, and so on, like a compression wave moving along a spring, until the curtain flaps out the window. A pulse of compressed air has moved from the door to the curtain. This pulse of compressed air is called a **compression.**

When you quickly close the door as in Figure 26.3b, the door pushes neighboring air molecules out of the room. This produces an area of low pressure next to the door. Neighboring molecules then move into it, leaving a zone of lower pressure behind them. We say the air in this zone of lower pressure is *rarefied.* Other molecules farther from the door, in turn, move into these rarefied regions, resulting in a pulse of rarefied air moving from the door to the curtain. This is evident when the lower-pressure air reaches the curtain, which flaps inward. This pulse of low-pressure air is called a **rarefaction.**

For all wave motion, it is not the medium that travels across the room, but a *pulse* that travels. In both cases the pulse travels from the door to the curtain. We know this because in both cases the curtain moves *after* the door is opened or closed.

If you swing the door open and closed in periodic fashion, you can set up a wave of periodic compressions and rarefactions that will make the curtain swing in and out of the window. On a much smaller but more rapid scale, this is what happens when a tuning fork is struck or when the speaker in Figure 26.4 produces music. ✓ **As a source of sound vibrates, a series of compressions and rarefactions travels outward from the source.** The vibrations of the tuning fork and the waves it produces are considerably higher in frequency and lower in amplitude than in the case of the swinging door. You don't notice the effect of sound waves on the curtain, but you are well aware of them when they meet your sensitive eardrums.

FIGURE 26.4 ▲
The vibrating cone of the speaker produces the pleasing sound of music.



◀ **FIGURE 26.5**
Compressions and rarefactions travel from the tuning fork through the tube.

Consider sound waves in the tube shown in Figure 26.5. For simplicity, only the waves that travel in the tube are shown. When the prong of the tuning fork next to the tube moves toward the tube, a compression enters the tube. When the prong swings away, in the opposite direction, a rarefaction follows the compression. It is like the table-tennis paddle moving back and forth in a room packed with table-tennis balls. As the source vibrates, a series of compressions and rarefactions is produced.

CONCEPT CHECK **How does a sound wave travel through air?**

26.3 Media That Transmit Sound

Most sounds you hear are transmitted through the air, but put your ear to the ground as Native Americans did, and you can hear the hoofbeats of distant horses through the ground before you can hear them through the air. More practically, put your ear to a metal fence and have a friend tap it far away. The sound is transmitted louder and faster by the metal than by the air. ✓ **Sound travels in solids, liquids, and gases.**

Or click two rocks together underwater while your ear is submerged. You'll hear the clicking sound very clearly. If you've ever been swimming in the presence of motorized boats, you've probably noticed that you can hear the boats' motors much more clearly under water than above water. Solids and liquids are generally good conductors of sound—much better than air. The speed of sound differs in different materials. In general, sound is transmitted faster in liquids than in gases, and still faster in solids.

The boy in Figure 26.6 cannot hear the ringing bell when air is removed from the jar because sound cannot travel in a vacuum. The transmission of sound requires a medium. If there is nothing to compress and expand, there can be no sound. There may still be vibrations, but without a medium there is no sound.

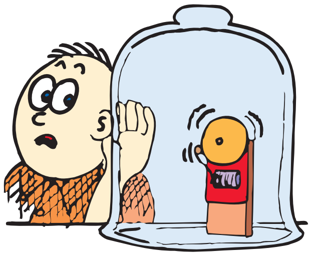


FIGURE 26.6 ▲
Sound can be heard from the ringing bell when air is inside the jar, but not when the air is removed.

CONCEPT CHECK **What media transmit sound?**

26.3 Media That Transmit Sound

Demonstration

Place a bell or ringing alarm clock in a bell jar. Using a vacuum pump, remove the air from the jar while the bell is ringing. Students will notice how the sound diminishes as the air is removed from the jar.

▶ **Teaching Tip** While the loudness of sound from the ringing doorbell diminishes, discuss the movement of sound through different media—gases, liquids, and solids (vibrating table tennis balls analogy). Ask why sound moves faster in warm air. (Faster-moving balls take less time to bump into one another.)

CONCEPT CHECK Sound travels in solids, liquids, and gases.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**

26.4 Speed of Sound

Common Misconception

The speed of sound is the same in all media.

FACT The speed of sound depends on the medium, its temperature, and its elasticity.

▶ **Teaching Tip** Discuss the speed of sound through different media—four times as fast in water as in air—about fifteen times as fast in steel. The elasticity of these materials accounts for the different speeds. Explain why Native Americans used to place their ears to the ground to hear distant hoof beats and how one could (but should not) put an ear to a track to listen for distant trains.

▶ **Teaching Tip** Explain that sound travels faster in moist air than in dry air because H_2O molecules move faster than N_2 or O_2 molecules. This shortens the time between the collisions that transmit the sound energy. H_2O molecules move faster because they have less mass (18 amu) than O_2 (32 amu) and N_2 (28 amu). At the same temperature, molecules have the same KE, so the less massive ones move faster.

▶ **Teaching Tip** Point out that light travels quite fast, nearly one million times faster through air than sound travels.

CONCEPT CHECK The speed of sound in a gas depends on the temperature and the mass of the particles. The speed of sound in a material depends on elasticity.

Teaching Resources

- **Concept-Development Practice Workbook** *26-1*
- **Next-Time Question** *26-1*
- **Laboratory Manual** *72*

think!

How far away is a storm if you note a 3-second delay between a lightning flash and the sound of thunder? *Answer: 26.4*

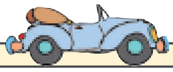
26.4 Speed of Sound

Have you ever watched a distant person chopping wood or hammering, and noticed that the sound of the blow takes time to reach your ears? You see the blow before you hear it. This is most noticeable in the case of lightning. You hear thunder *after* you see the lightning. These experiences are evidence that sound is much slower than light.

✓ **The speed of sound in a gas depends on the temperature of the gas and the mass of the particles in the gas.** The speed of sound in dry air at 0°C is about 330 meters per second, or about 1200 kilometers per hour, about one-millionth the speed of light. Water vapor in the air and increased temperatures increase this speed slightly. This makes sense, for the faster-moving molecules in warm air bump into each other more often and therefore can transmit a pulse in less time. For each degree increase in air temperature above 0°C, the speed of sound in air increases by about 0.60 m/s. So in air at a normal room temperature of about 20°C, sound travels at about 340 m/s. The speed of sound in a gas also depends on the mass of its particles. Lighter particles such as hydrogen molecules and helium atoms move faster and transmit sound much more quickly than heavier gases such as oxygen and nitrogen, found in air.

The speed of sound in a solid material depends not on the material's density, but on its elasticity. Elasticity is the ability of a material to change shape in response to an applied force, and then resume its initial shape once the distorting force is removed. ✓ **The speed of sound in a material depend on the material's elasticity.** Steel is very elastic; putty is inelastic.[26.4] In elastic materials, the atoms are relatively close together and respond quickly to each other's motions, transmitting energy with little loss. Sound travels about fifteen times faster in steel than in air, and about four times faster in water than in air.

CONCEPT CHECK What determines the speed of sound in a medium?



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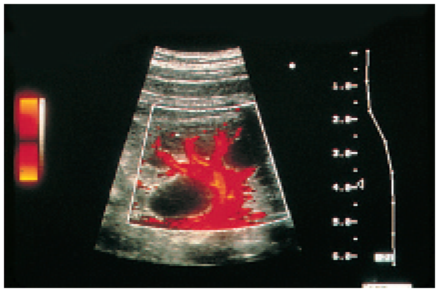


Ultrasound Imaging A technique for harmlessly "seeing" inside a body uses high-frequency sound (ultrasound) instead of X-rays. Ultrasound that enters the body is reflected more strongly from the outside of an organ than from its inside, and we get a picture of the outline of the organ. When ultrasound is incident upon a moving object, the reflected sound has a slightly different frequency. Using this Doppler effect, a physician can "see" the beating heart of a developing fetus that is only 11 weeks old.

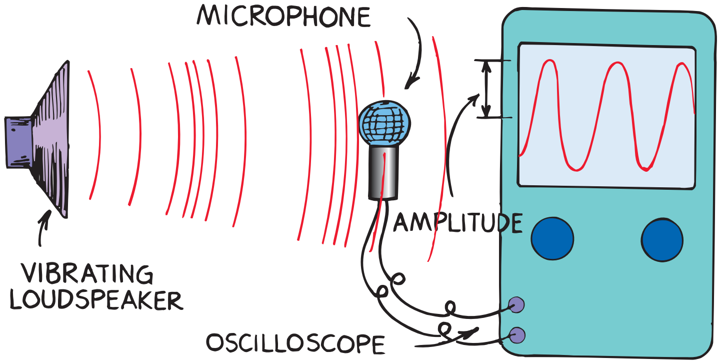
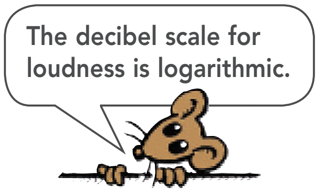


FIGURE 26.7
The loudspeaker at the left is a paper cone that vibrates in rhythm with an electric signal. The sound sets up similar vibrations in the microphone, which are displayed on the screen of an oscilloscope. The wave on the oscilloscope reveals information about the sound.

26.5 Loudness

The intensity of a sound is proportional to the square of the amplitude of a sound wave. ✓ **Sound intensity is objective and is measured by instruments. Loudness, on the other hand, is a physiological sensation sensed in the brain.** It differs for different people. Loudness is subjective but is related to sound intensity. The unit of intensity for sound is the decibel (dB), after Alexander Graham Bell, inventor of the telephone. The oscilloscope shown in Figure 26.7 measures sound.



Some common sources and sound levels are given in Table 26.1. Starting with zero at the threshold of hearing for a normal ear, an increase of each 10 dB means that sound intensity increases by a factor of 10. A sound of 10 dB is 10 times as intense as sound of 0 dB; 20 dB is not twice but 10 times as intense as 10 dB, or 100 times as intense as the threshold of hearing. A 60-dB sound is 100 times as intense as a 40-dB sound.

Roughly, the sensation of loudness follows this decibel scale. We hear a 100-dB sound to be about as much louder than a 70-dB sound as the 70-dB sound is louder than a 40-dB sound because there is a 30-dB difference between the pairs of sound each time.

Table 26.1 Sound Levels

Source of Sound	Level (dB)
Jet engine, at 30 m	140
Threshold of pain	120
Loud rock music	115
Old subway train	100
Average factory	90
Busy street traffic	70
Normal speech	60
Library	40
Close whisper	20
Normal breathing	10
Hearing threshold	0

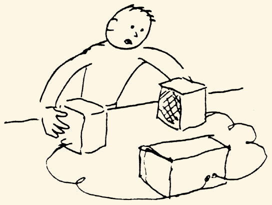
Physiological hearing damage begins at exposure to 85 decibels. The extent of damage depends on the length of exposure and on frequency characteristics. A single burst of sound can produce vibrations intense enough to tear apart the organ of Corti, the receptor organ in the inner ear. Less intense, but severe, noise can interfere with cellular processes in the organ and cause its eventual breakdown. Unfortunately, the cells of the Corti do not regenerate.

CONCEPT CHECK **What is the difference between sound intensity and loudness?**

26.5 Loudness

Demonstration

Play mono music from a tape recorder through a pair of enclosed stereo speakers placed side by side facing the class. First, play one speaker. Then play both in phase. The resulting sound is slightly louder than with one speaker. Reverse the speaker wires to one of the speakers to reverse its phase. (Speaker systems for stereos have polarity indications on their terminals.) The sound is much less intense than from the single speaker. With the speakers still facing forward, vary the separation distance and illustrate the wavelength dependence of the interference. (As the distance between the speakers becomes greater, so does the loudness of the sound. Sound with wavelengths greater than the distance between speakers is canceled. Note the variations in the quality of the sound. Finally, face the speakers toward each other with only a small gap between them. Play one, and then both, in phase. Then reverse the polarity of one of the speakers. The result is almost total silence. Sound at virtually all wavelengths is being canceled by destructive interference. As you increase the distance between the speakers, shorter wavelengths avoid total destructive interference, and the sound level increases. Spectacular!



▶ **Teaching Tip** The loudest sounds emitted by a creature are those from the Blue Whale. They can emit sounds at a volume greater than 180 dB in water, but pitched too low for humans to detect without sensitive equipment.

CONCEPT CHECK Sound intensity is objective and is measured by instruments. Loudness is a physiological sensation sensed in the brain.

26.6 Natural Frequency

Key Term
natural frequency

▶ **Teaching Tip** Compare the sounds of a couple of pennies dropped on a hard surface—one dated before 1982 and one after. The old penny is made of 95% copper and 5% zinc, and sounds noticeably different than the newer pure zinc core pennies plated with copper.

▶ **Teaching Tip** Note that the human ear can discriminate among more than 300,000 tones!

CONCEPT CHECK When an object composed of an elastic material is disturbed, it vibrates at is own special set of frequencies.

26.7 Forced Vibration

Key Term
forced vibration

CONCEPT CHECK Sounding boards are an important part of all stringed musical instruments because they are forced into vibration and produce the sound.

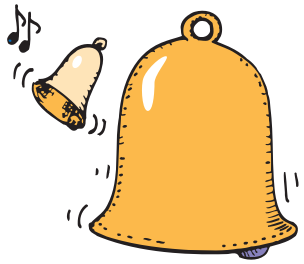


FIGURE 26.8 ▲
The natural frequency of the smaller bell is higher than that of the big bell, and it rings at a higher pitch.

26.6 Natural Frequency

Drop a wrench and a baseball bat on the floor, and you hear distinctly different sounds. Objects vibrate differently when they strike the floor. Tap a wrench, and the vibrations it makes are different from the vibrations of a baseball bat, or of anything else.

✓ **When any object composed of an elastic material is disturbed, it vibrates at its own special set of frequencies, which together form its special sound.** We speak of an object's **natural frequency,** which is the frequency at which an object vibrates when it is disturbed. An object's natural frequency depends on the elasticity and shape of the object. The bells shown in Figure 26.8 and tuning forks vibrate at their own characteristic frequencies. Interestingly enough, most things—from planets to atoms and almost everything else in between—have a springiness to them and vibrate at one or more natural frequencies. A natural frequency is one at which minimum energy is required to produce forced vibrations. It is also the frequency that requires the least amount of energy to continue this vibration.

CONCEPT CHECK What happens when an elastic material is disturbed?

FIGURE 26.9 ▲
When the string is plucked, the washtub is set into forced vibration and serves as a sounding board.

26.7 Forced Vibration

When you strike an unmounted tuning fork, the sound it makes is faint. Strike a tuning fork while holding its base on a tabletop, and the sound is relatively loud. Why? It is because the table is forced to vibrate, and its larger surface sets more air in motion. The tabletop becomes a sounding board, and can be forced into vibration with forks of various frequencies. This is a case of a forced vibration. A **forced vibration** occurs when an object is made to vibrate by another vibrating object that is nearby.

The washtub in Figure 26.9 serves as a sounding board. ✓ **Sounding boards are an important part of all stringed musical instruments because they are forced into vibration and produce the sound.** The vibration of guitar strings in an acoustical guitar would be faint if they weren't transmitted to the guitar's wooden body. The mechanism in a music box is mounted on a sounding board. Without the sounding board, the sound the music box mechanism makes is barely audible.

CONCEPT CHECK Why are sounding boards an important part of stringed instruments?

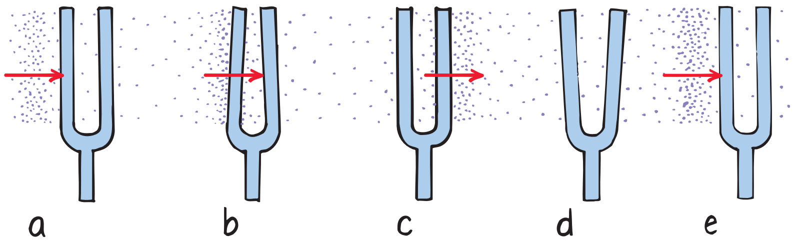
26.8 Resonance

Resonance is a phenomenon that occurs when the frequency of a vibration forced on an object matches the object's natural frequency and a dramatic increase in amplitude occurs. Resonance means to re-sound, or sound again. Putty doesn't resonate because it isn't elastic, and a dropped handkerchief is too limp. ✓ **An object resonates when there is a force to pull it back to its starting position and enough energy to keep it vibrating.**

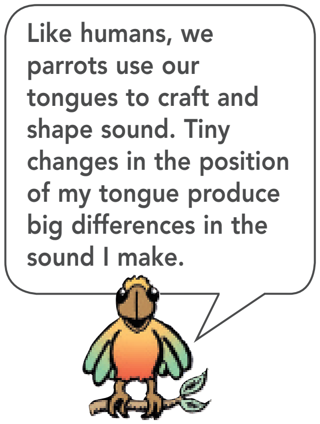
A common experience illustrating resonance occurs on a swing like the one shown in Figure 26.10. When pumping a swing, you pump in rhythm with the natural frequency of the swing. More important than the force with which you pump is the timing. Even small pumps, or even small pushes from someone else, if delivered in rhythm with the natural frequency of the swinging motion, produce large amplitudes.

FIGURE 26.10 ▲
Pumping a swing in rhythm with its natural frequency produces larger amplitudes.

FIGURE 26.11 ▼
The stages of resonance are shown for a tuning fork. **a.** The first compression meets the fork and gives it a tiny and momentary push. **b.** The fork bends. **c.** The fork returns to its initial position just at the time a rarefaction arrives. **d.** It keeps moving and overshoots in the opposite direction. **e.** When it returns to its initial position, the next compression arrives to repeat the cycle.



A common classroom demonstration of resonance uses a pair of tuning forks adjusted to the same frequency and spaced about a meter apart. When one of the forks is struck, it sets the other fork into vibration as shown in Figure 26.11. This is a small-scale version of pushing a friend on a swing—it's the timing that's important. When a sound wave impinges on the fork, each compression gives the prong a tiny push. Since the frequency of these pushes corresponds to the natural frequency of the fork, the pushes successively increase the amplitude of the fork's vibration. This is because the pushes occur at the right time and are repeatedly in the same direction as the instantaneous motion of the fork.



26.8 Resonance

Key Term
resonance

Demonstration

Show resonance using a long stove pipe. Put three layers of wire window screen on crossed wires 1/4 of the way up from the bottom of the stove pipe. Heat gently over a Bunsen burner (not so hot as to melt the screen). The screen becomes a white-noise generator, while the tube is the frequency selector that resonates at the fundamental frequency of the tube. When the tube is removed from the flame, it continues to sound as the wire screen cools. Turn the pipe horizontal until the sound subsides for a few seconds, and then turn it back to vertical—the sound returns. Very impressive!

▶ **Teaching Tip** Give other examples of resonance; the chattering vibration of a glass shelf when a radio placed on it plays a certain note; the loose front end of a car that vibrates at only certain speeds; crystal glass shattered by a singer's voice; troops marching in step across a bridge.

Forced vibrations, resonance, and interference provide a useful background for the same concepts applied to light in following chapters.

PAUL

CONCEPT CHECK An object resonates when there is a force to pull it back to its starting position and enough energy to keep it vibrating.

26.9 Interference

Common Misconception
Sound cannot cancel sound.

FACT Sound waves, like any waves, can interfere constructively or destructively.

▶ **Teaching Tip** Review interference by sketching overlapping sine curves on the board (Figure 26.13, or Figure 25.10 on p. 498).

Now you're ready for a series of fantastic demonstrations—perhaps the most unforgettable of your course!

Paul

Demonstration

Remove the foam cover from a small speaker (a few centimeters in diameter). Connect the speaker to the auxiliary output of a portable tape recorder. Play music through the speaker. The music will sound quite tinny. Then produce a baffle (large flat piece of cardboard or whatever) with a hole slightly smaller than the size of the speaker cut in its middle. Place the speaker behind the hole and note the much-improved sound quality. (The baffle reduces the interference between the back and front waves.) Place the same speaker behind a hole in a small closed box to show even better quality.

FIGURE 26.12 ▲
In 1940, four months after being completed, the Tacoma Narrows Bridge in the state of Washington was destroyed by a 40-mile-per-hour wind.

If the forks are not adjusted for matched frequencies, the timing of pushes will be off and resonance will not occur. When you tune your radio set, you are similarly adjusting the natural frequency of the electronics in the set to match one of the many incoming signals. The set then resonates to one station at a time, instead of playing all the stations at once.

Resonance occurs whenever successive impulses are applied to a vibrating object in rhythm with its natural frequency. English infantry troops marching across a footbridge in 1831 inadvertently caused the bridge to collapse when they marched in rhythm with the bridge's natural frequency. Since then, it is customary for troops to "break step" when crossing bridges. The Tacoma Narrows Bridge disaster in 1940, shown in Figure 26.12, is attributed to wind-generated resonance. A mild 40-mile-per-hour wind gale produced a fluctuating force that resonated with the natural frequency of the bridge, steadily increasing the amplitude over several hours until the bridge collapsed.

CONCEPT CHECK What causes resonance?

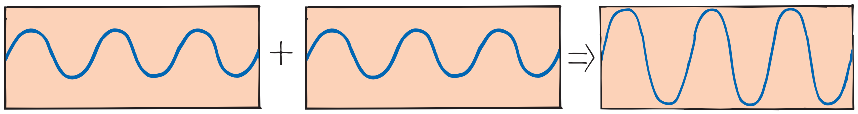
26.9 Interference

Sound waves, like any waves, can be made to interfere. A comparison of interference for transverse waves and longitudinal waves is shown in Figure 26.13. For sound, the crest of a wave corresponds to a compression, and the trough of a wave corresponds to a rarefaction. In either case, when the crests of one wave overlap the crests of another wave, there is constructive interference and an increase in amplitude. Or when the crests of one wave overlap the troughs of another wave, there is destructive interference and a decrease in amplitude. ✓ **When constructive interference occurs with sound waves, the listener hears a louder sound. When destructive interference occurs, the listener hears a fainter sound or no sound at all.** The listener in Figure 26.14a is equally distant from two sound speakers that simultaneously trigger identical sound waves of constant frequency. The listener hears a louder sound because the waves add. The compressions and rarefactions arrive in phase, that is, in step.

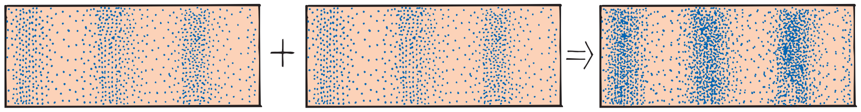
In Figure 26.14b, the listener moved to the side so that paths from the speakers differ by a half wavelength. The rarefactions from one speaker reach the listener at the same time as compressions from the other. It's like the crest of one water wave exactly filling in the trough of another water wave—destructive interference. (If the speakers emit many frequencies, not all wavelengths destructively interfere for a given difference in path lengths.)

Go Online
PHSchool.com
For: Links on interference
Visit: www.SciLinks.org
Web Code: csn – 2609

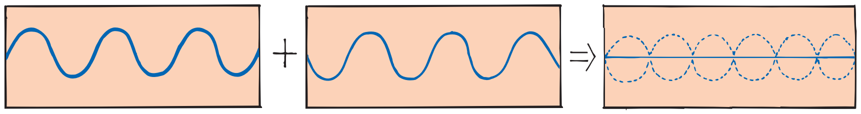
FIGURE 26.13
Both transverse and longitudinal waves display wave interference when they are superimposed.



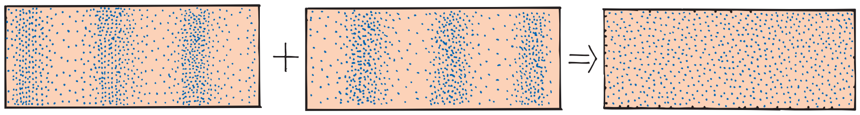
a. Two identical transverse waves in phase produce a wave of increased amplitude.



b. Two identical longitudinal waves in phase produce a wave of increased amplitude.



c. Two identical transverse waves that are out of phase destroy each other.



d. Two identical longitudinal waves that are out of phase destroy each other.

Destructive interference of sound waves is usually not a problem because there is usually enough reflection of sound to fill in canceled spots. Nevertheless, "dead spots" are sometimes evident in poorly designed theaters and gymnasiums, where sound waves reflected off walls interfere with unreflected waves to form zones of low amplitude. Often, moving your head a few centimeters in either direction can make a noticeable difference.

Destructive sound interference is a useful property in antinoise technology. Noisy devices such as jackhammers are being equipped with microphones that send the sound of the device to electronic microchips. The microchips create mirror-image wave patterns of the sound signals. For the jackhammer, this mirror-image sound signal is fed to earphones worn by the operator. Sound compressions (or rarefactions) from the hammer are neutralized by mirror-image rarefactions (or compressions) in the earphones. The combination of signals neutralizes the jackhammer noise. Noise-canceling earphones, shown in Figure 26.15, are already common for pilots. Some automobiles enjoy quiet riding due to noise cancellation. Noise-detecting microphones inside the car pick up engine or road noise. Speakers in the car then emit an opposite signal that cancels out those noises, so the human ear can't detect them. Similarly, the cabins of some airplanes are now quieted with antinoise technology.

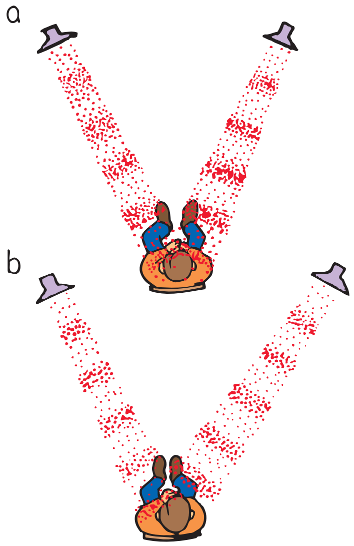


FIGURE 26.14
The sound waves from two speakers interfere. **a.** Waves arrive in phase. **b.** Waves arrive out of phase.

CONCEPT CHECK What are the effects of constructive and destructive interference?

Teaching Tip Explain that a speaker produces waves from both its front and its rear. These waves are 180° out of phase. As it produces a compression in front, it produces a rarefaction in back, and vice versa. When sound reaches your ears from both the front and back of a speaker, destructive interference occurs. This is most pronounced for long waves where the difference in the distances traveled from the speaker to you is relatively small. An uncovered speaker sounds tinny because it produces little sound energy for wavelengths much longer than its diameter. The long-wavelength bass notes are canceled. This cancellation is notably reduced when the baffle is introduced.

CONCEPT CHECK When constructive interference occurs with sound waves, the listener hears a louder sound. When destructive interference occurs, the listener hears a fainter sound or no sound at all.

Teaching Resources

- **Reading and Study Workbook**
- **Transparency *54***
- **Presentation*EXPRESS***
- **Interactive Textbook**

26.10 Beats

Key Term
beats

▶ **Teaching Tip** Tell students they can produce beats next time they are in a room with a ventilation fan. If they hum at the same frequency as the hum of the fan, they will hear beats.

▶ **Teaching Tip** You can show interference and beats with an oscilloscope trace of a pair of sound sources slightly out of sync.

FIGURE 26.15 ▲
Ken Ford tows gliders in quiet comfort when he wears his noise-canceling earphones.

26.10 Beats

When two tones of slightly different frequency are sounded together, a regular fluctuation in the loudness of the combined sounds is heard. The sound is loud, then faint, then loud, then faint, and so on. This periodic variation in the loudness of sound is called **beats.** Beats are an interesting and special case of interference.

Beats can be heard when two slightly mismatched tuning forks, like the ones shown in Figure 26.16, are sounded together. Because one fork vibrates at a frequency different from the other, the vibrations of the forks will be momentarily in step, then out of step, then in again, and so on. When the combined waves reach your ears in step—say when a compression from one fork overlaps a compression from the other—the sound is a maximum. A moment later, when the forks are out of step, a compression from one fork is met with a rarefaction from the other, resulting in a minimum. The sound that reaches your ears throbs between maximum and minimum loudness and produces a tremolo effect.

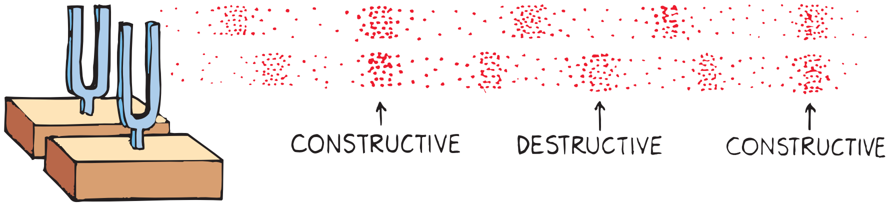
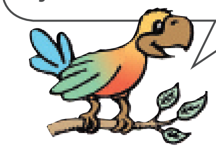


FIGURE 26.16 ▲
The interference of two sound sources of slightly different frequencies produces beats.

If you walk side by side with someone who has a different stride, there will be times when you are both in step, and times when you are both out of step. Suppose, for example, that you take exactly 70 steps in one minute and your friend takes 72 steps in the same time. Your friend gains two steps per minute on you. A little thought will show that you two will be momentarily in step twice each minute. In general, when two people with different strides walk together, the number of times they are in step in each unit of time is equal to the difference in the frequencies of their steps. This applies also to a pair of tuning forks. When one fork vibrates 264 times per second, and the other fork vibrates 262 times per second, they are in step twice each second. A beat frequency of 2 hertz is heard.

A sound wave traveling through the ear canal vibrates the eardrum, which vibrates three tiny bones, which vibrate the fluid-filled cochlea. Inside the cochlea, tiny hair cells convert the pulse into an electrical signal to the brain. Ear plugs typically reduce noise by about 30 dB.



Beats can be nicely displayed on an oscilloscope. When sound signals of slightly different frequencies are fed into an oscilloscope, graphical representations of their pressure patterns can be displayed both individually and when the sounds overlap. Figure 26.17 shows the wave forms for two waves separately, and superposed. Although the separate waves are of constant amplitude, we see amplitude variations in the superposed wave form. Careful inspection of the figure shows this variation is produced by the interference of the two superposed waves. Maximum amplitude of the composite wave occurs when both waves are in phase, and minimum amplitude occurs when both waves are completely out of phase. Like the walkers in the previous example, the waves are in step twice each second, producing a beat frequency of 2 Hz. The 10- and 12-Hz waves, chosen for convenience here, are infrasonic, so they and their beats are inaudible. Higher-frequency audible waves behave exactly the same way and can produce audible beats.

If you overlap two combs of different teeth spacings as shown in Figure 26.18, you'll see a moiré pattern that is related to beats. The number of beats per length will equal the difference in the number of teeth per length for the two combs.

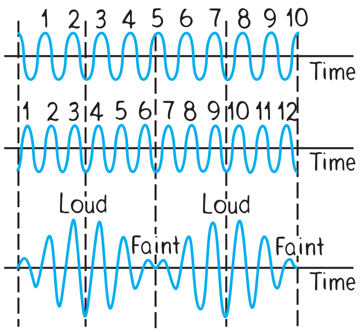


FIGURE 26.17 ▲
Sinusoidal representations of a 10-Hz sound wave and a 12-Hz sound wave during a 1-second time interval. When the two waves overlap, they produce a composite wave with a beat frequency of 2 Hz.

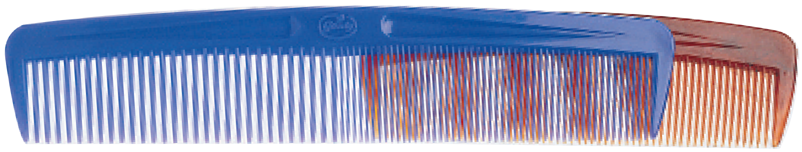


FIGURE 26.18 ▲
The unequal spacings of the combs produce a moiré pattern that is similar to beats.

Beats can occur with any kind of wave and are a practical way to compare frequencies. To tune a piano, a piano tuner listens for beats produced between a standard tuning fork and a particular string on the piano. When the frequencies are identical, the beats disappear. The members of an orchestra tune up by listening for beats between their instruments and a standard tone produced by an oboe.

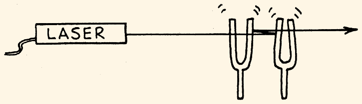
CONCEPT CHECK **What causes beats?**

think!

What is the beat frequency when a 262-Hz and a 266-Hz tuning fork are sounded together? A 262-Hz and a 272-Hz?
Answer: 26.10

Demonstration

Show beats by bouncing laser light off a pair of vibrating tuning forks as shown below.



CONCEPT CHECK When two tones of slightly different frequency are sounded together, a regular fluctuation in the loudness of the combined sounds is heard.

Teaching Resources

- **Reading and Study Workbook**
- **Transparency *55***
- **Presentation*EXPRESS***
- **Interactive Textbook**

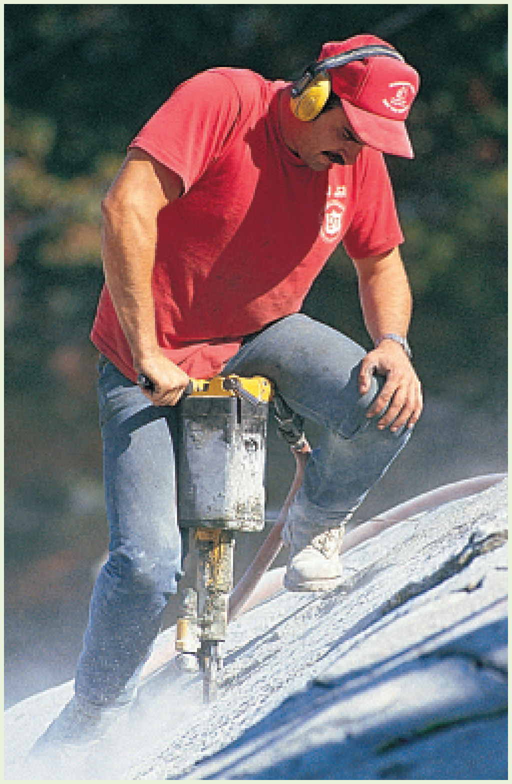
Science, Technology, and Society

CRITICAL THINKING Students' examples may vary. Accept all reasonable responses. Hearing can be protected by limiting (or avoiding) time spent in excessively noisy environments or by wearing ear protectors such as ear plugs.

▶ **Teaching Tip** The loudest sounds emitted by a creature are those from the Blue Whale. They can emit sounds at a volume greater than 180 db in water, but the sounds are pitched too low for humans to detect without sensitive equipment.

Science, Technology, and Society

Noise and Your Health



Most of us try to protect our eyes from excess light, but few give the same care to our ears. Near loudspeakers during her first time at a concert, Allison was alarmed at the pain in her ears. Her friends meant to reassure her when they told her she'd get used to it. But what they didn't tell her was that after the fine tuning of her ears was blasted, she wouldn't know the difference.

Industrial noise is even more damaging to the ears than amplified music because of its sudden high-energy peaks. Loud motorcycles, jackhammers, chain saws, and power tools not only produce steady high-volume sound, but also produce sporadic peaks of energy that can destroy tiny hair cells in the inner ear. When these tiny sensory cells in the inner ear are destroyed they can *never* be restored. Noise-induced hearing loss is insidious.

Fortunately for music devotees, damage caused by energetic peaks is somewhat limited by an inadequate response of electronic amplifiers and loudspeakers. Similarly for live music where most of the sound comes from amplifying equipment. If amplifying equipment were more responsive to sudden sound bursts, hearing loss at concerts would be more severe.

The impact of hearing loss isn't fully apparent until compounded by age. Today's young people will be tomorrow's old people—probably the hardest of hearing ever. Start now to care for your ears and prevent further hearing loss!

Critical Thinking Describe some situations you might find yourself in that could cause hearing loss. What can you do to protect your hearing?

26 REVIEW

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For: Self-Assessment
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Web Code: csa – 2600

Concept Summary

- All sounds originate in the vibrations of material objects.
- As a source of sound vibrates, a series of compressions and rarefactions travels outward from the source.
- Sound travels in solids, liquids, and gases.
- The speed of sound in a gas depends on the temperature of the gas and the mass of the particles in the gas.
- The speed of sound in a material depends on the material's elasticity.
- Sound intensity is objective and is measured by instruments. Loudness, on the other hand, is a physiological sensation sensed in the brain.
- When an object composed of an elastic material is disturbed, it vibrates at its own special set of frequencies, which together form its special sound.
- Sounding boards are an important part of all stringed musical instruments because they are forced into vibration and produce the sound.
- An object resonates when there is a force to pull it back to its starting position and enough energy to keep it vibrating.
- When constructive interference occurs with sound waves, the listener hears a louder sound. When destructive interference occurs, the listener hears a fainter sound or no sound at all.
- When two tones of slightly different frequency are sounded together, a fluctuation in the loudness of the combined sounds is heard; the sound is loud, then faint, then loud, then faint, and so on.

Key Terms

pitch *(p. 515)*
infrasonic *(p. 515)*
ultrasonic *(p. 515)*
compression *(p. 516)*
rarefaction *(p. 516)*
natural frequency *(p. 520)*
forced vibration *(p. 520)*
resonance *(p. 521)*
beats *(p. 524)*

think! Answers

26.4 For a speed of sound in air of 340 m/s, the distance is (340 m/s) × (3 s) = about 1000 m or 1 km. Time for the light is negligible, so the storm is about 1 km away.

26.10 The 262-Hz and 266-Hz forks will produce 4 beats per second, that is, 4 Hz (266 Hz minus 262 Hz). The tone heard will be halfway between, at 264 Hz, as the ear averages the frequencies. The 262-Hz and 272-Hz forks will sound like a tone at 267 Hz beating 10 times per second, or 10 Hz, which some people cannot hear. Beat frequencies greater than 10 Hz are normally too rapid to be heard.

26 REVIEW

Teaching Resources

- Teacher*EXPRESS*
- Conceptual Physics Alive! DVDs
  Vibrations and Sound I, II

26 ASSESS

Check Concepts

1. Vibrating objects
2. Pitch is subjective, but it increases as frequency increases.
3. 20–20,000 Hz
4. Infrasonic—below 20 Hz; ultrasonic—above 20,000 Hz
5. a. Compressions are regions of high pressure, while rarefactions are regions of low pressure.
   b. By a vibrating source
6. No. Sound requires a medium.
7. a. 340 m/s
   b. Sound travels faster at higher temperatures.
8. Faster in water, and faster again in steel
9. The atoms are closer together, and solids and liquids are more elastic mediums.
10. Loudness is subjective because it is a physiological sensation that differs for different people.
11. They have different natural frequencies.
12. The frequency is characteristic of the object's shape, size, and composition.
13. More surface is forced to vibrate and push more air.
14. Resonance is forced vibration at the natural frequency.
15. Tissue paper has no natural frequency.
16. By input of vibrations at a frequency that matches the natural frequency of the object
17. The circuit in the radio is adjusted to resonate with the broadcast frequency.
18. Yes, it is destructive interference.

---

26 ASSESS

Check Concepts

Section 26.1

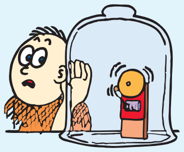
1. What is the source of all sounds?
2. How does pitch relate to frequency?
3. What is the average frequency range of a young person's hearing?
4. Distinguish between *infrasonic* and *ultrasonic* sound.

Section 26.2

5. **a.** Distinguish between *compressions* and *rarefactions* of a sound wave.
   b. How are compressions and rarefactions produced?

Section 26.3

6. Light can travel through a vacuum, as is evidenced when you see the sun or the moon. Can sound travel through a vacuum also? Explain why or why not.



Section 26.4

7. **a.** How fast does sound travel in dry air at room temperature?
   b. How does air temperature affect the speed of sound?
8. How does the speed of sound in air compare with its speed in water and in steel?
9. Why does sound travel faster in solids and liquids than in gases?

Section 26.5

10. Is sound intensity subjective or is loudness subjective? Why?

Section 26.6

11. Why do different objects make different sounds when dropped on a floor?
12. What does it mean to say that everything has a natural frequency of vibration?

Section 26.7

13. Why is sound louder when a vibrating source is held to a sounding board?

Section 26.8

14. What is the relationship between forced vibration and resonance?
15. Why can a tuning fork or bell be set into resonance, while tissue paper cannot?
16. How is resonance produced in a vibrating object?
17. What does tuning in a radio station have to do with resonance?

Section 26.9

18. Is it possible for one sound wave to cancel another? Explain.
19. Why does destructive interference occur when the path lengths from two identical sources differ by half a wavelength?

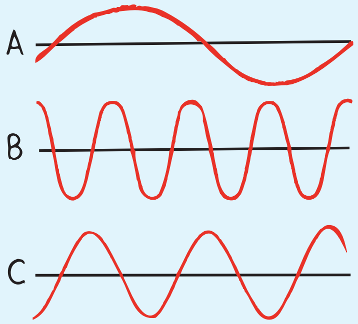
Section 26.10

20. How does interference of sound relate to beats?
21. What is the beat frequency when a 494-Hz tuning fork and a 496-Hz tuning fork are sounded together?

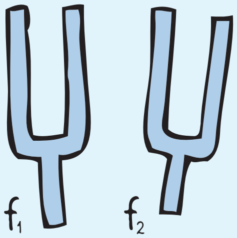
Think and Rank ……

Rank each of the following sets of scenarios in order of the quantity or property involved. List them from left to right. If scenarios have equal rankings, then separate them with an equal sign. (e.g., A = B)

22. The three waves below have the same frequency and travel in different media. Rank their speeds from greatest to least.



23. A pair of tuning forks of frequencies f_1 and f_2 are sounded together.



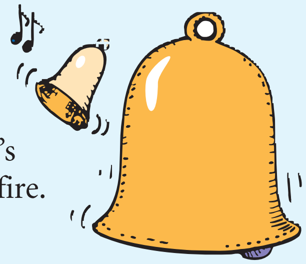
Rank from greatest to least the beat frequencies produced by the following pairs of tuning forks.

(A) $f_1 = 650$ Hz; $f_2 = 654$ Hz
(B) $f_1 = 300$ Hz; $f_2 = 305$ Hz
(C) $f_1 = 200$ Hz; $f_2 = 208$ Hz
(D) $f_1 = 800$ Hz; $f_2 = 801$ Hz

Think and Explain ……

24. If the moon blew up, why wouldn't we be able to hear it?

25. When watching at a baseball game, we often hear the bat hitting the ball after we actually see the hit. Why?



26. In the stands of a racetrack, you notice smoke from the starter's gun before you hear it fire. Explain.

27. In an Olympic competition, a microphone picks up the sound of the starter's gun and sends it electrically to speakers at every runner's starting block. Why?

28. Why will marchers at the end of a long parade following a band be out of step with marchers nearer the band?

29. You watch a distant farmer driving a stake into the ground with a sledgehammer. He hits the stake at a regular rate of one stroke per second. You hear the sound of the blows exactly synchronized with the blows you see. And then you hear one more blow after you see him stop hammering. How far away is the farmer?

30. When a sound wave propagates past a point in the air, what are the changes that occur in the pressure of air at this point?

31. If the speed of sound depended on its frequency, would you enjoy a concert sitting in the second balcony?

19. The crests of one coincide with the troughs of the other.

20. Beats are a result of periodic interference.

21. 496 Hz − 494 Hz = 2 Hz

Think and Rank ……

22. A, C, B

23. C, B, A, D

Think and Explain ……

24. No medium (air) between moon and Earth

25. Light travels faster than sound.

26. Speed of sound is slow compared to enormous speed of light.

27. Electronic gun gets starting signal to all runners simultaneously.

28. There is a time delay for sound from a marching band near the front of a long parade to reach the marchers at the end.

29. 340 m (Sound delay was 1 s, and $v \approx$ 340 m/s, so $d =$ 340 m.)

30. Air pressure increases and decreases at a rate equal to the frequency of the sound source.

31. No. Different frequencies arrive at different times. Music is jumbled.

32. Speed doesn't change. It depends only on the medium. The wavelength is "compressed" to half size.

33. Sound spreads out and is less intense with distance, both to and from reflecting surface. The reflecting surface is not perfect.

34. $10^{2.0}/10^{0.0} = 100$ times more intense

35. 10^5 or 100,000 times louder

36. More surface vibrates and more air is pushed. The time decreases because more sound energy is sent out, so the tuning fork loses energy more rapidly.

37. The "sympathetic strings" resonate with the sounds from the plucked strings.

38. Tighten; she is approaching zero beats, meaning matched frequencies.

39. If rhythm matches natural frequency, balcony could collapse. It happens.

40. Sounding board is smaller and lighter.

41. Resonance

42. Longer λ for electromagnetic wave due to greater speed ($\lambda = c/f$ "stretched" more at high speed.)

43. Interference cancels jackhammer sound in earphones. It does not cancel your voice.

Think and Solve

44. $\lambda = v/f = (340 \text{ m/s})/(20/\text{s}) =$ 17 m (about 56 feet); $\lambda = v/f = (340 \text{ m/s})/(20{,}000/\text{s}) = 0.017 \text{ m} = 1.7 \text{ cm}$

45. $v = 340$ m/s and $t = .05$ s so $d = vt = (340 \text{ m/s})(.05 \text{ s}) =$ 17 m

26 ASSESS *(continued)*

32. If the frequency of sound is doubled, what change will occur in its speed? What change will occur in its wavelength?

33. Why is an echo weaker than the original sound?

34. How much more intense is a close whisper than a sound at the threshold of hearing?

35. The signal-to-noise ratio for a tape recorder is listed at 50 dB, meaning that when music is played back, the intensity level of the music is 50 dB greater than that of the noise from tape hiss and so forth. By what factor is the sound intensity of the music greater than that of the noise?

36. If the handle of a tuning fork is held solidly against a table, the sound becomes louder. Why? How will this affect the length of the time the fork keeps vibrating? Explain, using the law of energy conservation.

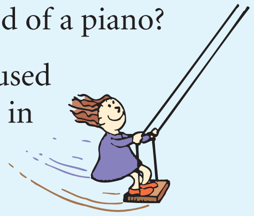
37. The sitar, an Indian musical instrument, has a set of strings that vibrate and produce music, even though they are never plucked by the player. These "sympathetic strings" are identical to the plucked strings and are mounted below them. What is your explanation?

38. Suppose a piano tuner hears 2 beats per second when listening to the combined sound from her tuning fork and the piano note being tuned. After slightly tightening the string, she hears 1 beat per second. Should she loosen or should she further tighten the string?

39. Why is it dangerous for people in the balcony of an auditorium to stamp their feet in a steady rhythm?

40. Why is the sound of a harp soft in comparison with the sound of a piano?

41. What physics principle is used by Laura when she pumps in rhythm with the natural frequency of the swing?



42. Suppose a sound wave and an electromagnetic wave have the same frequency. Which has the longer wavelength?

43. A special device transmits out-of-phase sound to a jackhammer operator through earphones. Over the noise of the jackhammer, the operator can easily hear your voice while you are unable to hear his. Explain.

Think and Solve

44. Sound waves travel at approximately 340 m/s. What is the wavelength of a sound with a frequency of 20 Hz? What is the wavelength of a sound with a frequency of 20 kHz?

45. A bat flying in a cave emits a sound and receives its echo 0.10 s later. Show that the distance to the wall of the cave is 17 m.

46. An oceanic depth-sounding vessel surveys the ocean bottom with ultrasonic sound that travels 1530 m/s in seawater. Find the depth of the water if the time delay of the echo to the ocean floor and back is 8 seconds.

47. On a field trip to Echo Cave, you clap your hands and receive an echo 1 second later. How far away is the cave wall?

48. Susie hammers on a block of wood when she is 85 m from a large brick wall. Each time she hits the block, she hears an echo 0.5 s later. With this information, show that the speed of sound is 340 m/s.

49. On a keyboard, you strike middle C, which has a frequency of 256 Hz.
   a. Show that the period of one vibration of this tone is 0.00391 s.
   b. As the sound leaves the instrument at a speed of 340 m/s, show that its wavelength in air is 1.33 m.

50. Suppose your friend is foolish enough to play his keyboard instrument underwater, where the speed of sound is 1,500 m/s.
   a. Show that the wavelength of the middle-C tone in water would be 5.86 m.
   b. Explain why middle C (or any other tone) has a longer wavelength in water than in air.

51. Two sounds, one at 240 Hz and the other at 243 Hz, occur at the same time. What beat frequency do you hear?

52. Two notes are sounding, one of which is 440 Hz. If a beat frequency of 5 Hz is heard, what is the other note's frequency?

53. What beat frequencies are possible with tuning forks of frequencies 256, 259, and 261 Hz?

Activities • • • • •

54. Suspend the wire grill of a refrigerator or oven shelf from a string, the ends of which you hold to your ears. Let a friend gently stroke the grill with pieces of broom straw and other objects. The effect is best appreciated if you are in a relaxed condition with your eyes closed. Describe and explain your observations.

55. Wet your finger and rub it slowly around the rim of a thin-rimmed stemmed glass while you hold its base firmly against a tabletop with your other hand. Describe and explain your observations.

56. Blow over the tops of two identical empty bottles and see if the tone produced is of the same pitch. Then put one in a freezer and try the procedure again. Sound will travel more slowly in the colder denser air of the cold bottle and the note will be lower. Try it and see.

More Problem-Solving Practice
Appendix F

46. $d = \bar{v}t = (1530\ \text{m/s})(4\ \text{s}) = 6120\ \text{m}$

47. $v = 340\ \text{m/s}$ and $t = 0.5\ \text{s}$ so $d = vt = (340\ \text{m/s})(0.5\ \text{s}) = 170\ \text{m}$

48. Speed = distance traveled ÷ time taken = $(2 \times 85\ \text{m}) \div 0.5\ \text{s} = 170\ \text{m}/0.5\ \text{s} = 340\ \text{m/s}$.

49. **a.** $T = 1/f = 1/(256\ \text{Hz}) = 0.00391\ \text{s}$, or 3.91 ms.
   b. $v = \lambda f$, so $\lambda = v/f = (340\ \text{m/s})/(256\ \text{Hz}) = 1.33\ \text{m}$.

50. **a.** $\lambda = v/f = (1500\ \text{m/s}) \div (256\ \text{Hz}) = 5.86\ \text{m}$
   b. Wave travels farther in each period, so λ is elongated.

51. 243 Hz − 240 Hz = 3 Hz

52. Either 445 Hz or 435 Hz

53. 3 possible beat frequencies, 2 Hz, 3 Hz, and 5 Hz.

Activities • • • • • • • • • • • • •

54. Students should hear the vibrations from the grill. The sound travels through the grill, through the string, and to the ears.

55. Students will hear the sound resonating. The friction of the finger produces standing waves in the glass.

56. This illustrates how air temperature affects the speed of sound. The colder bottle will produce a lower pitch due to lower molecular speeds and lower speed of sound.

Teaching Resources

- Computer Test Bank
- Chapter and Unit Tests