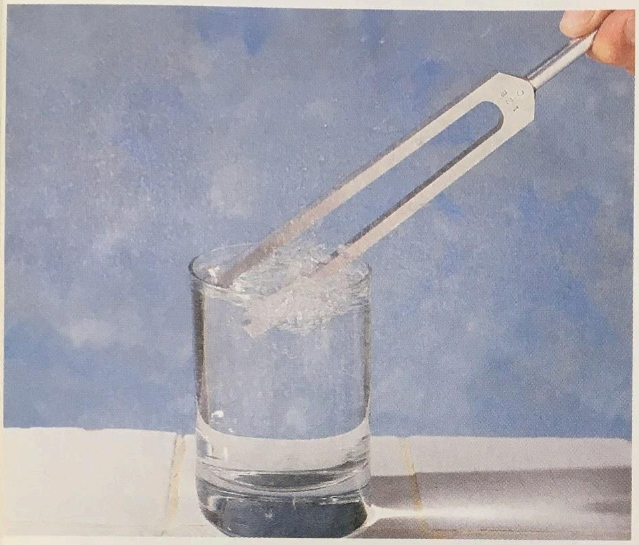
Chapter 26

Sound



Vibrations carry energy.

Pretend an entire room is filled with Ping-Pong table tennis balls, and in the middle of the room is a big paddle. You shake the paddle back and forth. What happens? When you move the paddle to the right, it hits some Ping-Pong balls and moves them to the right. They in turn hit others, moving them to the right, and so on. You set up a "Ping-Pong ripple" that moves across the room. The process is repeated the next time you move the paddle to the right, and another Ping-Pong ripple follows the first one. As you keep shaking the paddle back and forth, you keep creating Ping-Pong ripples that flow across the room. Can you see that what you are doing is making a longitudinal wave? At the far side of the room, Ping-Pong impulses arrive at the same frequency as the vibration of your paddle.

Molecules of air behave like tiny Ping-Pong balls. Place a tuning fork in the middle of a room and strike it with a rubber hammer. What happens? The surrounding air molecules are set into motion just like balls being hit by a paddle. Longitudinal waves flow through the air with a frequency equal to that of the vibrating prongs of the tuning fork. We hear these vibrations as sound. There is very little difference between the idea of a shaking paddle bumping into Ping-Pong balls and a vibrating tuning fork bumping into air molecules. In both cases vibrations are carried throughout the surrounding medium—the balls or the air.

Figure 26.1 ▲
Vibrate a Ping-Pong paddle in the midst of a lot of Ping-Pong balls, and they will transmit rhythmic pulses.

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26.1 The Origin of Sound

All sounds are produced by 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. 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 vibrating source equals the frequency of sound waves produced.

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 fog horn 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.

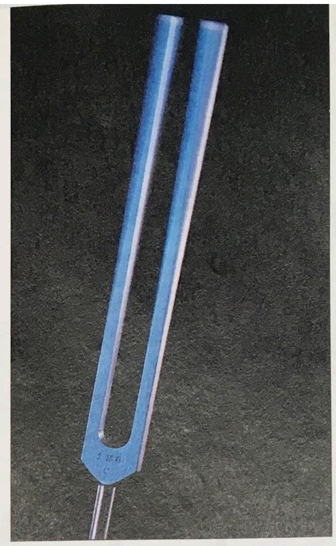

Figure 26.2 ▲
The source of all sound waves is vibration.

26.2 Sound in Air

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

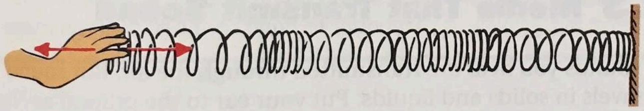

Figure 26.3 ▲
A compression travels along the spring.

For a clearer picture of this process, consider the long room shown in Figure 26.4. At one end is an open window with a curtain over it. At the other end is a door.

When you quickly open the door (top sketch), 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 (bottom sketch), the door pushes neighboring air molecules out of the room. This produces an area of low pressure next to the door. Neighboring molecules then

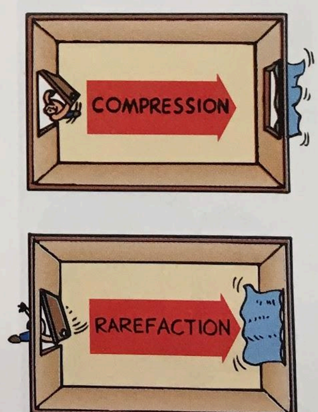

Figure 26.4 ▲
(Top) When the door is opened, a compression travels across the room. (Bottom) When the door is closed, a rarefaction travels across the room.

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 time the disturbance is 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. 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.

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 Ping-Pong paddle moving back and forth in a room packed with Ping-Pong balls. As the source vibrates, a series of compressions and rarefactions is produced.

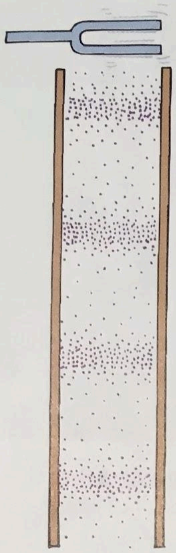

Figure 26.5 ▲
Compressions and rarefactions traveling from the tuning fork through the tube.

26.3 Media That Transmit Sound

Most sounds you hear are transmitted through the air. But sound also travels in solids and liquids. 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.

Or click two rocks together under water 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.

Sound cannot travel in a vacuum (Figure 26.6). 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.

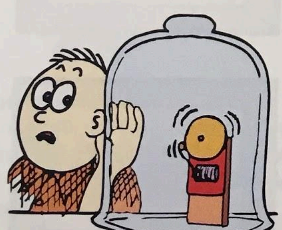

Figure 26.6 ▲
Sound can be heard from the ringing bell when air is inside the jar, but not when the air is removed.

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 a flash of lightning (unless you're at the source). These experiences are evidence that sound is much slower than light.

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 increases this speed slightly. Increased temperature increases the speed of sound also. A little thought will show that 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 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 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. Steel is very elastic; putty is inelastic.* 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.

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Question

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

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 such as the oscilloscope shown in Figure 26.7.

LINK TO TECHNOLOGY

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.

Answer

For a speed of sound in air of 340 m/s, the distance is (340 m/s) × (3 s) = 1020 m. Time for the light is negligible, so the storm is slightly more than 1 km away.

* You may be surprised that steel is considered elastic and putty inelastic. After all, that stretchy material that keeps our socks up is called *elastic,* and putty is more stretchy than steel. But elasticity is not "stretchability;" it's the tendency of a material to resume its initial shape after having been exposed to a distorting force. Some very stiff materials are elastic!

Table 26.1	
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

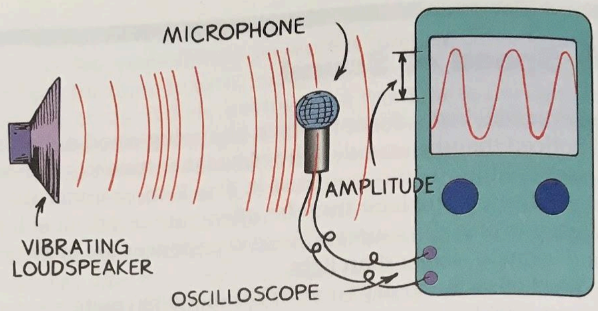


Figure 26.7 ▲
The radio loudspeaker at the left is a paper cone that vibrates in rhythm with an electric signal. The sound that is produced sets up similar vibrations in the microphone (center), which are displayed on the screen of an oscilloscope (right). The shape of the waveform on the oscilloscope reveals information about the sound.

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. Despite subjective variations, loudness varies nearly as the logarithm of intensity (powers of ten). The unit of intensity for sound is the decibel (dB), after Alexander Graham Bell, inventor of the telephone. 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 of this, we say that human hearing is approximately logarithmic.

26.6 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? This 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 **forced vibration.**

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. The vibration of guitar strings in an acoustical guitar would be faint if they weren't transmitted to the guitar's wooden body. Sounding boards are important in all stringed musical instruments.

Figure 26.8 ▲
When the string is plucked, the washtub is set into forced vibration and serves as a sounding board.

DOING PHYSICS

Water Taps

Pour water into a glass while repeatedly tapping the glass with a spoon. As the tapped glass is being filled, does the pitch of the sound increase or decrease? If it increases, the glass (including its water) is vibrating faster. If the pitch decreases, the glass and water are vibrating more slowly. Why should adding water change the natural frequency?

Activity

26.7 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 depends on factors such as the elasticity and shape of the object. Bells 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.

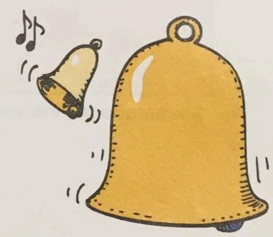


Figure 26.9 ▲
The natural frequency of the smaller bell is higher than that of the big bell, and it rings at a higher pitch.

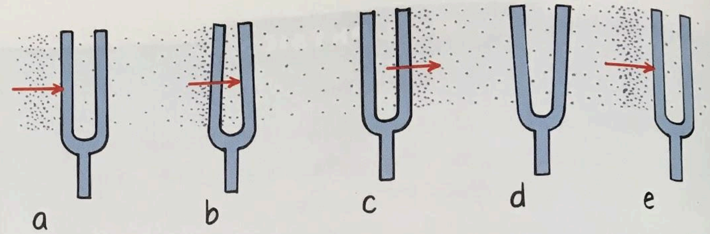
26.8 Resonance

When the frequency of a forced vibration on an object matches the object's natural frequency, a dramatic increase in amplitude occurs. This phenomenon is called **resonance.** Resonance means to resound, or sound again. Putty doesn't resonate because it isn't elastic, and a dropped handkerchief is too limp. In order for something to resonate, it needs 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. 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 ▶
Stages of resonance. (a) The first compression meets the fork and gives it a tiny and momentary push. The fork bends (b) and then returns to its initial position (c) just at the time a rarefaction arrives. It keeps moving and (d) overshoots in the opposite direction. Just when it returns to its initial position (e), the next compression arrives to repeat the cycle. Now it bends farther because it is already moving.



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. 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 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.

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 is not restricted to wave motion. It 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, Figure 26.12, is attributed to wind-generated resonance!

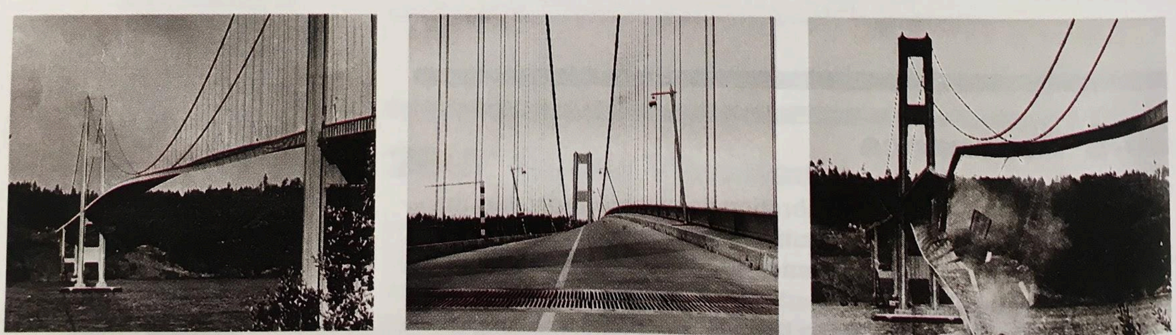


Figure 26.12 ▲
In 1940, four months after being completed, the Tacoma Narrows Bridge in the state of Washington was destroyed by a 40-mile-per-hour wind. The mild gale produced a fluctuating force that is said to have resonated with the natural frequency of the bridge, steadily increasing the amplitude over several hours until the bridge collapsed.

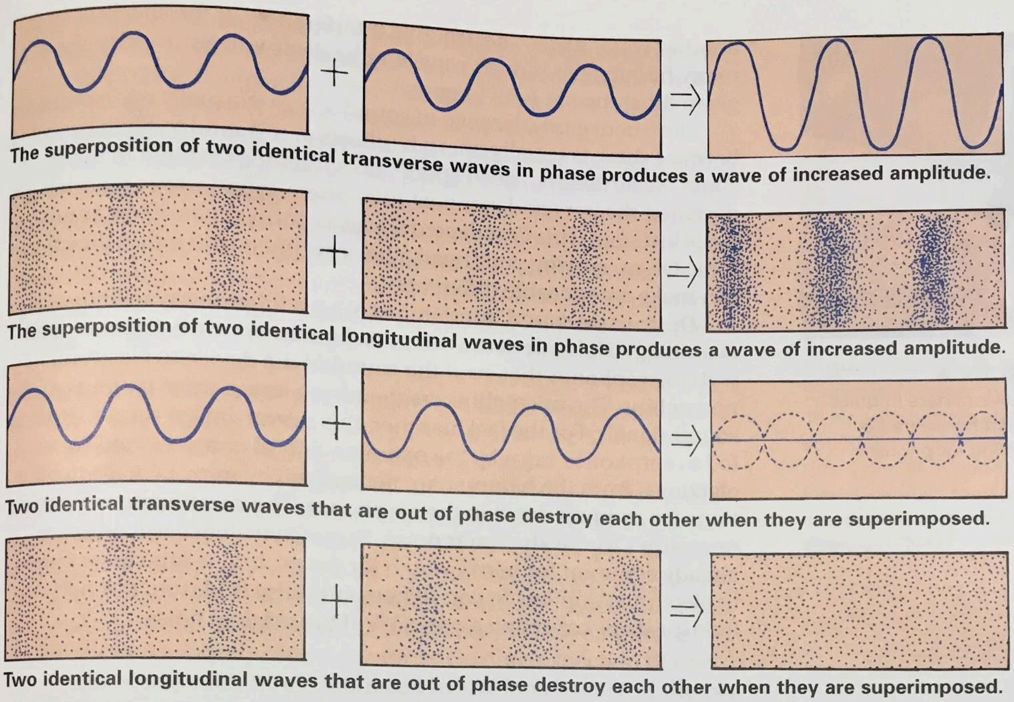


Figure 26.13 ▲
Wave interference for transverse and longitudinal waves.

26.9 Interference

Sound waves, like any waves, can be made to interfere. Recall that wave interference was discussed in the previous chapter. A comparison of interference for transverse waves and longitudinal waves is shown in Figure 26.13. 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. For sound, the crest of a wave corresponds to a compression, and the trough of a wave corresponds to a rarefaction. Interference occurs for both transverse and longitudinal waves.

Interference affects the loudness of sounds. If you are equally distant from two sound speakers that simultaneously trigger identical sound waves of constant frequency (see Figure 26.14, top), the sound is louder because the waves add. The compressions and rarefactions arrive in phase, that is, in step.

If you move to the side so that paths from the speakers differ by a half-wavelength (see Figure 26.14, bottom), rarefactions from one speaker reach you at the same time as compressions from the other. It's like the crest of one water wave exactly filling in the trough of

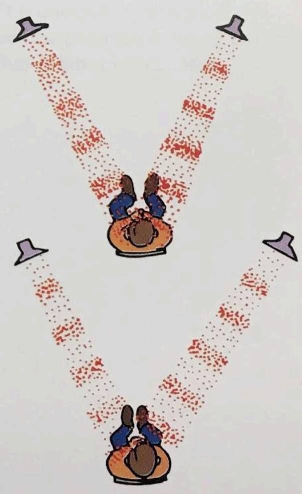


Figure 26.14 ▲
Interference of sound waves. (Top) Waves arrive in phase. (Bottom) Waves arrive out of phase.

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

another water wave—destructive interference. (If the speakers emit many frequencies, not all wavelengths destructively interfere for a given difference in path lengths.)

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 are already common for pilots. Watch for the antinoise principle applied to electronic mufflers in cars, where antinoise is blasted through loudspeakers, canceling about 95% of the original noise.

26.10 Beats

An interesting and special case of interference occurs 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. This periodic variation in the loudness of sound is called **beats.**

Beats can be heard when two slightly mismatched tuning forks 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.

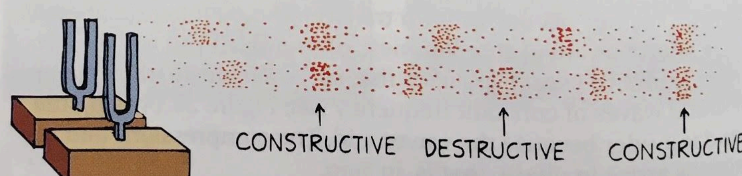


Figure 26.16 ▲
The interference of two sound sources of slightly different frequencies produces beats.

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.

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.

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

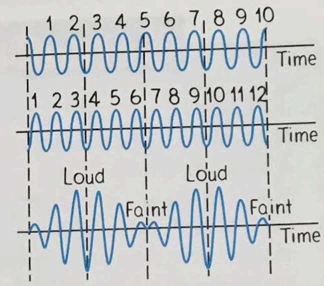
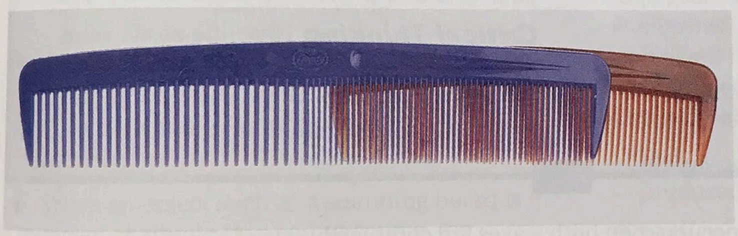


Figure 26.17 ▲
Sinusoidal representations of a 10-Hz sound wave and a 12-Hz sound wave during a 1-second time interval. When the two waves overlap, they produce a composite wave with a beat frequency of 2 Hz.



◀ **Figure 26.18**
The unequal spacings of the combs produce a moiré pattern that is similar to beats.

Question

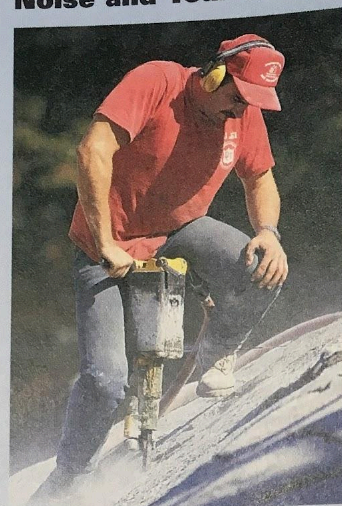
What is the beat frequency when a 262-Hz and a 266-Hz tuning fork are sounded together? A 262-Hz and a 272-Hz?

Answer

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.

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, Meidor 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?

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, 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 26.18).

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 or some other instrument.