26 Sound

Pretend the whole room is filled with Ping-Pong balls, and in the middle is a big paddle. You shake the paddle back and forth. What happens? The Ping-Pong balls are made to shake back and forth also. Their frequency of shaking back and forth will be the same as the frequency at which the paddle is shaken. Or instead, place a tuning fork in the middle of a room and strike it with a rubber hammer. What happens? The surrounding air molecules are made to vibrate in rhythm with 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 the vibrations are carried throughout the surrounding medium—the balls or the air.

Fig. 26-1 Vibrate a Ping-Pong paddle in the midst of a lot of Ping-Pong balls, and they will vibrate also.

26.1 The Origin of Sound

All sounds are produced by the vibrations of material objects. In a piano, violin, and guitar, the sound wave is produced by the vibrating strings; in a saxophone, by a vibrating reed; in a flute, by a fluttering column of air blown out the mouthpiece. Your voice results from the vibration of your vocal chords.

Fig. 26-2 The source of all sound waves is something that vibrates.

In each of these cases a vibrating source sends a disturbance through the surrounding medium, usually air, in the form of longitudinal waves. Under ordinary conditions, the frequency of the vibrating source and the frequency of the sound waves produced are the same.

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

The human ear can normally hear pitches corresponding to the range of frequencies between about 20 and 20 000 hertz. As we grow older, the limits of this human hearing range shrink. 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 and ultrasonic sound waves.

26.2 The Nature of Sound in Air

Clap your hands and you produce a wave pulse that travels out in all directions. The pulse vibrates the air in the same way that a similar pulse would vibrate a coiled spring or a Slinky. Each particle moves to and fro along the direction of motion of the expanding wave.

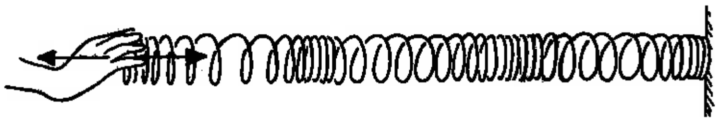


Fig. 26-3 A compression travels along the spring.

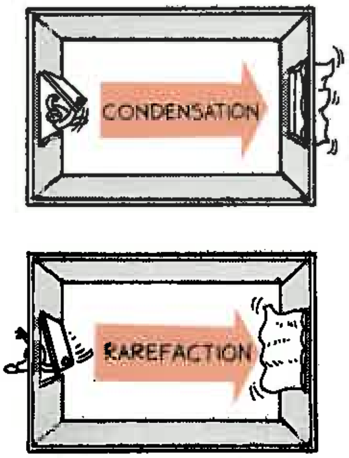


Fig. 26-4 (Top) When the door is opened, a condensation travels across the room. (Bottom) When the door is closed, a rarefaction travels across the room.

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 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. The neighboring molecules, in turn, push into their neighbors, and so on, like a compression traveling 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 **condensation**.

When you 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 move into it, leaving a zone of lower pressure behind them. We say this zone of lower-pressure air is *rarefied*. Other molecules farther away from the door, in turn, move into these rarefied regions, and a disturbance again travels across the room. When the lower-pressure air reaches the curtain, it flaps inward. This time the disturbance is a **rarefaction**.

As for all wave motion, it is not the medium itself 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 continually swing the door open and closed in periodic fashion, you can set up a wave of periodic condensations 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 depicted. When the prong of the tuning fork next to the tube moves toward the tube, a condensation enters the tube. When the prong swings away, in the opposite direction, a rarefaction follows the condensation. It is like the Ping-Pong paddle moving to and fro in a room packed with Ping-Pong balls. As the source vibrates, a series of compressions and rarefactions is produced.

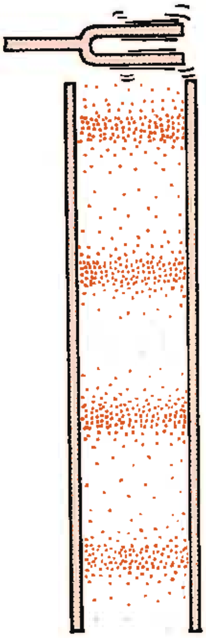


Fig. 26-5 Condensations and rarefactions traveling from the tuning fork through the tube.

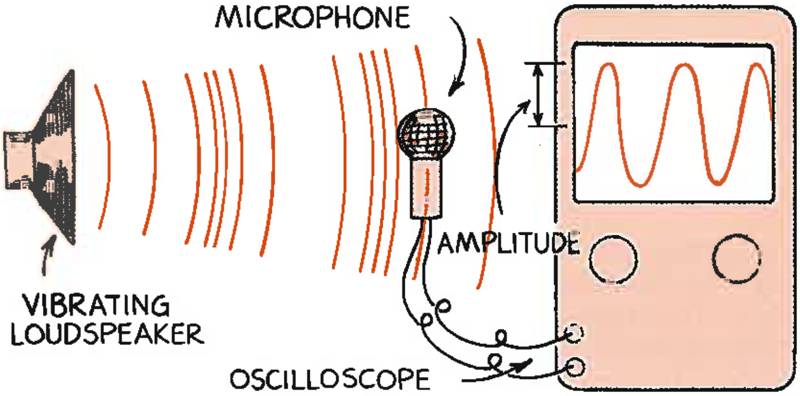


Fig. 26-6 The radio loudspeaker at the left is a paper cone that vibrates in rhythm with an electric signal. The sound that is produced sets up similar vibrations in the microphone (center), which are displayed on the screen of an oscilloscope (right). The shape of the waveform on the oscilloscope reveals information about the sound.

► Question

Do condensations and rarefactions in a sound wave travel in the same direction or in opposite directions from one another?

26.3 Media That Transmit Sound

Most sounds you hear are transmitted through the air. But sound also travels through solids and liquids. Put your ear to the ground as American Indians did, and you can hear the hoofbeats of distant horses before you can hear them in air. More practically, put your ear to a metal fence and have a friend tap it from far away. The sound is more pronounced in the metal than in the air. The metal atoms are more compact and more resilient ("springy") than molecules in the air, so sound is more readily conducted in metals than in air.

Or click a couple of rocks together under water while your ear is submerged. You will hear the clicking sound very clearly. If you've ever been swimming in the presence of motorized boats, you probably noticed that you can hear the motors of the boats much more clearly underwater than above water. Solids and liquids are generally excellent conductors of sound—much better than air.

Sound will not travel in a vacuum (Figure 26-7). The transmission of sound requires a medium. If there is nothing to compress and expand, there can be no sound.

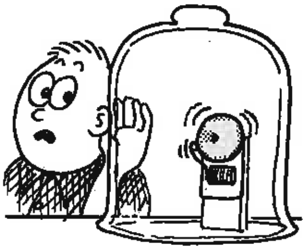


Fig. 26-7 Sound can be heard from the ringing bell when air is inside the jar, but when the air is removed by a vacuum pump, no sound can be heard.

26.4 The Speed of Sound

Have you ever watched a person at a distance chopping wood or hammering, and noticed that the sound of the blow takes an appreciable 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 for the slower speed of sound compared to light.

► Answer

They travel in the same direction.

The speed of sound in dry air at 0°C is about 330 meters per second, nearly 1200 kilometers per hour. Water vapor in the air increases this speed slightly. Increased temperature increases the speed of sound also. A little thought will show 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 rise in air temperature above 0°C, the speed of sound in air increases by 0.6 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 on the elasticity of the material. An elastic material is one that, when distorted, returns quickly to its initial shape when the distorting force is removed. An elastic substance such as steel (in contrast to putty, which is an inelastic substance) has resilience and can transmit energy with little loss. Steel is "springy" because the atoms in steel are close together and are very elastic. Sound will travel about fifteen times as fast in steel as in air. In water, sound will travel about four times as fast as in air.

▶ **Question**

About how far away is a thunderstorm when you notice a 3-second delay between the flash of lightning and the sound of thunder?

26.5 Forced Vibration

If you strike an unmounted tuning fork, the sound it makes is faint. Hold the base of the fork on a table top, and the sound is relatively loud. This is because the table is forced to vibrate, and its larger surface sets more air in motion. The table top 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 to produce the pleasant sounds that are heard. Without the sounding board, the sound the music-box mechanism makes is barely audible. Similarly, stringed musical instruments are made with sounding boards.

Fig. 26-8 The forced vibrations in the sounding board make the sounds audible.

▶ **Answer**

If you assume that the speed of sound in air is about 340 m/s, the sound of the thunder will travel (340 m/s) × (3 s) = 1020 m. You can assume no measurable time delay for the light, so the storm is slightly more than 1 km away.

26.6 Natural Frequency

Drop a wrench and a baseball bat on the floor, and you hear distinctly different sounds. This is because both 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 will vibrate 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, of course, vibrate at their own characteristic frequencies. And interestingly enough, most things—from planets to atoms and almost everything else in between—have a springyness 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 for the continuation of vibration.

Fig. 26-9 The natural frequency of the smaller bell is higher than that of the big bell, and it rings at a higher pitch.

26.7 Resonance

When the frequency of forced vibrations on an object matches the object's natural frequency, a dramatic increase in amplitude occurs. This phenomenon is called **resonance**. Literally, resonance means to resound, or sound again. Putty doesn't resonate because it isn't elastic, and a dropped hankerchief 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.

Fig. 26-10 Pumping a swing in rhythm with its natural frequency produces larger amplitudes.

A common classroom demonstration of resonance is illustrated with a pair of tuning forks adjusted to the same frequency and spaced a meter or so 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 condensation gives the prong a tiny push. Since the frequency of these pushes corresponds to the natural frequency of the fork, the pushes will 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.

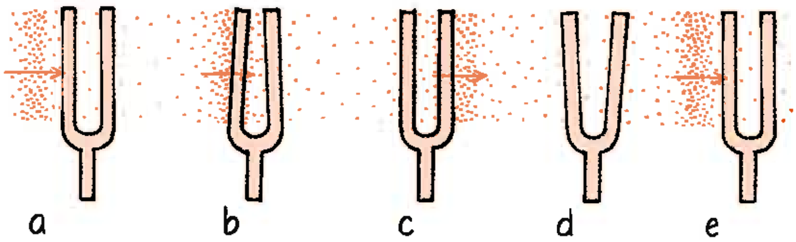


Fig. 26-11 Stages of resonance. (a) The first condensation meets the fork and gives it a tiny and momentary push. The fork bends (b) and then returns to its initial position (c) just at the time a rarefaction arrives. It keeps moving and (d) overshoots in the opposite direction. Just when it returns to its initial position (e), the next condensation arrives to repeat the cycle. Now it bends farther because it is already moving.

If the forks are not adjusted for matched frequencies, the timing of pushes is 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 stations at once.

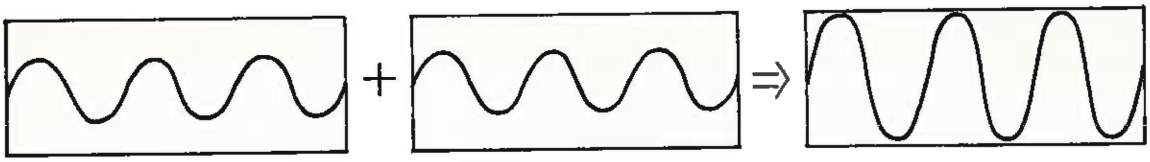
Resonance is not restricted to wave motion. It occurs whenever successive impulses are applied to a vibrating object in rhythm with its natural frequency. English cavalry troops marching across a footbridge in 1831 inadvertently caused the bridge to collapse when they marched in rhythm with the bridge's natural frequency. Since then, it is customary to order troops to "break step" when crossing bridges. A bridge disaster in this century was caused by wind-generated resonance (Figure 26-12).

Fig. 26-12 In 1940, four months after being completed, the Tacoma Narrows Bridge in the state of Washington was destroyed by wind-generated resonance. The mild gale produced a fluctuating force in resonance with the natural frequency of the bridge, steadily increasing the amplitude over several hours until the bridge collapsed.

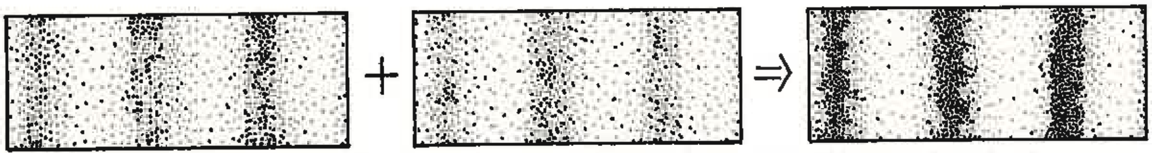
The effects of resonance are all about us. Resonance underscores not only the sound of music, but the color of autumn leaves, the height of ocean tides, the operation of lasers, and a vast multitude of phenomena that add wonder and fascination to the world about us.

26.8 Interference

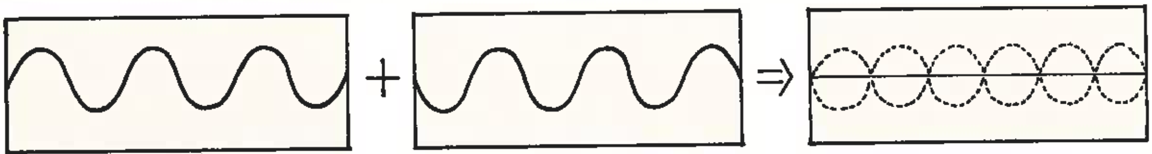
Sound waves, like any waves, can be made to exhibit interference. Recall that wave interference was discussed in the last chapter. A comparison of interference for transverse waves and longitudinal waves is shown in Figure 26-13. In either case, when the crests of one wave overlap the crests of another wave, there is an increase in amplitude. Or when the crest of one wave overlaps the trough of another wave, there is a decrease in amplitude. In the case of sound, the crest of a wave corresponds to a condensation, and the trough of a wave corresponds to a rarefaction. Interference occurs for both transverse and longitudinal waves.



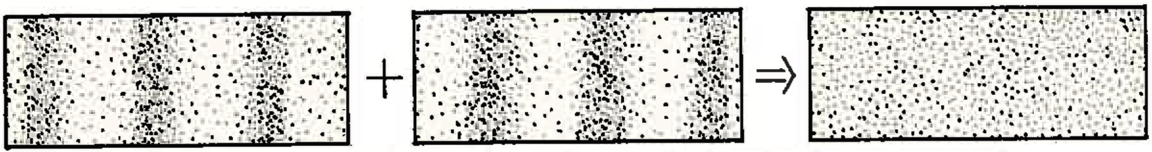
The superposition of two identical transverse waves in phase produces a wave of increased amplitude.



The superposition of two identical longitudinal waves in phase produces a wave of increased amplitude.



Two identical transverse waves that are out of phase destroy each other when they are superposed.



Two identical longitudinal waves that are out of phase destroy each other when they are superposed.

Fig. 26-13 Wave interference for transverse and longitudinal waves.

An interesting case of sound interference is illustrated in Figure 26-14. If you are an equal distance from two sound speakers that each emit an identical tone of constant frequency, the sound is louder because the effects of each speaker add. The condensations and rarefactions of the tones arrive in phase, that is, in step. However, if you move to the side so that the paths from the speakers to you differ by a half-wavelength, then the rarefactions that reach you from one speaker will be filled in by the condensations from the other speaker. This is destructive interference. It is just as if the crest of one water wave exactly filled in the trough of another water wave. If the region is devoid of any reflecting surfaces, little or no sound will be heard!

If the speakers emit a whole range of frequencies, not all wavelengths will destructively interfere for a given difference in path lengths. Interference of this type is usually not a problem, because there is usually enough reflection of sound to fill in cancelled spots. Nevertheless, "dead spots" are sometimes evident in poorly designed theaters or in gymnasiums, where sound waves reflected off walls interfere with unreflected waves to form zones of low amplitude. Moving your head a few centimeters in either direction can make a noticeable difference.

Fig. 26-14 Interference of sound waves. (Top) Waves arrive in phase. (Bottom) Waves arrive out of phase.

26.9 Beats

An interesting and special case of interference occurs when two tones of slightly different frequencies 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 different frequency 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 condensation from one fork overlaps a condensation from the other—the sound is a maximum. A moment later, when the forks are out of step, a condensation 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

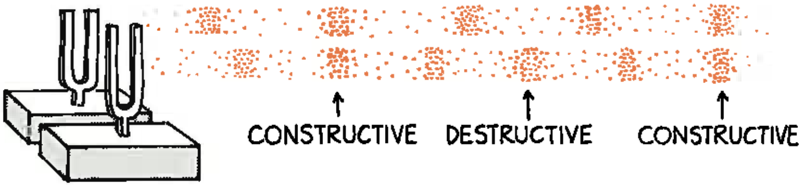


Fig. 26-15 The interference of two sound sources of slightly different frequencies produces beats.

on you. A little thought will show that you two will be momentarily in step twice each minute. In general, if two people with different strides walk together, the number of times they are in step each minute is equal to the difference in the frequencies of the steps. This applies also to the pair of tuning forks. If one fork vibrates 264 times per second, and the other fork vibrates 262 times per second, they will be in step twice each second. A beat frequency of 2 hertz will be heard.

► **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 fork?

Fig. 26-16 The unequal spacings of the combs produce a moiré pattern that is similar to 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 26-16).

Beats can occur with any kind of wave and are a practical way to compare frequencies. To tune a piano, for example, a piano tuner listens for beats produced between a standard tuning fork and that of 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 that of a standard tone produced by an oboe or some other instrument.

► **Answer**

The 262-Hz and 266-Hz forks will produce 4 beats per second, that is, at 4 Hz (or 266 Hz − 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 at 10 Hz, which some people will not be able to hear. Beat frequencies greater than 10 Hz are too rapid to be heard normally.

26 Chapter Review

Concept Summary

Sound waves are produced by the vibrations of material objects.

- A disturbance in the form of a longitudinal wave travels away from the vibrating source.
- High-pitch sounds are produced by sources vibrating at high frequency, while low-pitch sounds are produced by low-frequency sources.

Sound waves consist of traveling pulses of high-pressure zones, or condensations, alternating with traveling pulses of low-pressure zones, or rarefactions.

- Sound can travel through gases, liquids, and solids, but not through a vacuum.
- Sound travels fastest through very elastic materials, such as steel.

Every object vibrates at its own set of natural frequencies.

- When an object such as a sounding board is forced to vibrate by a sound source, the sound becomes louder.
- When an object is forced to vibrate at one of its own natural frequencies, resonance occurs and the sound becomes much louder.

Like any waves, two sound waves can exhibit interference and can make the sound louder or cancel the sound.

- Rapid changes in loudness known as beats occur when two tones very close in frequency are heard at the same time.

Important Terms

beats (26.9)
condensation (26.2)
forced vibration (26.5)
infrasonic (26.1)
natural frequency (26.6)
pitch (26.1)
rarefaction (26.2)
resonance (26.7)
ultrasonic (26.1)

Review Questions

1. What is the source of all sounds? (26.1)
2. How does pitch relate to frequency? (26.1)
3. What is the average frequency range of human hearing? (26.1)
4. Distinguish between *infrasonic* and *ultrasonic* sound. (26.1)
5. a. Distinguish between *condensations* and *rarefactions* of a sound wave.
   b. How is each produced? (26.2)
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? (26.3)
7. a. Approximately how fast does sound travel in dry air?
   b. Does its speed depend on air temperature? (26.4)
8. How does the speed of sound in air compare to its speed in water and in steel? (26.4)
9. Why does sound travel faster in solids and liquids than in gases? (26.4)
10. Why is sound louder when a vibrating source is held to a sounding board? (26.5)
11. Why do different objects make different sounds when dropped on a floor? (26.6)

12. What does it mean to say that everything has a natural frequency of vibration? (26.6)

13. What is the relationship between forced vibration and resonance? (26.7)

14. Why can a tuning fork or bell be set into resonance, whereas a piece of tissue paper cannot? (26.7)

15. How is resonance produced in a vibrating object? (26.7)

16. How is the process of adjusting the frequency of a tuning fork similar to dialing a station on the radio? (26.7)

17. Is it possible for one sound wave to cancel another? Explain. (26.8)

18. Why does destructive interference occur when the path lengths from two identical sources differ by a half wavelength? (26.8)

19. How does interference of sound relate to beats? (26.9)

20. What is the beat frequency when a 494-Hz tuning fork and a 496-Hz tuning fork are sounded together? (26.9)

Activities

1. Suspend the wire grill of a refrigerator or oven shelf from a string, the ends of which you hold to your ears (Figure A). 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. Be sure to try this.

Fig. A

2. In the bathtub or when swimming, submerge your head and listen to the sound you make when clicking your fingernails or tapping a pair of stones together. Compare the sound with that you make when both the source and your ears are above water. You'll find it is difficult to hear when the source and your ears are in different media, as when your head is submerged and the sound source is in the air. Most of the sound energy is reflected at the boundary between the two media rather than transmitted through it.

3. If you blow air across the top of a pop bottle, a puff of air (condensation) travels downward, bounces from the bottom, and travels back to the opening. When it arrives (less than a thousandth of a second later), it disturbs the flow of air that you are still producing across the top. This causes a slightly bigger puff of air to start again on its way down the bottle. This happens repeatedly until a very large (and loud) vibration is built up and you hear it as sound. The pitch of the sound depends on the time taken for the back-and-forth trip, which depends on the depth of the bottle. If the bottle is empty, a long wave is reinforced and a relatively low tone is produced. With liquid in the bottle, the bottom is closer to the top and the pitch is higher. With a series of bottles properly filled, you can make your own music.

4. As you pour water into a glass, repeatedly tap the glass with a spoon. As the tapped glass is being filled, does the pitch of the sound increase or decrease? Think about this before you try it and hear for yourself.

Think and Explain

1. If you are in the stands at a track meet and are far from the starter, you'll notice the smoke from the starter's gun before you hear it fire. Why?

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

3. You watch a distant farmer driving a stake into the ground with a sledge hammer. 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?

4. 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?

5. When a person talks after inhaling helium gas, the voice is high-pitched. This is principally because helium molecules move faster past the vocal chords than do molecules of air. Why do helium molecules move faster? (*Hint*: The helium molecule is significantly lighter than any of the molecules that compose air. The molecules of all gases at the same temperature have the same average kinetic energy. If an elephant and a mouse ran into a barn door with the same kinetic energy, which of the two had the higher speed?)

6. 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.

7. 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?

8. Suppose three tuning forks of frequency 260 Hz, 262 Hz, and 266 Hz are available. What beat frequencies are possible for pairs of forks sounded together?

9. 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?

10. Do all people in a group hear the same music when they listen to it attentively? (Do all see the same sight when looking at a painting? Do all taste the same flavor when sampling the same cheddar cheese? Do all perceive the same aroma when smelling the same flower? Do all feel the same texture when touching the same fabric? Do all come to the same conclusion when listening to a logical presentation of ideas?)