Part Four

Sound

This DVD is the pits—billions of them inscribed in an array that is scanned by a laser beam at millions of pits per second. The sequence of pits detected as light and dark spots forms a binary code that is converted into sound we hear and pixels of light we see on a screen. I'm holding a Blu-Ray® DVD that is read by a blue laser, which nicely plays in my PlayStation 3®. It holds adequate information to produce a picture with 1920 × 1080 pixel resolution. That's over 2 millions pixels of picture for each picture that changes some 30 times a second! And all of this from merely a bunch of ones and zeros. That's physics!

19 Vibrations and Waves

1 Diane Reindeau shows her class how waves are generated by vibrations in a classroom wave demonstrator. 2 Frank Oppenheimer at the San Francisco Exploratorium shows a straight-line trace when a swinging pendulum bob leaks sand on a stationary conveyor belt. 3 When the conveyor belt moves in uniform motion, a sine curve is traced.

The Exploratorium in San Francisco is not only a world-class museum of science and technology, it is also perhaps the best place on planet Earth to teach a physics class. I was honored to do so in the years 1982–2000. The Exploratorium is special because of its founder, Frank Oppenheimer, the younger brother of more famous J. Robert Oppenheimer, the director of the Los Alamos lab during World War II. Frank's passion for doing physics was surpassed only by his passion for teaching it. I was enormously privileged to share my classroom with him when vibrations, waves, and musical sounds were the topic. I remember after one of his brilliant presentations he quietly asked me how he did. Almost tearfully I responded, "You were great." For it was true. In addition to his explanations of physics being great, he himself exuded a personal greatness—with his insistence on excellence, a lack of pretentiousness, and a respect for invention and play, and for his students. Frank was the most-loved teacher in my experience.

Frank Oppenheimer suffered in the political witch hunts of the 1950s when he admitted membership in the American Communist Party back in the depths of the Depression, along with many idealistic citizens who were sensitive to the nation's high unemployment at the time. Frank told me that after he refused to give the names of other members to the House Un-American Activities Committee, he was hounded by the FBI. Despite high accomplishments in physics, and despite international awards in physics, he was barred from practicing physics. He was, however, allowed to be a cattle farmer and teach general science at Pagosa Springs High School in Colorado. Frank went on to say that adding insult to injury, his neighbors were warned by government agents to keep a wary eye on his potential "un-American activities." Frank devoted the rest of his life to exposing the general public to the wonders of science, which culminated in the Exploratorium in San Francisco.

I dedicated the Fifth Edition of my *Conceptual Physics* to him. Before Frank died in 1985, he contributed this paragraph, which I used as the book's opening paragraph:

"By trying to understand the natural world around us, we gain confidence in our ability to determine whom to trust and what to believe about other matters as well. Without this confidence, our decisions about social, political, and economic matters are inevitably based entirely on the most appealing lie that someone else dishes out to us. Our appreciation of the noticings and discoveries of both scientists and artists therefore serves, not only to delight us, but also to help us make more satisfactory and valid decisions and to find better solutions for our individual and societal problems."

Frank's main motive for founding the Exploratorium was to lift people by encouraging them to do for themselves, and think for themselves—a way of teaching that is now widespread.

Good Vibrations

In a general sense, anything that moves back and forth, to and fro, side to side, in and out, or up and down is vibrating. A *vibration* is a periodic wiggle in time. A periodic wiggle in both space and time is a *wave*. A wave extends from one place to another. Light and sound are both vibrations that propagate throughout space as waves, but two very different kinds of waves. Sound is a mechanical wave, the propagation of vibrations through a material medium—a solid, liquid, or gas. If there is no medium to vibrate, then no sound is possible. Sound cannot travel in a vacuum. But light can, for, as we shall learn in later chapters, light is a vibration of electric and magnetic fields—an electromagnetic wave of pure energy. Although light can pass through many materials, it needs none. This is evident when it propagates through the vacuum between the Sun and Earth. The source of all waves—mechanical or electromagnetic—is something that is vibrating. We shall begin our study of vibrations and waves by considering the motion of a simple pendulum.

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Tutorial
Waves and Vibrations

Vibration of a Pendulum

If we suspend a stone at the end of a piece of string, we have a simple pendulum. Likewise for a sand-filled container suspended at the end of a vertical pole that swings to and fro. In the opening photos of this chapter, Frank Oppenheimer shows how sand leaking from such a pendulum traces a straight line on a stationary conveyor belt, and then, when the belt moves at constant speed, produces a special curve known as a **sine curve.** A sine curve is a pictorial representation of a wave produced by simple harmonic motion.[1]

Pendulums swing to and fro with such regularity that, for a long time, they were used to control the motion of most clocks. They can still be found in grandfather clocks and cuckoo clocks. Galileo discovered that the time a pendulum takes to swing to and fro through small distances depends only on the *length of the pendulum.*[2] The

In 1848, Jean Foucault devised a very long pendulum, that when swinging appears to be changing directions during the day. Actually, Earth revolves underneath the pendulum.

[1] The condition for simple harmonic motion is that the restoring force is proportional to the displacement from equilibrium. This condition is met, at least approximately, for most vibrations. The component of weight that restores a displaced pendulum to its equilibrium position is directly proportional to the pendulum's displacement (for small angles)—likewise for a bob attached to a spring. Recall from Chapter 12, Hooke's law for a spring: $F = k\Delta x$, where the force to stretch (or compress) a spring is directly proportional to the distance stretched (or compressed).

[2] The equation for the period of a simple pendulum for small arcs is $T = 2\pi\sqrt{\frac{L}{g}}$, where T is the period, L is the length of the pendulum, and g is the acceleration of gravity.

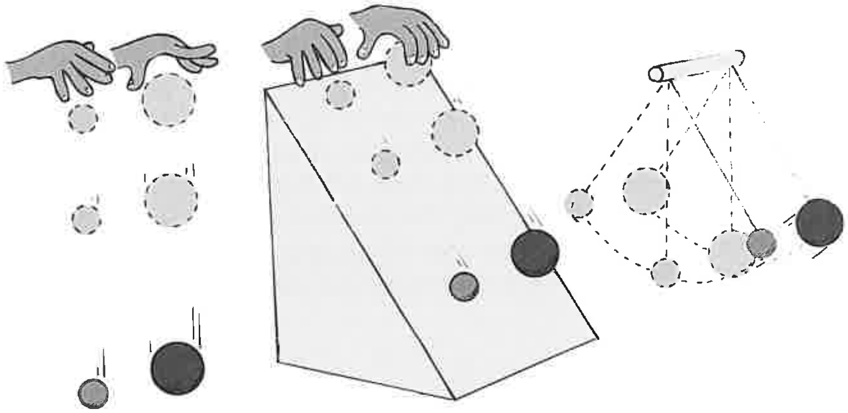


FIGURE 19.1

If you drop two balls of different mass, they accelerate at *g*. Let them slide without friction down the incline, and they slide together at the same fraction of *g*. Tie them to strings of the same length so they are pendulums, and they swing to and fro in unison. In all cases, the motions are independent of mass.

time of a to-and-fro swing, called the **period,** does not depend on the mass of the pendulum or on the size of the arc through which it swings.

A long pendulum has a longer period than a short pendulum; that is, it swings to and fro less frequently than a short pendulum. A grandfather clock's pendulum with a length of about 1 meter, for example, swings with a leisurely period of 2 seconds, while the much shorter pendulum of a cuckoo clock swings with a period that is less than a second. In addition to length, the period of a pendulum depends on the acceleration of gravity. Oil and mineral prospectors use very sensitive pendulums to detect slight differences in this acceleration, which is affected by the densities of underlying formations.

Wave Description

A sine curve can also be traced by a bob attached to a spring undergoing vertical simple harmonic motion (Figure 19.2). As previously mentioned, a sine curve is a pictorial representation of a wave. As for a water wave, the high points of a sine wave are called *crests* and the low points are called *troughs*. The straight dashed line represents the "home" position, or midpoint of the vibration. The term **amplitude** refers to the distance from the midpoint to the crest (or trough) of the wave. So the amplitude equals the maximum displacement from equilibrium.

The **wavelength** of a wave is the distance from the top of one crest to the top of the next crest. Or, equivalently, the wavelength is the distance between any successive identical parts of the wave. The wavelengths of waves at the beach are measured in meters, the wavelengths of ripples in a pond are measured in centimeters, and the wavelengths of light are measured in billionths of a meter (nanometers).

How frequently a vibration occurs is described by its **frequency.** The frequency of a vibrating pendulum, or of an object on a spring, specifies the number of to-and-fro vibrations it makes in a given time (usually 1 second). A complete to-and-fro oscillation is one vibration. If it occurs in 1 second, the frequency is one vibration per second. If two vibrations occur in 1 second, the frequency is two vibrations per second.

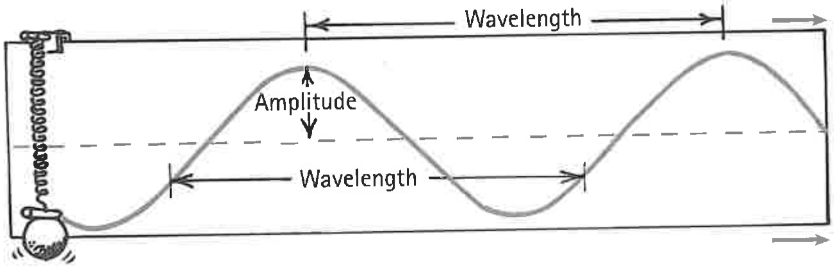


FIGURE 19.2

INTERACTIVE FIGURE

When the bob vibrates up and down, a marking pen traces a sine curve on paper that is moved horizontally at constant speed.

The unit of frequency is called the **hertz** (Hz), after Heinrich Hertz, who demonstrated radio waves in 1886. One vibration per second is 1 hertz; two vibrations per second is 2 hertz, and so on. Higher frequencies are measured in kilohertz (kHz, thousands of hertz), and still higher frequencies in megahertz (MHz, millions of hertz) or gigahertz (GHz, billions of hertz). AM radio waves are measured in kilohertz, and FM radio waves are measured in megahertz; radar and microwave ovens operate at gigahertz frequencies. A station at 960 kHz on the AM radio dial, for example, broadcasts radio waves that have a frequency of 960,000 vibrations per second. A station at 101.7 MHz on the FM dial broadcasts radio waves with a frequency of 101,700,000 hertz. These radio-wave frequencies are the frequencies at which electrons are forced to vibrate in the antenna of a radio station's transmitting tower. So we see that the source of all waves is something that vibrates. The frequency of the vibrating source and the frequency of the wave it produces are the same.

FIGURE 19.3

Electrons in the transmitting antenna vibrate 940,000 times each second and produce 940-kHz radio waves.

The frequency of a "classical" wave—such as a sound wave, water wave, or radio wave—matches the frequency of its vibrating source. (In the quantum world of atoms and photons, the rules are different.)

The **period** of a vibration or wave is the time for one complete vibration. If an object's frequency is known, its period can be calculated, and vice versa. Suppose, for example, that a pendulum makes two vibrations in 1 second. Its frequency is 2 Hz. The time needed to complete one vibration—that is, the period of vibration—is 1/2 second. Or, if the vibration frequency is 3 Hz, then the period is 1/3 second. The frequency and period are the inverse of each other:

$$\text{Frequency} = \frac{1}{\text{period}}$$

or, vice versa,

$$\text{Period} = \frac{1}{\text{frequency}}$$

CHECK POINT

1. An electric toothbrush completes 90 cycles every second. What is (a) its frequency? (b) its period?
2. Gusts of wind make the Willis Tower in Chicago sway back and forth, completing a cycle in 10 s. What is (a) its frequency? (b) its period?

Check Your Answers

1. (a) 90 cycles per second is 90 Hz; (b) 1/90 s.
2. (a) 1/10 Hz; (b) 10 s.

Wave Motion

Most information about our surroundings arrives in some form of waves. It is through wave motion that sounds are transported to our ears, light to our eyes, and electromagnetic signals to our radios and wireless phones. Through *wave motion,* energy can be transferred from a source to a receiver without the transfer of matter between the two points.

Wave motion can be most easily understood by first considering the simple case of a horizontally stretched rope. If one end of such a rope is shaken up and down, a rhythmic disturbance travels along the rope. Each particle of the rope moves up and down, while, at the same time, the disturbance moves along the length of the rope. The medium, rope or whatever, returns to its initial condition after the disturbance has passed. What is propagated is the disturbance, not the medium itself.

Numerous fans at a concert or stadium "do the wave" by rising from their seats, swinging their arms high, then sitting back in their seats—all in appropriate sequence.

Perhaps a more familiar example of wave motion is provided by a water wave. If a stone is dropped into a quiet pond, waves will travel outward in expanding circles, the centers of which are at the source of the disturbance. In this case, we might think that water is being transported with the waves, since water is splashed onto previously dry ground when the waves meet the shore. We should realize, however, that, barring obstacles, the water will flow back into the pond, and things will be much as they were in the beginning. The surface of the water will have been disturbed, but the water itself will have gone nowhere. A leaf on the surface will bob up and down as the waves pass, but will end up where it started. Again, the medium returns to its initial condition after the disturbance has passed—even in the extreme case of a tsunami.

Let us consider another example of a wave to illustrate that what is transported from one location to another is a disturbance in a medium, not the medium itself. If you view a field of tall grass from an elevated position on a gusty day, you will see waves travel across the grass. The individual stems of grass do not leave their places; instead, they swing to and fro. Furthermore, if you stand in a narrow footpath, the grass that blows over the edge of the path, brushing against your legs, is very much like the water that doused the shore in our earlier example. While wave motion continues, the tall grass swings back and forth, vibrating between definite limits but going nowhere. When the wave motion stops, the grass returns to its initial position.

Mechanical waves require a medium. A Slinky needs its coils; ocean waves need water; sound from a bugle needs air; "doing the wave" in a stadium needs exuberant fans.

Wave Speed

The speed of periodic wave motion is related to the frequency and wavelength of the waves. We can understand this by considering the simple case of water waves (Figures 19.4 and 19.5). Imagine that we fix our eyes on a stationary point on the surface of water and observe the waves passing by this point. We can measure how much time passes between the arrival of one crest and the arrival of the next one (the period) and also observe the distance between crests (the wavelength). We know that speed is defined as distance divided by time. In this case, the distance is one wavelength and the time is one period, so **wave speed** = wavelength/period.

For example, if the wavelength is 10 m and the time between crests at a point on the surface is 0.5 s, the wave moves 10 m in 0.5 s and its speed is 10 m divided by 0.5 s, or 20 m/s.

Since period is the inverse of frequency, the formula wave speed = wavelength/period can also be written

$$\text{Wave speed} = \text{frequency} \times \text{wavelength}$$

This relationship holds true for all kinds of waves, whether they are water waves, sound waves, or light waves.

FIGURE 19.4

Water waves.

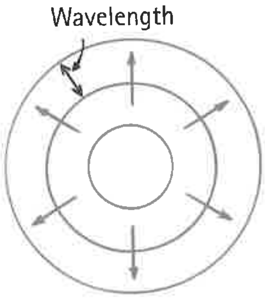


FIGURE 19.5

A top view of water waves.

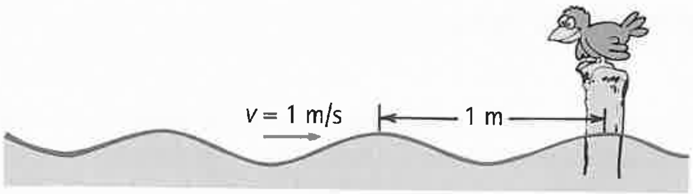


FIGURE 19.6

INTERACTIVE FIGURE

If the wavelength is 1 m, and one wavelength per second passes the pole, then the speed of the wave is 1 m/s.

The speed v of a wave can be expressed by the equation $v = f\lambda$, where f is the wave frequency and λ (the Greek letter lambda) is the wavelength of the wave.

CHECK POINT

1. If a train of freight cars, each 10 m long, rolls by you at the rate of three cars each second, what is the speed of the train?
2. If a water wave oscillates up and down three times each second and the distance between wave crests is 2 m, what is its frequency? What is its wavelength? What is its wave speed?

Check Your Answers

1. 30 m/s. We can see this in two ways. (a) According to the speed definition from Chapter 2, $v = d/t = (3 \times 10\text{ m})/1\text{ s} = 30\text{ m/s}$, since 30 m of train passes you in 1 s. (b) If we compare our train to wave motion, where wavelength corresponds to 10 m and frequency is 3 Hz, then speed = frequency × wavelength = $3\text{ Hz} \times 10\text{ m} = 3/\text{s} \times 10\text{ m} = 30\text{ m/s}$.
2. The frequency of the wave is 3 Hz, its wavelength is 2 m, and its wave speed = frequency × wavelength = $3/\text{s} \times 2\text{ m} = 6\text{ m/s}$.

Transverse Waves

Fasten one end of a rope to a wall and hold the free end in your hand. If you suddenly shake the free end up and then down, a pulse will travel along the rope and back (Figure 19.7). In this case, the motion of the rope (up and down arrows) is at right angles to the direction of wave speed. The right-angled, or sideways, motion is called *transverse motion.* Now shake the rope with a regular, continuing up-and-down motion, and the series of pulses will produce a wave. Since the motion of the medium (the rope, in this case) is transverse to the direction the wave travels, this type of wave is called a **transverse wave.**

FIGURE 19.7

A transverse wave.

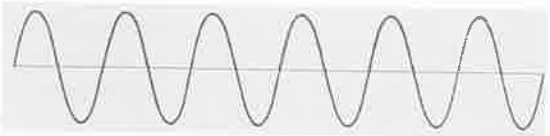
Waves in the stretched strings of musical instruments and on the surfaces of liquids are transverse. We will see later that electromagnetic waves, which make up radio waves and light, are also transverse.

Practicing Physics

Here we have a sine curve that represents a transverse wave. With a ruler, measure the wavelength and amplitude of the wave.

Wavelength ______

Amplitude ______



Longitudinal Waves

Not all waves are transverse. Sometimes parts that make up a medium move to and fro in the same direction in which the wave travels. Motion is *along* the direction of the wave rather than at right angles to it. This produces a **longitudinal wave.**

Both a transverse wave and a longitudinal wave can be demonstrated with a spring or a Slinky stretched out on the floor, as shown in Figure 19.8. A transverse wave is demonstrated by shaking the end of a Slinky from side to side in a direction perpendicular to the Slinky. A longitudinal wave is demonstrated by rapidly pulling and pushing the end of the Slinky toward and away from you in a direction parallel to the Slinky. In this case, we see that the medium vibrates parallel to the direction of energy transfer. Part of the Slinky is compressed, and a wave of *compression* travels along the spring. In between successive compressions is a stretched region, called a *rarefaction*. Both compressions and rarefactions travel in the same direction along the Slinky. Sound waves are longitudinal waves.

Sound requires a medium. It can't travel in a vacuum because there's nothing to compress and stretch.

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Video

Longitudinal vs. Transverse Waves

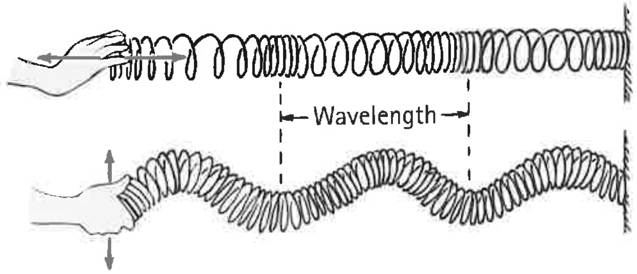

FIGURE 19.8

INTERACTIVE FIGURE

Both waves transfer energy from left to right. (a) When the end of the Slinky is pushed and pulled rapidly along its length, a longitudinal wave is produced. (b) When it's shaken from side to side, a transverse wave is produced.

Waves that have been generated by earthquakes and that travel in the ground are of two main types: longitudinal P waves and transverse S waves. (Geology students often remember P waves as "push–pull" waves, and S waves as "side-to-side" waves.) S waves cannot travel through liquid matter, but P waves can travel through both molten and solid parts of Earth's interior. Study of these waves reveals much about Earth's interior.

The wavelength of a longitudinal wave is the distance between successive compressions or, equivalently, the distance between successive rarefactions. The most common example of longitudinal waves is sound in air. Elements of air vibrate to and fro about some equilibrium position as the waves move by. We will treat sound waves in detail in Chapter 20.

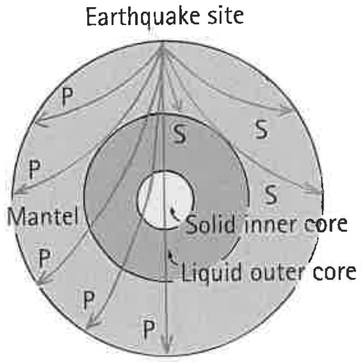

FIGURE 19.9

P and S waves generated by an earthquake.

Wave Interference

Whereas a material object such as a rock will not share its space with another rock, more than one vibration or wave can exist at the same time in the same space. If we drop two rocks in water, the waves produced by each can meet and produce **wave interference.** The overlapping of waves can form an **interference pattern.** Within the pattern, wave effects may be increased, decreased, or neutralized.

When more than one wave occupies the same space at the same time, the displacements add at every point. This is the *superposition principle.* So, when the crest of one wave overlaps the crest of another, their individual effects add together to produce a wave of increased amplitude. This is called *constructive interference*

(Figure 19.10). When the crest of one wave overlaps the trough of another, their individual effects are reduced. The high part of one wave simply fills in the low part of another. This is called *destructive interference*.

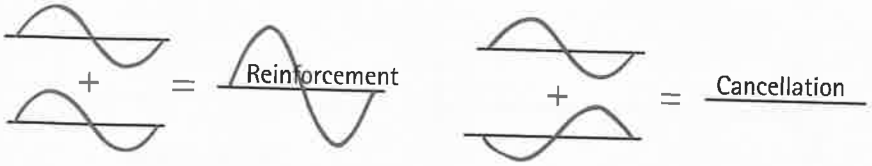

FIGURE 19.10
Constructive and destructive interference in a transverse wave.

Wave interference is easiest to see in water. In Figure 19.11 we see the interference pattern made when two vibrating objects touch the surface of water. We can see the regions where a crest of one wave overlaps the trough of another to produce regions of zero amplitude. At points along these regions, the waves arrive out of step. We say they are *out of phase* with each other.

Interference is characteristic of all wave motion, whether the waves are water waves, sound waves, or light waves. We will treat the interference of sound in the next chapter and the interference of light in Chapter 29.

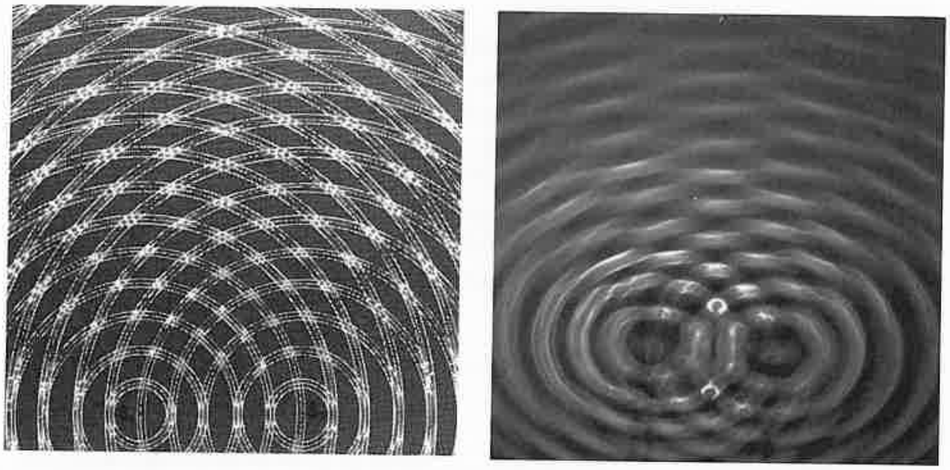

FIGURE 19.11
Two sets of overlapping water waves produce an interference pattern. The left image is an idealized drawing of the expanding waves from the two sources. The right image is a photograph of an actual interference pattern.

Standing Waves

If we tie a rope to a wall and shake the free end up and down, we produce a train of waves in the rope. The wall is too rigid to shake, so the waves are reflected back along the rope. By shaking the rope just right, we can cause the incident and reflected waves to form a **standing wave,** where parts of the rope, called the *nodes,* appear to be standing still. Nodes are the regions of minimal or zero displacement, with minimal or zero energy. *Antinodes* (not labeled in Figure 19.12), on the other hand, are the regions of maximum displacement and maximum energy. You can hold your fingers just over and under the nodes and the rope doesn't touch them. Other parts of the rope, especially the antinodes, would make contact with your fingers. Antinodes occur halfway between nodes.

Standing waves are the result of interference (and, as we will see in Chapter 20, *resonance*). When two sets of waves of equal amplitude and wavelength pass through each other in opposite directions, the waves are steadily in and out of phase with each other. This occurs for a wave that reflects upon itself. Stable regions of constructive and destructive interference are produced.

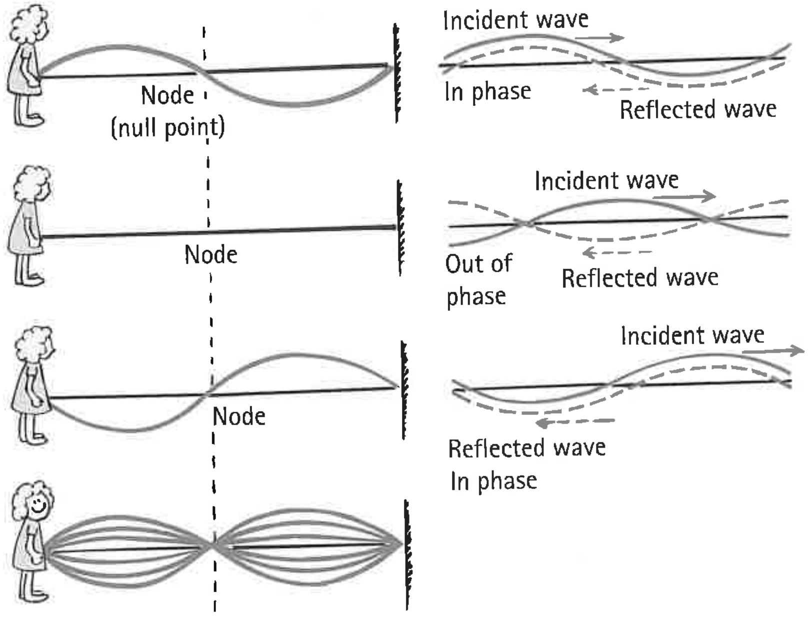

FIGURE 19.12

INTERACTIVE FIGURE

The incident and reflected waves interfere to produce a standing wave.

It is easy to make standing waves yourself. Tie a rope—or better, a rubber tube—to a firm support. Shake the tube from side to side with your hand. If you shake the tube with the right frequency, you will set up a standing wave, as shown in Figure 19.13a. Shake the tube with twice the frequency, and a standing wave of half the previous wavelength, having two loops, will result (Figure 19.13b). (The distance between successive nodes is a half wavelength; two loops constitute a full wavelength.) If you triple the frequency, a standing wave with one-third the original wavelength, having three loops, will result (Figure 19.13c); and so forth.

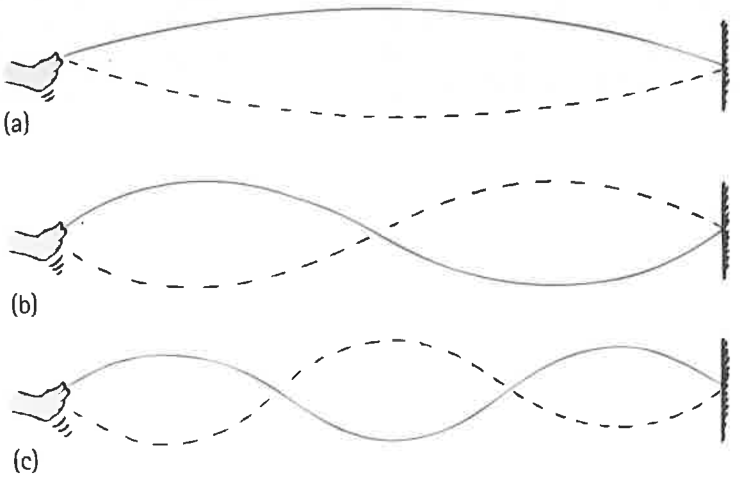

FIGURE 19.13

INTERACTIVE FIGURE

(a) Shake the rope until you set up a standing wave of one segment (1/2 wavelength).
(b) Shake with twice the frequency and produce a wave with two segments (1 wavelength).
(c) Shake with three times the frequency and produce three segments (1 1/2 wavelengths).

An organ pipe or flute makes sound by standing waves of air in a column of air.

Standing waves are set up in the strings of musical instruments when plucked, bowed, or struck. They are set up in the air in an organ pipe, a trumpet, or a clarinet and the air of a soda-pop bottle when air is blown over the top. Standing waves can be set up in a tub of water or in a cup of coffee by sloshing the tub or cup back and forth with the right frequency. Standing waves can be produced with either transverse or longitudinal vibrations.

CHECK POINT

1. Is it possible for one wave to cancel another wave so that no amplitude remains at certain points?
2. Suppose you set up a standing wave of three segments, as shown in Figure 19.13c. If you shake with twice as much frequency, how many wave segments will occur in your new standing wave? How many wavelengths?

Check Your Answers

1. Yes. This is called destructive interference. In a standing wave in a rope, for example, parts of the rope have no amplitude—the nodes.
2. If you impart twice the frequency to the rope, you'll produce a standing wave with twice as many segments. You'll have six segments. Since a full wavelength has two segments, you'll have three complete wavelengths in your standing wave.

FIGURE 19.14

Satchmo produces standing waves of sound in his trumpet.

Doppler Effect

A pattern of water waves produced by a bug jiggling its legs and bobbing up and down in the middle of a quiet puddle is shown in Figure 19.15. The bug is not going anywhere but is merely treading water in a fixed position. The waves it makes are concentric circles, because wave speed is the same in all directions. If the bug bobs in the water at a constant frequency, the distance between wave crests (the wavelength) is the same in all directions. Waves encounter point A as frequently as they encounter point B. This means that the frequency of wave motion is the same at points A and B, or anywhere in the vicinity of the bug. This wave frequency is the same as the bobbing frequency of the bug.

Suppose the jiggling bug moves across the water at a speed less than the wave speed. In effect, the bug chases part of the waves it has produced. The wave pattern is distorted and is no longer made of concentric circles (Figure 19.16). The center of the outer wave was made when the bug was at the center of that circle. The center of the next smaller wave was made when the bug was at the center of that circle, and so forth. The centers of the circular waves move in the direction of the swimming bug. Although the bug maintains the same bobbing frequency as before, an observer at B would see the waves coming more often. The observer would measure a higher frequency. This is because each successive wave has a shorter distance to travel and therefore arrives at B more frequently than if the bug weren't moving toward B. An observer at A, on the other hand, would measure a *lower* frequency because of the longer time between wave-crest arrivals. This is because, in order to reach A, each crest has to travel farther than the one ahead of it due to the bug's motion. This change in frequency due to the motion of the source (or receiver) is called the **Doppler effect** (after the Austrian scientist Christian Doppler, 1803–1853).

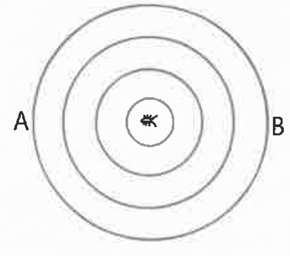

FIGURE 19.15

Top view of water waves formed by a stationary bug jiggling in still water.

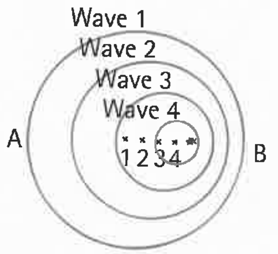

FIGURE 19.16

INTERACTIVE FIGURE

Water waves formed by a bug swimming in still water toward point B.

Water waves spread over the flat surface of the water. Sound and light waves, on the other hand, travel in three-dimensional space in all directions like an expanding balloon. Just as circular waves are closer together in front of the swimming bug, spherical sound or light waves ahead of a moving source are closer together and reach a receiver more frequently.

The Doppler effect is evident when you hear the changing pitch of an ambulance siren as it passes you. When the vehicle approaches, the pitch is higher than normal (like a higher note on a musical scale). This is because the crests of the sound waves encounter your ear more frequently. And when the vehicle passes and moves away, you hear a drop in pitch because the crests of the waves are hitting your ear less frequently.

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Tutorial
Doppler Effect
Video
Doppler Effect

Be clear about the distinction between *frequency* and *speed*. How frequently a wave vibrates is altogether different from how fast it moves from one location to another.

The Doppler effect also occurs for light. When a light source approaches, there is an increase in its measured frequency; and when it recedes, there is a decrease in its frequency. An increase in frequency is called a *blue shift,* because the increase is toward the high-frequency (or blue) end of the color spectrum. A decrease in frequency is called a *red shift,* referring to a shift toward the lower-frequency (or red) end of the color spectrum. Distant galaxies, for example, show a red shift in the light they emit. A measurement of this shift permits a calculation of their speeds of recession. A rapidly spinning star shows red-shifted light from the side turning away from us and blue-shifted light from the side turning toward us. This enables astronomers to calculate the star's spin rate.

FIGURE 19.17

INTERACTIVE FIGURE

The pitch (frequency) of sound is higher when a source is moving toward you, and lower when the source is moving away.

CHECK POINT

While you're at rest, a sound source moves toward you. Do you measure the speed of its sound wave to be greater or less than if the source were stationary?

Check Your Answer

Neither! It is the *frequency* of a wave that undergoes a change where there is motion of the source, not the *wave speed*. Be clear about the distinction between frequency and speed.

Bow Waves

When the speed of a source is as great as the speed of the waves it produces, something interesting occurs. The waves pile up in front of the source. Consider the bug in our previous example when it swims as fast as the wave speed. Can you see that the bug will keep up with the waves it produces? Instead of the waves moving ahead of the bug, they superimpose and hump up on one another directly in front of the bug (Figure 19.18). The bug moves right along with the leading edge of the waves it is producing.

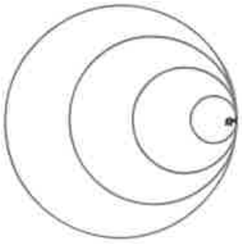

FIGURE 19.18

Wave pattern created by a bug swimming at wave speed.

A similar thing happens when an aircraft travels at the speed of sound. In the early days of jet aircraft, it was believed that this pile-up of sound waves in front of the airplane imposed a "sound barrier" and that in order to go faster than the speed of sound, the plane would have to "break the sound barrier." What actually happens is that the overlapping wave crests disrupt the flow of air over the wings, making it more difficult to control the aircraft. But the barrier is not real. Just as a boat can easily travel faster than the waves it produces, an aircraft with sufficient power easily travels faster than the speed of sound. Then we say that it is *supersonic.* A supersonic airplane flies into smooth, undisturbed air because no sound wave can propagate out in front of it. Similarly, a bug swimming faster than the speed of water waves finds itself always entering into water with a smooth, unrippled surface.

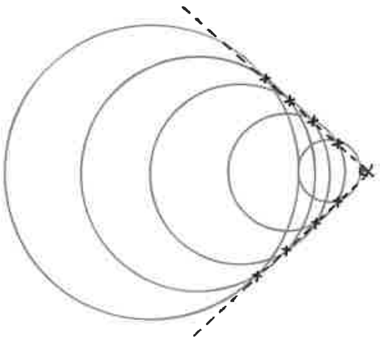

FIGURE 19.19

A bow wave, the pattern produced by a bug swimming faster than wave speed. The points at which adjacent waves overlap (×) produce the V shape.

When the bug swims faster than wave speed, ideally it produces a wave pattern, as shown in Figure 19.19. It outruns the waves it produces. The waves overlap at the edges and produce a V shape, called a **bow wave,** which appears to be dragging behind the bug. The familiar bow wave generated by a speedboat knifing through the water is not a typical oscillatory wave. It is a disturbance produced by the overlapping of many circular waves.

Some wave patterns made by sources moving at various speeds are shown in Figure 19.20. Note that after the speed of the source exceeds wave speed, increased speed of the source produces a narrower V shape.[3]

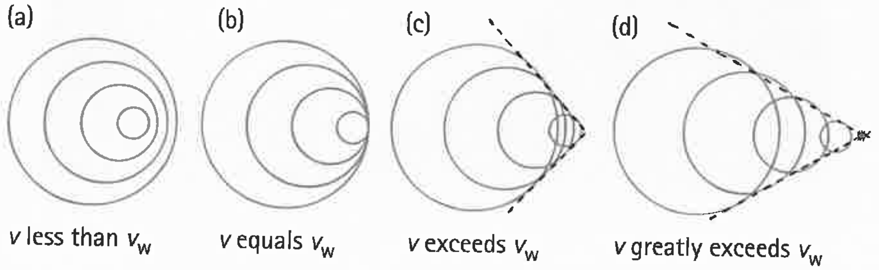

FIGURE 19.20

Patterns produced by a bug swimming at successively greater speeds. Overlapping at the edges occurs only when the bug swims faster than wave speed.

Shock Waves

A speedboat knifing through the water generates a two-dimensional bow wave. A supersonic aircraft similarly generates a three-dimensional **shock wave.** Just as a bow wave is produced by overlapping circles that form a V, a shock wave is produced by overlapping spheres that form a cone. And, just as the bow wave of a speedboat spreads until it reaches the shore of a lake, the conical wave generated by a supersonic craft spreads until it reaches the ground.

The bow wave of a speedboat that passes by can splash and douse you if you are at the water's edge. In a sense, you can say that you are hit by a "water boom." In the same way, when the conical shell of compressed air that sweeps behind a supersonic aircraft reaches listeners on the ground below, the sharp crack they hear is described as a **sonic boom.**

We don't hear a sonic boom from slower-than-sound, or subsonic, aircraft because the sound waves reaching our ears are perceived as one continuous tone. Only when the aircraft moves faster than sound do the waves overlap to reach the listener in a single burst. The sudden increase in pressure is much the same in effect as the sudden expansion of air produced by an explosion. Both processes direct a burst of high-pressure air to the listener. The ear is hard pressed to distinguish between the high pressure from an explosion and the high pressure from many overlapping waves.

A water skier is familiar with the fact that next to the high crest of the V-shaped bow wave is a V-shaped depression. The same is true of a shock wave, which usually consists of two cones: a high-pressure cone generated at the bow of the supersonic aircraft and a low-pressure cone that follows at the tail of the aircraft.[4] The edges of these cones are visible in the photograph of the supersonic bullet in Figure 19.22. Between these two cones, the air pressure rises sharply to above atmospheric pressure, then falls below atmospheric pressure before sharply returning to normal beyond the inner tail cone (Figure 19.23). This overpressure suddenly followed by underpressure intensifies the sonic boom.

A common misconception is that sonic booms are produced when an aircraft flies through the "sound barrier"—that is, just as the aircraft surpasses the speed of sound. This is the same as saying that a boat produces a bow wave when it first overtakes its own waves. This is not so. The fact is that a shock wave and its

FIGURE 19.21

This aircraft is producing a cloud of water vapor that has just condensed out of the rapidly expanding air in the rarefied region behind the wall of compressed air.

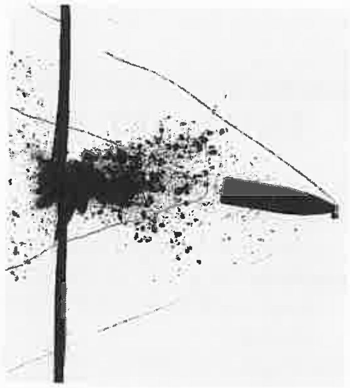

FIGURE 19.22

Shock wave of a bullet piercing a sheet of Plexiglas. Light deflecting as the bullet passes through the compressed air makes the shock visible. Look carefully and see the second shock wave originating at the tail of the bullet.

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[3] Bow waves generated by boats in water are more complex than is indicated here. Our idealized treatment serves as an analogy for the production of the less complex shock waves in air.

[4] Shock waves are often more complex and involve multiple cones.

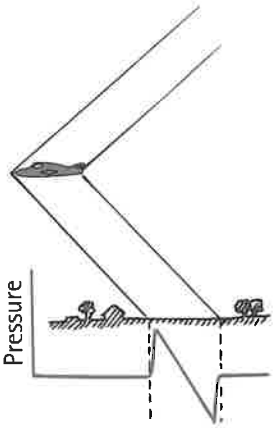


FIGURE 19.23

The shock wave is actually made up of two cones—a high-pressure cone with the apex at the bow of the aircraft and a low-pressure cone with the apex at the tail. A graph of the air pressure at ground level between the cones takes the shape of the letter N.

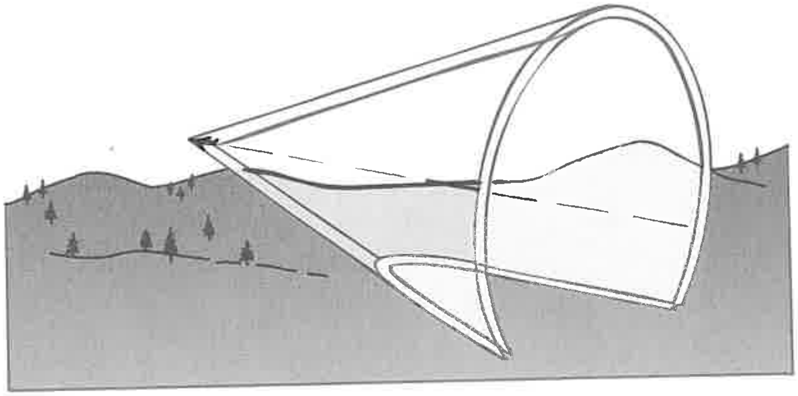


FIGURE 19.24

A shock wave.

resulting sonic boom are swept continuously behind and below an aircraft traveling faster than sound, just as a bow wave is swept continuously behind a speedboat. In Figure 19.25, listener B is in the process of hearing a sonic boom. Listener C has already heard it, and listener A will hear it shortly. The aircraft that generated this shock wave may have broken through the sound barrier many minutes ago!

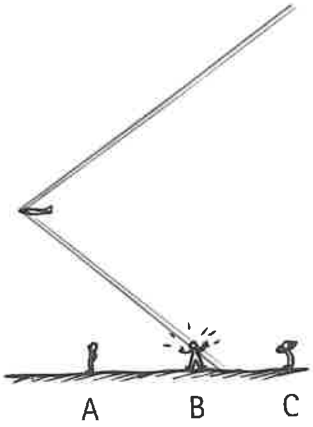


FIGURE 19.25

The shock wave has not yet reached listener A, but it is now reaching listener B and has already reached listener C.

It is not necessary that the moving source be "noisy" to produce a shock wave. Once an object is moving faster than the speed of sound, it will *make* sound. A supersonic bullet passing overhead produces a crack, which is a small sonic boom. If the bullet were larger and disturbed more air in its path, the crack would be more boom-like. When a lion tamer cracks a circus whip, the cracking sound is actually a sonic boom produced by the tip of the whip when it travels faster than the speed of sound. Both the bullet and the whip are not in themselves sound sources, but, when traveling at supersonic speeds, they produce their own sound as they generate shock waves.

SUMMARY OF TERMS

Sine curve The waveform traced by simple harmonic motion, which can be made visible on a moving conveyor belt by a pendulum swinging at right angles above the moving belt.

Amplitude For a wave or vibration, the maximum displacement on either side of the equilibrium (midpoint) position.

Wavelength The distance between successive crests, troughs, or identical parts of a wave.

Frequency For a vibrating body or medium, the number of vibrations per unit time. For a wave, the number of crests that pass a particular point per unit time.

Hertz The SI unit of frequency. One hertz (symbol Hz) equals one vibration per second.

Period The time in which a vibration is completed. The period of a wave equals the period of the source and is equal to 1/frequency.

Wave speed The speed with which waves pass a particular point:

$$\text{Wave speed} = \text{frequency} \times \text{wavelength}$$

Transverse wave A wave in which the medium vibrates in a direction perpendicular (transverse) to the direction in which the wave travels. Light waves and water waves are transverse.

Longitudinal wave A wave in which the medium vibrates in a direction parallel (longitudinal) to the direction in which the wave travels. Sound waves are longitudinal.

Wave interference Phenomenon that occurs when two waves meet while traveling along the same medium.

Interference pattern The pattern formed by superposition of different sets of waves that produces reinforcement in some places and cancellation in others.

Standing wave A stationary wave pattern formed in a medium when two sets of identical waves pass through the medium in opposite directions.

Doppler effect The shift in received frequency due to motion of a vibrating source toward or away from a receiver.

Bow wave The V-shaped disturbance created by an object moving across a liquid surface at a speed greater than the wave speed.

Shock wave The cone-shaped disturbance created by an object moving at supersonic speed through a fluid.

Sonic boom The loud sound resulting from the incidence of a shock wave.

SUMMARY OF EQUATIONS

$$\text{Frequency} = \frac{1}{\text{period}}$$

$$\text{Period} = \frac{1}{\text{frequency}}$$

$$\text{Wave speed} = \frac{\text{wavelength}}{\text{period}} \text{ or frequency} \times \text{wavelength}$$

REVIEW QUESTIONS

Good Vibrations

1. What is a *wiggle in time* called? What do you call a *wiggle in space* and time?
2. What is the source of all waves?

Vibration of a Pendulum

3. What is meant by the *period* of a pendulum?
4. Which has the longer period, a short or a long pendulum?

Wave Description

5. How is a sine curve related to a wave?
6. Distinguish between these different aspects of a wave: period, amplitude, wavelength, and frequency.
7. How many vibrations per second are represented in a radio wave of 101.7 MHz?
8. How do *frequency* and *period* relate to each other?

Wave Motion

9. In one word, what is it that moves from source to receiver in wave motion?
10. Does the medium in which a wave travels move with the wave? Give examples to support your answer.

Wave Speed

11. What is the relationship among frequency, wavelength, and wave speed?

Transverse Waves

12. In what direction are the vibrations relative to the direction of wave travel in a transverse wave?

Longitudinal Waves

13. In what direction are the vibrations relative to the direction of wave travel in a longitudinal wave?
14. The wavelength of a transverse wave is the distance between successive crests (or troughs). What is the wavelength of a longitudinal wave?

Wave Interference

15. What is meant by the *superposition principle?*
16. Distinguish between *constructive interference* and *destructive interference.*
17. What kinds of waves can show interference?

Standing Waves

18. What is a *node*? What is an *antinode?*
19. Are standing waves a property of transverse waves, of longitudinal waves, or of both?

Doppler Effect

20. In the Doppler effect, does frequency change? Does wavelength change? Does wave speed change?
21. Can the Doppler effect be observed with longitudinal waves, with transverse waves, or with both?
22. What is meant by a blue shift and a red shift for light?

Bow Waves

23. How fast must a bug swim to keep up with the waves it produces? How fast must it move to produce a bow wave?
24. How fast does a supersonic aircraft fly compared with the speed of sound?
25. How does the V shape of a bow wave depend on the speed of the source?

Shock Waves

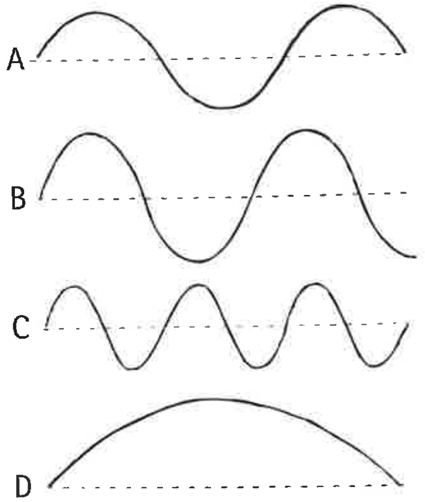
26. A bow wave on the surface of water is two-dimensional. How about a shock wave in air?
27. True or false: A sonic boom occurs only when an aircraft is breaking through the sound barrier. Defend your answer.
28. True or false: In order for an object to produce a sonic boom, it must be "noisy." Give two examples to support your answer.

PROJECTS

1. Tie a rubber tube, a spring, or a rope to a fixed support and produce standing waves. See how many nodes you can produce.
2. Wet your finger and rub it slowly around the rim of a thin-rimmed, stemmed wine glass while you hold the base of the glass firmly to a tabletop with your other hand. The friction of your finger will excite standing waves in the glass, much like the wave made on the strings of a violin by the friction from a violin bow. Try it with a metal bowl.
3. Write a letter to Grandma and tell her how waves can cancel one another, as well as what some of the applications of this physical phenomenon are these days.

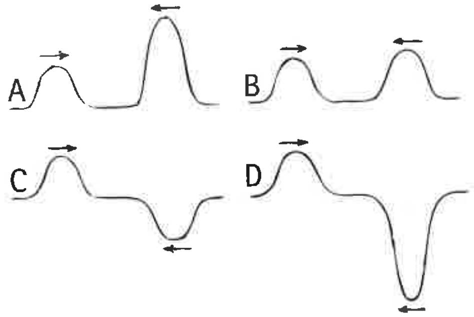
RANKING

1. All the waves shown have the same speed in the same medium. Use a ruler and rank these waves from most to least for

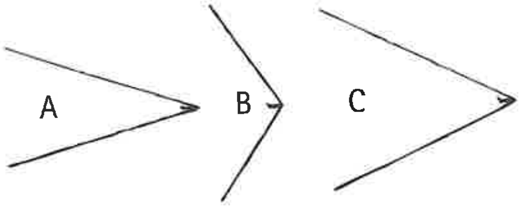


a. amplitude.
b. wavelength.
c. frequency.
d. period.

2. Shown above right are four different pairs of transverse wave pulses that move toward each other. At some point in time, the pulses meet and interact (interfere) with each other. Rank the four cases, from most to least, on the basis of the height of the peak that results when the centers of the pulses coincide.



3. The siren of a fire engine is heard in situations A, B, and C. Rank the pitch heard, from greatest to least, when the fire engine is traveling
   a. toward the listener at 30 km/h.
   b. toward the listener at 50 km/h.
   c. away from the listener at 20 km/h.
4. The shock waves A, B, C are produced by supersonic aircraft. Rank their speeds from greatest to least.



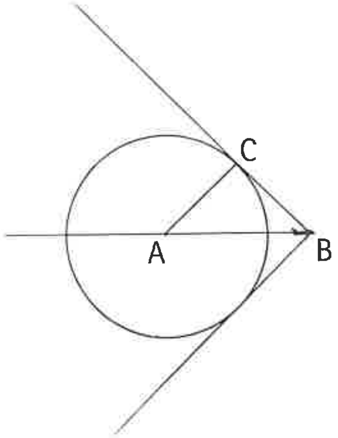
EXERCISES

1. Does the period of a pendulum depend on the mass of the bob? On the length of the string?
2. A heavy person and a light person swing to and fro on swings of the same length. Who has the longer period?
3. If a pendulum is shortened, does its frequency increase or decrease? What about its period?
4. A grandfather pendulum clock keeps perfect time. Then it is relocated to a summer home high in the mountains. Does it run faster, slower, or the same? Explain.
5. You pick up an empty briefcase and let it swing to and fro at its natural frequency. If the case were filled with books, would the natural frequency be lower, greater, or the same as before?
6. Is the time required to swing to and fro (the period) on a playground swing longer or shorter when you stand rather than sit? Explain.
7. What happens to the period of a wave when the frequency decreases?
8. Does it make sense that the mass of a bob in a simple pendulum doesn't affect the frequency of the pendulum? Defend your answer.
9. What happens to the wavelength of a wave when the frequency decreases?
10. If the speed of a wave doubles while the frequency remains the same, what happens to the wavelength?
11. If the speed of a wave doubles while the wavelength remains the same, what happens to the frequency?

12. You use a vice to firmly clamp one end of a hacksaw blade. You twang the free end and it vibrates. If you do the same, but first place a wad of clay on the free end, how, if at all, will the frequency of vibration differ? Would it make a difference if the wad of clay were stuck to the middle? Explain. (Why could this question have been asked back in Chapter 8?)
13. The needle of a sewing machine moves up and down in simple harmonic motion. Its driving force comes from a rotating wheel that is powered by an electric motor. How do you suppose the period of the up-and-down needle compares with the period of the rotating wheel?
14. If you shake the end of a spring to produce a wave, how does the frequency of the wave compare with the frequency of your shaking hand? Does your answer depend on whether you're producing a transverse wave or a longitudinal wave? Defend your answer.
15. What kind of motion should you impart to the nozzle of a garden hose so that the resulting stream of water approximates a sine curve?
16. What kind of motion should you impart to a stretched coiled spring (or Slinky) to provide a transverse wave? To provide a longitudinal wave?
17. What kind of wave is each of the following? (a) An ocean wave rolling toward Waikiki Beach. (b) The sound of one whale calling another whale under water. (c) A pulse sent down a stretched rope by snapping one end of it.
18. If a gas tap is turned on for a few seconds, someone a couple of meters away will hear the gas escaping long before she smells it. What does this indicate about the speed of sound and the speed at which molecules diffuse through the sound-carrying medium?
19. If we double the frequency of a vibrating object or the wave it produces, what happens to the period?
20. Do the two terms *wave speed* and *wave frequency* refer to the same thing? Defend your answer.
21. Red light has a longer wavelength than violet light. Which has the greater frequency?
22. What is the frequency of the second hand of a clock? The minute hand? The hour hand?
23. Consider a wave traveling along a thick rope tied to a thin rope. Which of these three wave characteristics does *not* undergo change—speed, frequency, or wavelength?
24. If you dip your finger repeatedly into a puddle of water, it creates waves. What happens to the wavelength if you dip your finger more frequently?
25. How does the frequency of vibration of a small object floating in water compare with the number of waves passing it each second?
26. In terms of wavelength, show how far a wave travels in one period.
27. What is the source of mechanical waves and of electromagnetic waves?
28. How many nodes, not including the endpoints, are there in a standing wave that is two wavelengths long? Three wavelengths long?
29. A rock is dropped in water, and waves spread over the flat surface of the water. What becomes of the energy in these waves when they die out?
30. The wave patterns seen in Figures 19.4 and 19.5 are composed of circles. What does this tell you about the speed of waves moving in different directions?
31. Why is lightning seen before thunder is heard?
32. A banjo player plucks the middle of a string pinned down at both ends. Where are the nodes of the standing wave in the string? What is the wavelength of the vibrating string?
33. Violinists sometimes bow a string to produce maximum vibration (antinodes) at one-quarter and three-quarters of the string length rather than at the middle of the string. Then the string vibrates with a wavelength equal to the string length rather than twice the string length. (See Figures 19.13a and b). What is the effect on frequency when this occurs?
34. A bat chirps as it flies toward a wall. Is the frequency of the echoed chirps it receives higher, lower, or the same as the emitted ones?
35. A railroad locomotive is at rest with its whistle shrieking, then starts moving toward you. (a) Does the frequency of sound that you hear increase, decrease, or stay the same? (b) How about the wavelength reaching your ear? (c) How about the speed of sound in the air between you and the locomotive?
36. Why is there a Doppler effect when the source of sound is stationary and the listener is in motion? In which direction should the listener move to hear a higher frequency? A lower frequency?
37. When you blow your horn while driving toward a stationary listener, the listener hears an increase in frequency of the horn. Would the listener hear an increase in horn frequency if he or she were also in a car traveling at the same speed in the same direction as you are? Explain.
38. Is there an appreciable Doppler effect when the motion of the source is at right angles to a listener? Explain.
39. How does the Doppler effect aid police in detecting speeding motorists?
40. Astronomers find that light emitted by a particular element at one edge of the Sun has a slightly higher frequency than light from that element at the opposite edge. What do these measurements tell us about the Sun's motion?
41. Would it be correct to say that the Doppler effect is the apparent change in the speed of a wave due to motion of the source? (Why is this question a test of reading comprehension as well as a test of physics knowledge?)
42. How does the phenomenon of interference play a role in the production of bow waves or shock waves?
43. What can you say about the speed of a boat that makes a bow wave?
44. Does the conical angle of a shock wave open wider, narrow down, or remain constant as a supersonic aircraft increases its speed?
45. If the sound of an airplane does not come from the part of the sky where the plane is seen, does this imply that the airplane is traveling faster than the speed of sound? Explain.
46. Does a sonic boom occur at the moment when an aircraft exceeds the speed of sound? Explain.
47. Why is it that a subsonic aircraft, no matter how loud it may be, cannot produce a sonic boom?
48. Imagine a superfast fish that is able to swim faster than the speed of sound in water. Would such a fish produce a "sonic boom"?
49. Make up a multiple-choice question that would check a classmate's understanding of the distinction between a transverse wave and a longitudinal wave.
50. Make up two multiple-choice questions that would check a classmate's understanding of any of the terms that describe a wave.

PROBLEMS

1. What is the frequency, in hertz, that corresponds to each of the following periods?
   (a) 0.10 s
   (b) 5 s
   (c) 1/60 s
2. What is the period, in seconds, that corresponds to each of the following frequencies?
   (a) 10 Hz
   (b) 0.2 Hz
   (c) 60 Hz
3. A skipper on a boat notices wave crests passing his anchor chain every 5 s. He estimates the distance between wave crests to be 15 m. He also correctly estimates the speed of the waves. Show that this speed is 3 m/s.
4. A weight suspended from a spring is seen to bob up and down over a distance of 20 cm twice each second. What is its frequency? Its period? Its amplitude?
5. A mosquito flaps its wings 600 vibrations per second, which produces the annoying 600-Hz buzz. Given that the speed of sound is 340 m/s, how far does the sound travel between wing beats? In other words, find the wavelength of the mosquito's sound.
6. On a keyboard, you strike middle C, whose frequency is 256 Hz.
   (a) What is the period of one vibration of this tone?
   (b) As the sound leaves the instrument at a speed of 340 m/s, what is its wavelength in air?
7. As shown in the drawing, the half-angle of the shock wave cone generated by a supersonic airplane is 45°. What is the speed of the plane relative to the speed of sound?



• **8.** An astronaut on the Moon attaches a small brass ball to a 1.00-m length of string and makes a simple pendulum. She times 15 complete swings in a time of 75 seconds. From this measurement she calculates the acceleration due to gravity on the Moon. What is her result?

CHAPTER 19 ONLINE RESOURCES

PhysicsPlace.com™

Interactive Figures

- 19.2, 19.6, 19.8, 19.12, 19.13, 19.16, 19.17

Tutorials

- Waves and Vibrations
- Doppler Effect

Videos

- Longitudinal vs. Transverse Waves
- Doppler Effect

Quizzes

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20 Sound

1 Ken Ford was one of the first to wear noise-canceling earphones when towing gliders in quiet comfort. **2** Chris Chiaverina, former president of the American Association of Physics Teachers, and Tom Rossing, recipient of the Acoustics Gold Medal by the Acoustical Society of America, produce sounds on a hang, a new hand-played steel instrument. **3** Singer, composer, and chemistry professor John Suchocki produces pleasing sounds with his voice and guitar.

One of the world's great combinations of physicist, author, and physics educator is Kenneth W. Ford, who was a University of California professor, a college president, and head of the American Institute of Physics before he became a classroom teacher in grades 9 through 12 at Germantown Academy in Pennsylvania. An expert and author of books on quantum physics, his passions also include teaching, flying small airplanes and gliders, and his wife Joanne. He is also a dear friend and rides "shotgun" in the writing of my physics books. *Conceptual Physics* is a beneficiary of Ken's deep and extensive knowledge of physics. I am grateful that he tweaks most all my writing before it goes to press, so that there is a higher likelihood that the physics is correct.

When I first wrote *Conceptual Physics,* Ken's textbook *Basic Physics* was an inspiration to me, as were the three volumes of *Feynman's Lectures on Physics* and *Physics for the Inquiring Mind* by Eric Rogers. Ken was one of the first to write a review of *Conceptual Physics.* He gave it much praise, adopted it for his own classes, and alerted me to some of its errors, which I quickly corrected. It is said that if you want to learn physics, teach it. I add, if you want to learn more about physics, write a textbook on it. I continually learn, much more due to the input of Ken Ford.

Ken Ford

Years ago, as seen in his photo above, Ken was a user of noise-canceling earphones when flying noisy aircraft. More recently, his book *In Love With Flying* emphasizes his greater passion for motorless flight—soaring. In Ken's portrait, notice Planck's constant on the license plate of his hybrid and a Diamond Soaring Badge on his lapel.

Let's learn a bit of the physics that Ken Ford loves.

Nature of Sound

If a tree fell in the middle of a deep forest hundreds of kilometers away from any living being, would there be a sound? Different people will answer this question in different ways. "No," some will say, "sound is subjective and requires a listener. If there is no listener, there will be no sound." "Yes," others will say, "a sound is not something in a listener's head. A sound is an objective thing." Discussions like this one often are beyond agreement because the participants fail to realize that they are arguing not about the nature of sound, but about the definition of the word. Either side is correct, depending on the definition taken, but investigation can proceed only when a definition has been agreed upon. Scientists, such as the four shown on the previous page, take the objective position and define sound as a form of energy that exists whether or not it is heard, and they go on from there to investigate its nature.

Origin of Sound

Most sounds are waves produced by the vibrations of matter. In a piano, a violin, and a guitar, the sound is produced by the 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. Sounds in the air are caused by a wide variety of vibrations.

In each of these cases, the original vibration stimulates the vibration of something larger or more massive, such as 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 the surrounding medium, usually air, in the form of longitudinal waves. Under ordinary conditions, the frequencies of the vibrating source and sound waves are the same. We describe our subjective impression about the frequency of sound by the word **pitch.** Frequency corresponds to pitch: A high-pitched sound from a piccolo has a high frequency of vibration, and a low-pitched sound from a foghorn has a low frequency of vibration.

The ear of a young person 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, especially at the high-frequency end. Sound waves with frequencies below 20 hertz are **infrasonic,** and those with frequencies above 20,000 hertz are called **ultrasonic.** We cannot hear infrasonic and ultrasonic sound waves. Infrasonic: frequency too low for human hearing. Ultrasonic: frequency too high for human hearing.

Elephants communicate with one another with infrasonic waves. Their large ears help them to detect these low-frequency sound waves.

CHECK POINT

What is the wave frequency of sound produced by a 220-hertz tuning fork?

Check Your Answer

220 Hz.

Sound in Air

When we clap our hands, the sound produced is nonperiodic. It consists of a wave *pulse* that travels outward in all directions. To better understand how a pulse in air moves, consider a long room, as shown in Figure Figure 20.1a. At one end is an open window with a curtain over it. At the other end is a door. When we open the door, we 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 **compression.**

When we close the door (Figure 20.1b), the door pushes some air molecules out of the room. This produces an area of low pressure behind 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. This is evidenced by the curtain, which flaps inward. This time the disturbance is a **rarefaction.**

As with all wave motion, it is not the medium itself that travels across the room but the energy-carrying pulse. In both compression and rarefaction, 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 compressions and rarefactions that will cause the curtain to 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 periodic vibrations of the tuning fork and the waves produced are considerably higher in frequency and lower in amplitude than those caused by 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 20.2. 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 compression enters the tube. When the prong swings away in the opposite direction, a rarefaction follows the compression. It's like a Ping-Pong paddle moving to and fro in a room packed with Ping-Pong balls. As the source vibrates, a periodic series of compressions and rarefactions is produced. The frequency of the vibrating source and the frequency of the wave it produces are the same.

Pause to reflect on the physics of sound while you are listening to your radio sometime. The radio loudspeaker is a paper cone that vibrates in rhythm with an electrical signal. Air molecules next to the vibrating cone of the speaker are themselves set into vibration. This air, in turn, vibrates against neighboring particles, which, in turn, do the same, and so on. As a result, rhythmic patterns of compressed and

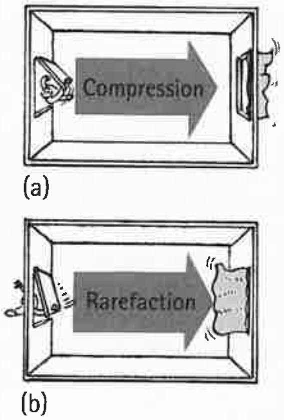


FIGURE 20.1

(a) When the door is opened, a compression travels across the room. (b) When the door is closed, a rarefaction travels across the room.

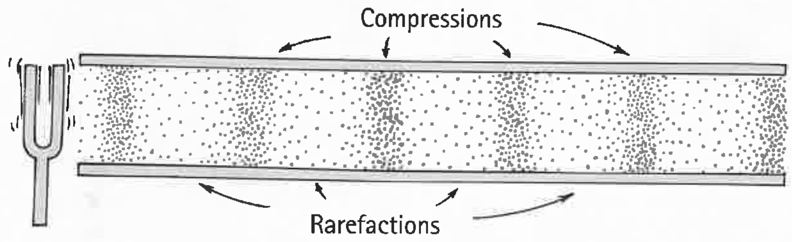


FIGURE 20.2

Compressions and rarefactions travel (both at the same speed in the same direction) from the tuning fork through the air in the tube.

FIGURE 20.3

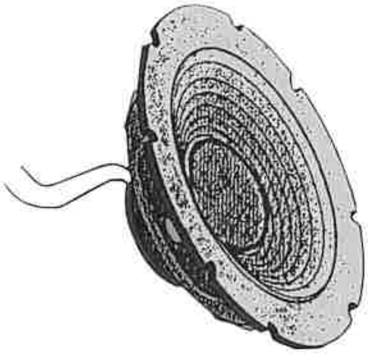
A Ping-Pong paddle vibrating in the midst of Ping-Pong balls produces vibration of the balls.

FIGURE 20.4

Waves of compressed and rarefied air, produced by the vibrating cone of the loudspeaker, make up the pleasing sound of music.

Loudspeaker

The loudspeaker of your radio or other sound-producing systems changes electrical signals into sound waves. The electrical signals pass through a coil wound around the neck of a paper cone. This coil, which acts as an electromagnet, is located near a permanent magnet. When current flows one way, magnetic force pushes the electromagnet toward the permanent magnet, pulling the cone inward. When current flows in the opposite direction, the cone is pushed outward. Vibrations in the electric signal cause the cone to vibrate. Vibrations of the cone then produce sound waves in the air. The physics of large loudspeakers applies to small ones, even those that fit in your ear.



rarefied air emanate from the loudspeaker, showering the whole room with undulating motions. The same process occurs with the bud earphones used with your iPod or other device wherein the speaker is small enough to fit in your ear. The resulting vibrating air sets your eardrum into vibration, which, in turn, sends cascades of rhythmic electrical impulses along the cochlea nerve canal and into the brain. And you listen to the sound of music.

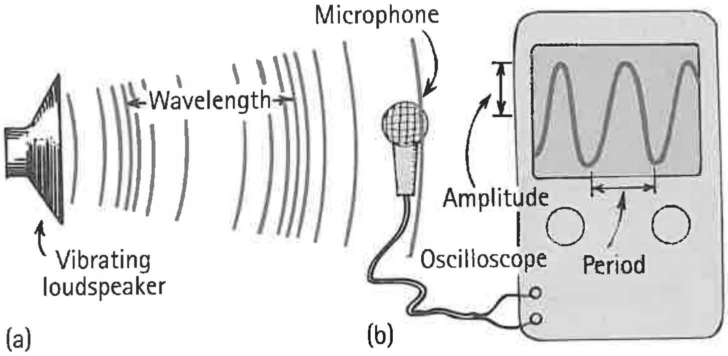


FIGURE 20.5
(a) Vibrations of the radio loudspeaker set up similar vibrations in the microphone, which are displayed on an oscilloscope.
(b) The shape of the waveform on the oscilloscope screen reveals information about the sound.

Media That Transmit Sound

Most sounds that we hear are transmitted through the air. However, any elastic substance—whether solid, liquid, gas, or plasma—can transmit sound. Elasticity is the property of a material that has changed shape in response to an applied force to resume its initial shape once the distorting force is removed. Steel is an elastic substance. In contrast, putty is inelastic.[1] In elastic liquids and solids, the atoms are relatively close together, respond quickly to one another's motions, and transmit energy with little loss. Sound travels about 4 times faster in water than in air and about 15 times faster in steel than in air.

Relative to solids and liquids, air is a poor conductor of sound. You can hear the sound of a distant train more clearly if your ear is placed against the rail. Similarly, a ticking watch placed on a table beyond hearing distance can be heard if you place your ear to the table. Or click some rocks together under water while your ear is submerged. You'll hear the clicking sound very clearly. If you've ever been swimming

Atoms and molecules in a medium tremble as they transmit sound. Sound cannot travel in a vacuum because there's nothing to do the trembling.

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[1] Elasticity is not "stretchiness," like a rubber band. Some very stiff materials are elastic—like steel.

Practicing Physics

Suspend the wire grille from a refrigerator or an oven from a string, holding the ends of the string to your ears. Let a friend gently stroke the grille with pieces of broom straw and with other objects. The effect is best appreciated when you are in a relaxed condition with your eyes closed. Be sure to try this!

in the presence of motorized boats, you probably noticed that you can hear the boats' motors much more clearly under water than above water. Liquids and crystalline solids are generally excellent conductors of sound—much better than air. The speed of sound is generally greater in solids than in liquids, and greater in liquids than in gases. Sound won't travel in a vacuum because there is nothing to compress and expand.

Speed of Sound in Air

If we watch a person at a distance chopping wood, or see a far-away baseball player hit a ball, we can easily see that the blow takes place an appreciable time before its sound reaches our ears. Likewise, thunder is heard after we see a flash of lightning. These common experiences show that sound requires a recognizable time to travel from one place to another. The speed of sound depends on wind conditions, temperature, and humidity. It does not depend on the loudness or the frequency of the sound; all sounds in the same medium travel at the same speed. The speed of sound in dry air at 0°C is about 330 meters per second, nearly 1200 kilometers per hour (a little more than one-millionth the speed of light). Water vapor in the air increases this speed slightly. Sound travels faster through warm air than cold air. This is to be expected because the faster-moving molecules in warm air bump into one another more often and therefore can transmit a pulse in less time.[2] For each degree rise in temperature above 0°C, the speed of sound in air increases by 0.6 meter per second. So, in air at a normal room temperature of about 20°C, sound travels at about 340 meters per second.

Your two ears are so sensitive to the differences in sound reaching them that you can tell from what direction a sound is coming with almost pinpoint accuracy. With only one ear, you would have no idea (and, in an emergency, might not know which way to jump).

CHECK POINT

1. Do compressions and rarefactions in a sound wave travel in the same direction or in opposite directions from one another?
2. What is the approximate distance of a thunderstorm when you note a 3-s delay between the flash of lightning and the sound of thunder?

Check Your Answers

1. They travel in the same direction.
2. Assuming that the speed of sound in air is about 340 m/s, in 3 s it will travel (340 m × 3 s) = 1020 m. There is no appreciable delay for the flash, so the storm is slightly more than 1 km away.

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[2] The speed of sound in a gas is about 3/4 the average speed of the gas molecules.

Reflection of Sound

We call the reflection of sound an *echo*. The fraction of energy carried by the reflected sound wave can be large if the surface is rigid and smooth, and less if the surface is soft and irregular. Sound energy not carried by the reflected sound wave is carried by the "transmitted" (absorbed) wave.

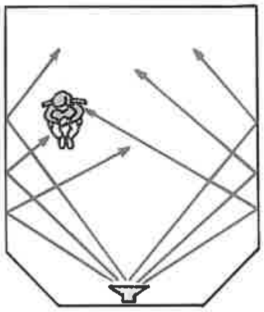

FIGURE 20.6
The angle of incident sound is equal to the angle of reflected sound.

Sound reflects from a smooth surface the same way that light does—the angle of incidence is equal to the angle of reflection (Figure 20.6). Sometimes, when sound reflects from the walls, ceiling, and floor of a room, the reflecting surfaces are too reflective and the sound becomes garbled. When sound undergoes multiple reflections and persists after the source has ceased emitting, we hear **reverberations.**

FIGURE 20.7
Special spongy walls absorb rather than reflect sound in this acoustical quiet room.

On the other hand, if the reflective surfaces are too absorbent, the sound level will be low and the hall will sound dull and lifeless. Reflection of sound in a room makes it sound lively and full, as you have probably discovered while singing in the shower. In the design of an auditorium or concert hall, a balance must be achieved between reverberation and absorption. The study of sound properties is called *acoustics.*

Bats hunt moths in darkness by echo location. Some moths are protected by a thick covering of fuzzy scales that deaden the echoes.

It is often advantageous to place highly reflective surfaces behind the stage to direct sound out to an audience. Reflecting surfaces are suspended above the stage in some concert halls. Most often they are large, shiny, plastic surfaces that also reflect light (Figure 20.8). A listener can look up at these reflectors and see the reflected images of the members of the orchestra. The plastic reflectors are somewhat curved, which increases the field of view. Both sound and light obey the same law of reflection, so if a reflector is oriented so that you can see a particular musical instrument, rest assured that you will hear it also. Sound from the instrument will follow the line of sight to the reflector and then to you.

FIGURE 20.8
The plastic plates above the orchestra reflect both light and sound. Adjusting them is quite simple: What you see is what you hear.

Refraction of Sound

When sound waves continue through a medium and bend, they undergo **refraction.** Sound waves bend when parts of the wave fronts travel at different speeds. This may happen in uneven winds or when sound is traveling through air of uneven temperatures. On a warm day, the air near the ground may be appreciably warmer than the rest of the air, so the speed of sound near the ground increases (Figure 20.9). Sound waves therefore tend to bend away from the ground, resulting in sound that does not seem to travel well. Refraction of sound is caused by differences in the speed of sound.

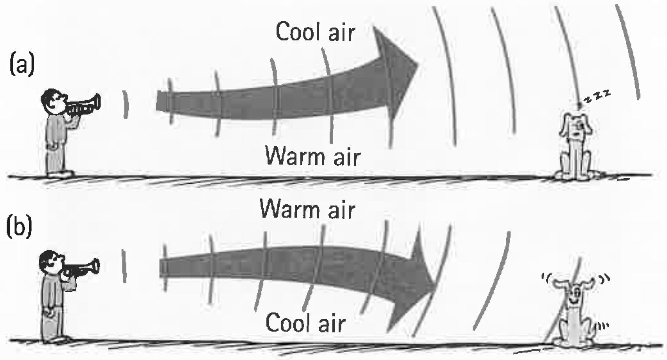

FIGURE 20.9
Sound waves are bent in air of uneven temperatures.

Note in Figure 20.9 that the directions of the sound waves are always at right angles to the wave fronts.

We hear thunder when the lightning is reasonably close, but we often fail to hear the thunder for distant lightning because of refraction. The sound travels slower at higher altitudes and bends away from the ground, so you may not hear it. The opposite often occurs on a cold day or at night when the layer of air near the ground is colder than the air above. Then the speed of sound near the ground is reduced. The higher speed of the wave fronts above causes a bending of the sound toward the ground, resulting in sound that can be heard over considerably longer distances. Sound refraction explains why you can clearly hear conversations over a campfire far across a lake at night. Sound does not always travel in straight-line paths.

The refraction of sound occurs under water, where the speed of sound varies with temperature. This poses a problem for surface vessels that bounce ultrasonic waves off the bottom of the ocean to chart the sea bottom's features. Refraction is a blessing to submarines that wish to escape detection. Because of thermal gradients and layers of water at different temperatures, the refraction of sound leaves gaps or "blind spots" in the water. This is where submarines hide. If it weren't for refraction, submarines would be easier to detect.

The multiple reflections and refractions of ultrasonic waves are used by physicians in a technique for harmlessly viewing inside the body without the use of X-rays. When high-frequency sound (ultrasound) enters the body, it is reflected more strongly from the outside of an organ than from its interior, and an image of the outline of the organ is obtained. 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 fetus as early as 11 weeks after conception (Figure 20.10).

FIGURE 20.10
A human fetus is clearly displayed on a viewing screen by ultrasound.

Ultrasound is used in medicine to produce images of internal body organs and babies in the womb and in industry to detect flaws in metal. Although the ultrasound echo technique may be relatively new to humans, it is old stuff to creatures such as bats and dolphins. Bats, for example, emit ultrasonic squeaks and locate objects by their echoes. Dolphins do this and more.[3] Whereas sound is a passive sense for us, it is an active sense for the dolphin who sends out sounds and then perceives its surroundings on the basis of their echoes. Sensing ultrasonic waves enables a dolphin to "see" through the bodies of other animals and people. Skin, muscle, and fat are almost transparent to dolphins, so they "see" only a thin outline of the body—but the bones,

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Refraction of Sound

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[3] The primary sense of the dolphin is acoustic, for vision is not a very useful sense in the often murky and dark depths of the ocean. What's more interesting, the dolphin can reproduce the sonic signals that paint the mental image of its surroundings; thus the dolphin probably communicates its experience to other dolphins by communicating the full acoustic image of what is "seen," placing it directly in the minds of other dolphins. It needs no word or symbol for "fish," for example, but communicates an image of the real thing—perhaps with emphasis highlighted by selective filtering, as we similarly communicate a musical concert to others via various means of sound reproduction. Small wonder that the language of the dolphin is very unlike our own!

FIGURE 20.15

In 1940, four months after being completed, the Tacoma Narrows Bridge in Washington State was destroyed by wind-generated resonance. A mild gale produced an irregular force in resonance with the natural frequency of the bridge, steadily increasing the amplitude of vibration until the bridge collapsed.

FIGURE 20.16

INTERACTIVE FIGURE

Pumping a swing in rhythm with its natural frequency produces a large amplitude.

Resonance is not restricted to wave motion. It occurs whenever successive impulses are applied to a vibrating object in rhythm with its natural frequency. Cavalry troops marching across a footbridge near Manchester, England, 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 in order to prevent resonance. A century later another major bridge disaster was caused by wind-generated resonance (Figure 20.15).

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 to the beauty of the world.

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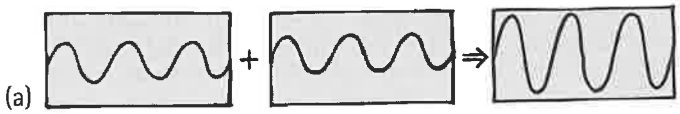
Resonance

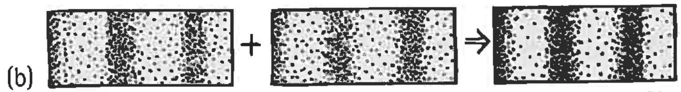
Resonance and Bridges

Interference

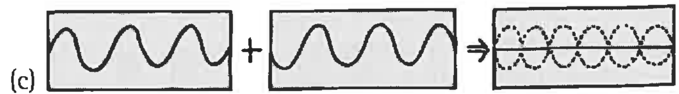
Sound waves, like any waves, can be made to exhibit **interference.** Recall that wave interference was discussed in the previous chapter. A comparison of interference for transverse waves and longitudinal waves is shown in Figure 20.17. In either case, when the crests of one wave overlap the crests of another wave,



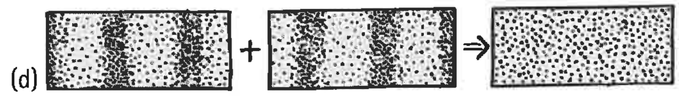
The superposition of two identical transverse waves in phase produces a wave of increased amplitude.



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



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



Two identical longitudina waves that are out of phase destroy each other when they are superimposed.

FIGURE 20.17

INTERACTIVE FIGURE

Constructive (a, b) and destructive (c, d) wave interference in transverse and longitudinal waves.

increased amplitude results. Or, when the crest of one wave overlaps the trough of another wave, decreased amplitude results. In the case of sound, the crest of a wave corresponds to a compression and the trough of a wave corresponds to a rarefaction. Interference occurs for all waves, both transverse and longitudinal.

An interesting case of sound interference is illustrated in Figure 20.18. If you are an equal distance from two sound speakers that emit identical tones of fixed frequency, the sound is louder because the effects of the two speakers add. The compressions and rarefactions of the tones arrive in step, or in *phase*. However, if you move to the side so that the paths from the speakers to you differ by a half wavelength, then the rarefactions from one speaker will be filled in by the compressions 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, canceling both. If the region is devoid of any reflecting surfaces, little or no sound will be heard!

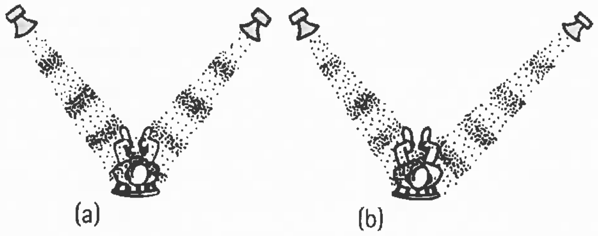

(a) (b)

FIGURE 20.18

INTERACTIVE FIGURE

Interference of sound waves.
(a) Waves arrive in phase and interfere constructively when the path lengths from the speakers are the same.
(b) Waves arrive out of phase and interfere destructively when the path lengths differ by half a wavelength (or 3/2, 5/2, etc.).

If the speakers emit a whole range of sounds with different frequencies, only some waves destructively interfere for a given difference in path lengths. So interference of this type 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 or music halls, where sound waves reflect off walls and interfere with nonreflected waves to produce zones of low amplitude. When you move your head a few centimeters in either direction, you may hear a noticeable difference.

Sound interference is dramatically illustrated when monaural sound is played by stereo speakers that are out of phase. Speakers are out of phase when the input wires to one speaker are interchanged (positive and negative wire inputs reversed). For a monaural signal, this means that when one speaker is sending a compression of sound, the other is sending a rarefaction. The sound produced is not as full and not as loud as from speakers properly connected in phase because the longer waves are being canceled by interference. This is dramatically illustrated in Figure 20.19. Shorter waves are canceled as the speakers are brought closer together, and when the pair of speakers is brought face to face against each other, very little sound is heard! Only the sound waves having the highest frequencies survive cancellation. You must try this to appreciate it.

FIGURE 20.19

If the positive and negative wire inputs to one of the stereo speakers are switched, the speakers are out of phase. When the speakers are far apart, monaural sound is not as loud as from properly phased speakers. When brought face to face, very little sound is heard. Interference is nearly complete as the compressions of one speaker fill in the rarefactions of the other!

Destructive sound interference is a useful property in *antinoise technology*. Such noisy devices as jackhammers are being equipped with microphones that send the sound of the device to electronic microchips, which 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 canceled by mirror-image rarefactions (or compressions) in the earphones. The combination of signals cancels the jackhammer noise. Noise-canceling earphones are already common for pilots (as worn by Ken, pictured at the outset of this chapter). The cabins of some airplanes are now quieted with antinoise technology. When they're not, that's when you should wear your noise-canceling earphones.

CHECK POINT

In the demonstration of Figure 20.19, why is it important that monaural sound be used?

Check Your Answer

You can cancel signals if they're identical, not the different signals fed to stereo speakers. Identical signals fed to both speakers produce monaural sound—just what you need for maximum destructive interference when you switch the phases of monaural signals.

FIGURE 20.20

When a mirror image of a sound signal combines with the sound itself, the sound is canceled.

Beats

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Interference and Beats

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** and is due to interference. Strike two slightly mismatched tuning forks and, because one fork vibrates at a different frequency than 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 our 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 our ears throbs between maximum and minimum loudness and produces a tremolo effect.

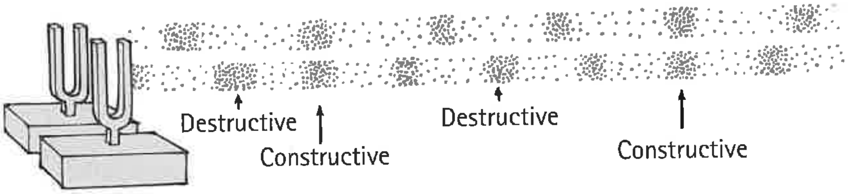


FIGURE 20.21
The interference of two sound sources of slightly different frequencies produces beats.

Why does Hollywood persist in playing engine noises whenever a spacecraft in outer space passes by? Wouldn't seeing them float by silently be far more dramatic?

We can understand beats by considering the analogous case of a tall person and short person walking side by side with different strides. At some moment they will be in step, a little later out of step, then in step again, and so on. Imagine that the tall person with longer legs takes exactly 70 steps in 1 minute, and the shorter person takes 72 steps in the same time. The shorter person gains 2 steps per minute on the taller person. A little thought will show that they will both 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 in each unit of time is equal to the difference in the frequencies of the steps. This applies also to the pair of tuning forks. If one fork undergoes 264 vibrations each 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. The overall tone will correspond to the average frequency, 263 hertz.

If we overlap two combs with different teeth spacing, we'll see a moiré pattern that is related to beats (Figure 20.22). The number of beats per length will equal the difference in the number of teeth per length for the two combs.

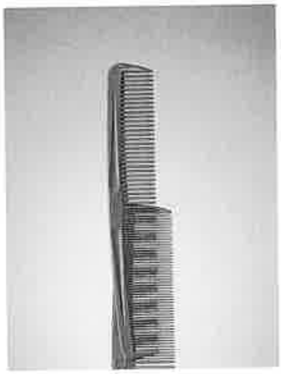


FIGURE 20.22
The unequal spacings of the combs produce a moiré pattern that is similar to beats.

Beats can occur with any kind of wave and can provide a practical way to compare frequencies. To tune a piano, for example, a piano tuner listens for beats produced between a standard frequency and the frequency of a particular string on the piano. When the frequencies are identical, the beats disappear. Beats can help you tune a variety of musical instruments. Simply listen for beats between the tone of your instrument and a standard tone produced by a piano or some other instrument.

Beats are utilized by dolphins in surveying the motions of things around them. When a dolphin sends out sound signals, beats may be produced when the echoes it receives interfere with the sound it sends. When there is no relative motion between the dolphin and the object returning the sound, the sending and receiving frequencies are the same and no beats occur. But when there is relative motion, the echo has a different frequency due to the Doppler effect, and beats are produced when the echo and emitted sound combine. The same principle is applied by the radar guns used by police officers. The beats between the signal that is sent and the one that is reflected are used to determine the speed of a car.

An intriguing and life-saving application of beats is used in detecting dangerous gases in mines. The air in some mines contains poisonous methane. There's a slight difference in the speed of sound in pure air and in air that contains methane. When a pair of small identical pipes are blown together, one by pure air from a reservoir and the other by the air in the mine, beats are heard if the air contains methane. If you work in a mine, do so in one where beats are not heard when this procedure is done!

CHECK POINT

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

Check Your Answers

For the 262-Hz and 266-Hz forks, the ear will hear 264 Hz, which will beat at 4 Hz (266 Hz – 262 Hz). For the 272-Hz and 262-Hz forks, 267 Hz will be heard, and some people will hear it throb 10 times each second (272 Hz – 262 Hz). Beat frequencies greater than 10 Hz are normally too rapid to be heard.

Radio Broadcasts

A radio receiver turns electromagnetic waves, which we cannot hear, into sound waves that we can hear. Every radio station has an assigned frequency at which it broadcasts. The electromagnetic wave transmitted at this frequency is the *carrier wave*. The relatively low-frequency sound signal to be communicated is superimposed on the much higher-frequency carrier wave in two principal ways: by slight variations in amplitude that match the audio frequency or by slight variations in frequency. This impression of the sound wave on the higher-frequency radio wave is *modulation*. When the *amplitude* of the carrier wave is modulated, we call it AM, or *amplitude modulation*. AM stations broadcast in the range of 535 to 1605 kilohertz. When the *frequency* of the carrier wave is modulated, we call it FM, or *frequency modulation*. FM stations broadcast in the higher-frequency range of 88 to 108 megahertz. Amplitude modulation is similar to rapidly changing the brightness of a constant-color lightbulb. Frequency modulation is similar to rapidly changing the color of a constant-intensity lightbulb.

Turning the knob of a radio receiver to select a particular station is like adjusting movable masses on the prongs of a tuning fork to make it resonate to the sound produced by another fork. In choosing a radio station, you adjust the frequency of an electrical circuit inside the radio receiver to match and resonate with the frequency of the desired station. You sort out one carrier wave from many. Then the impressed sound signal is separated from the carrier wave, amplified, and fed to the loudspeaker. It's nice to hear only one station at a time!

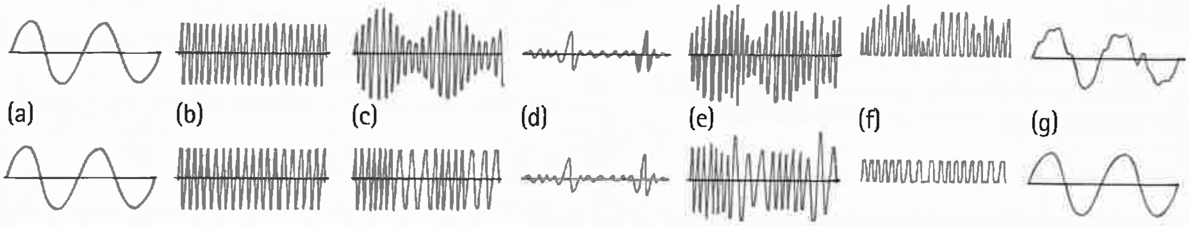


FIGURE 20.23

AM and FM radio signals. (a) Sound waves that enter a microphone. (b) Radio-frequency carrier wave produced by a transmitter without a sound signal. (c) Carrier wave modulated by signal. (d) Static interference. (e) Carrier wave and signal affected by static. (f) Radio receiver cuts out negative half of carrier wave. (g) Signal remaining is rough for AM because of static but is smooth for FM because the tips of the waveform are clipped without loss to the signal.

CHECK POINT

Is it correct to say that, in every case, without exception, any radio wave travels faster than any sound wave?

Check Your Answer

Yes, because any radio wave is an electromagnetic wave and travels at the speed of light. A sound wave, on the other hand, is a mechanical wave that travels in air about 340 m/s, about one-millionth the speed of a radio wave. So any radio wave travels appreciably faster than any sound wave.

SUMMARY OF TERMS

Pitch The highness or lowness of a tone related to wave frequency.

Infrasonic Describes a sound that has a frequency too low to be heard by the normal human ear.

Ultrasonic Describes a sound that has a frequency too high to be heard by the normal human ear.

Compression Condensed region of the medium through which a longitudinal wave travels.

Rarefaction Rarefied region (of reduced pressure) of the medium through which a longitudinal wave travels.

Reverberation Persistence of sound, as in an echo, due to multiple reflections.

Refraction Bending of sound or any wave caused by a difference in wave speeds.

Forced vibration The setting up of vibrations in an object by a vibrating force.

Natural frequency A frequency at which an elastic object naturally tends to vibrate if it is disturbed and the disturbing force is removed.

Resonance The response of a body when a forcing frequency matches its natural frequency.

Interference A result of superposing different waves, often of the same wavelength. Constructive interference results from crest-to-crest reinforcement; destructive interference results from crest-to-trough cancellation.

Beats A series of alternate reinforcements and cancellations produced by the interference of two waves of slightly different frequencies, heard as a throbbing effect in sound waves.

REVIEW QUESTIONS

Nature of Sound

1. How does a physicist usually define sound?

Origin of Sound

2. What is the relationship between *frequency* and *pitch?*
3. What is the average range of a young person's hearing?
4. Distinguish between *infrasonic* and *ultrasonic* sound waves.

Sound in Air

5. Distinguish between a *compression* and a *rarefaction.*
6. Cite evidence to support the fact that compressions and rarefactions travel in the same direction in a wave.

Media That Transmit Sound

7. Relative to solids and liquids, how does air rank as a conductor of sound?
8. Why will sound not travel in a vacuum?

Speed of Sound in Air

9. What factors does the speed of sound depend upon? What are some factors that it does *not* depend upon?
10. What is the speed of sound in dry air at 0°C?
11. Does sound travel faster in warm air than in cold air? Defend your answer.

Reflection of Sound

12. What is an *echo?*
13. What is a *reverberation?*

Refraction of Sound

14. What is the cause of refraction?
15. Does sound tend to bend upward or downward when its speed is less near the ground?
16. Why does sound sometimes refract under water?

Energy in Sound Waves

17. Which is normally greater, the energy in ordinary sound or the energy in ordinary light?
18. What ultimately becomes of the energy of sound in the air?

Forced Vibrations

19. Why will a struck tuning fork sound louder when it is held against a table?

Natural Frequency

20. Give at least two factors that determine the natural frequency of an object.

Resonance

21. How do forced *vibrations* relate to *resonance?*
22. When you listen to a radio, why do you hear only one station at a time rather than hearing all stations at once?
23. How did wind-generated resonance affect the Tacoma Narrows Bridge in the state of Washington in 1940?

Interference

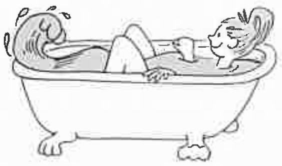
24. When is it possible for one wave to cancel another?
25. What kind of waves can exhibit interference?

Beats

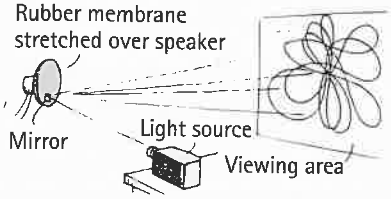
26. What physical phenomenon underlies the production of beats?
27. What beat frequency will occur when a 370-Hz and a 374-Hz sound source are sounded together?
28. How does a radio wave differ from a sound wave?

PROJECTS

1. In the bathtub, submerge your head and listen to the sound you make when clicking your fingernails together or tapping the tub beneath the water surface. Compare the sound by doing the same when both the source and your ears are above the water. At the risk of getting the floor wet, slide back and forth in the tub at different frequencies and see how the amplitude of the sloshing waves quickly builds up when you slide in rhythm with the waves. (The latter of these projects is most effective when you are alone in the tub.)



2. Stretch a piece of balloon rubber not too tightly over a radio loudspeaker. Glue a small, very lightweight piece of mirror, aluminum foil, or polished metal near one edge. Project a narrow beam of light on the mirror while your favorite music is playing and observe the beautiful patterns that are reflected on a screen or wall.



RANKING

1. Rank the speed of sound through the following from greatest to least:
   a. Air
   b. Steel
   c. Water

2. Rank the beat frequency from highest to lowest for the following pairs of sounds:
   a. 132 Hz, 136 Hz
   b. 264 Hz, 258 Hz
   c. 528 Hz, 531 Hz
   d. 1056 Hz, 1058 Hz

EXERCISES

1. Why do you not hear the sound of distant fireworks until after you see them?
2. If the Moon blew up, why would we not hear it?
3. Why would it be futile to attempt to detect sounds from other planets, even given the very best in audio detectors?
4. If you toss a stone in still water, concentric circles are formed. What form will waves have if a stone is tossed into smoothly flowing water?
5. Why do flying bees buzz?
6. A cat can hear sound frequencies up to 70,000 Hz. Bats send and receive ultra-high-frequency squeaks up to 120,000 Hz. Which hears sound of shorter wavelengths, cats or bats?
7. What does it mean to say that a radio station is "at 101.1 on your FM dial"?
8. Suppose a sound wave and an electromagnetic wave have the same frequency. Which has the longer wavelength?
9. Sound from source A has twice the frequency of sound from source B. Compare the wavelengths of sound from the two sources.
10. What happens to the wavelength of sound as the frequency increases?
11. In the stands of a racetrack, you notice smoke from the starter's gun before you hear it fire. Explain.
12. In Olympic competition, a microphone detects the sound of the starter's gun and sends it electrically to speakers at every runner's starting block. Why?
13. When a sound wave moves past a point in air, are there changes in the density of air at this point? Explain.

14. At the instant that a high-pressure region is created just outside the prongs of a vibrating tuning fork, what is being created inside between the prongs?
15. Why is it so quiet after a snowfall?
16. If a bell is ringing inside a bell jar, we can no longer hear it when the air is evacuated, but we can still see it. What differences in the properties of sound and light does this indicate?
17. Why is the Moon described as a "silent planet"?
18. As you pour water into a glass, you repeatedly tap the glass with a spoon. As the tapped glass is being filled, does the pitch of the sound increase or decrease? (What should you do to answer this question?)
19. If the speed of sound were dependent on its frequency, would you enjoy a concert sitting in the second balcony? Explain.
20. If the frequency of sound is doubled, what change will occur in its speed? In its wavelength?
21. Why does sound travel slower in cold air?
22. Why does sound travel faster in moist air? (*Hint:* At the same temperature, water vapor molecules have the same average kinetic energy as the heavier nitrogen and oxygen molecules in the air. How, then, do the average speeds of H_2O molecules compare with those of N_2 and O_2 molecules?)
23. Would the refraction of sound be possible if the speed of sound were unaffected by wind, temperature, and other conditions? Defend your answer.
24. Why can the tremor of the ground from a distant explosion be felt before the sound of the explosion can be heard?
25. What kinds of wind conditions would make sound more easily heard at long distances? Less easily heard at long distances?
26. Ultrasonic waves have many applications in technology and medicine. One advantage is that large intensities can be used without danger to the ear. Cite another advantage of their short wavelength. (*Hint:* Why do microscopists use blue light rather than white light to see detail?)
27. If the distance from a bugle is tripled, by what factor does the sound intensity decrease? Assume that no reflections affect the sound.
28. Why is an echo weaker than the original sound?
29. What two physics mistakes occur in a science fiction movie that shows a distant explosion in outer space, where you see and hear the explosion at the same time?
30. A rule of thumb for estimating the distance in kilometers between an observer and a lightning stroke is to divide the number of seconds in the interval between the flash and the sound by 3. Is this rule correct? Defend your answer.
31. If a single disturbance at an unknown distance emits both transverse and longitudinal waves that travel with distinctly different speeds in the medium, such as in the ground during an earthquake, how can the distance to the disturbance be determined?
32. Why will marchers at the end of a long parade following a band be out of step with marchers near the front?
33. Why is it a sensible procedure for soldiers to break step when marching over a bridge?
34. Why is the sound of a harp soft in comparison with the sound of a piano?
35. Your classmate says that the speed of sound and the frequency of sound depend on the medium in which it travels. What part of this statement do you disagree with?
36. Apartment dwellers will testify that bass notes are more distinctly heard from music played in nearby apartments. Why do you suppose lower-frequency sounds travel through walls, floors, and ceilings more easily?
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. Why does a dance floor heave only when certain kinds of dance steps are being performed?
39. A pair of loudspeakers on two sides of a stage are emitting identical pure tones (tones of a fixed frequency and fixed wavelength in air). When you stand in the center aisle, equally distant from the two speakers, you hear the sound loud and clear. Why does the intensity of the sound diminish considerably when you step to one side? (*Suggestion:* Use a diagram to make your point.)
40. A special device can transmit out-of-phase sound from a noisy jackhammer to its operator using earphones. Over the noise of the jackhammer, the operator can easily hear your voice while you are unable to hear his. Explain.
41. When two out-of-phase speakers are brought together as shown in Figure 20.19, which waves are most canceled, long waves or short waves? Why?
42. An object resonates when the frequency of a vibrating force either matches its natural frequency or is a submultiple of its natural frequency. Why will it not resonate to multiples of its natural frequency? (*Hint:* Think of pushing a child in a swing.)
43. How can a certain note sung by a singer cause a crystal glass to shatter?
44. Are beats the result of interference or of the Doppler effect, or of both?
45. Can it correctly be said that beats of sound are much the same thing as the rhythmic "beat" of music? Defend your answer.
46. Two sound waves of the same frequency can interfere, but, in order to produce beats, the two sound waves must be of different frequencies. Why?
47. Walking beside you, your friend takes 50 strides per minute while you take 48 strides per minute. If you start in step, you'll soon be out of step. When will you be in step again?
48. Suppose a piano tuner hears 3 beats per second when listening to the combined sound from a tuning fork and the piano wire being tuned. After slightly tightening the string, 5 beats per second are heard. Should the string be loosened or tightened?
49. A piano tuner using a 264-Hz tuning fork hears 4 beats per second. What are two possible frequencies of vibration of the piano wire?
50. A human cannot hear sound at a frequency of 100 kHz or sound at 102 kHz. But if you walk into a room in which two sources are emitting sound waves, one at 100 kHz and the other at 102 kHz, you'll hear sound. Explain.

PROBLEMS

1. What is the wavelength of a 340-Hz tone in air? What is the wavelength of a 34,000-Hz ultrasonic wave in air?
2. For years, marine scientists were mystified by sound waves detected by underwater microphones in the Pacific Ocean. These so-called T-waves were among the purest sounds in nature. Eventually they traced the source to underwater volcanoes, whose rising columns of bubbles resonated like organ pipes. What is the wavelength of a typical T-wave whose frequency is 7 Hz? (The speed of sound in seawater is 1530 m/s.)
3. An oceanic depth-sounding vessel surveys the ocean bottom with ultrasonic waves that travel 1530 m/s in seawater. The time delay of the echo to the ocean floor and back is 6 s. Show that the depth of the water directly below the vessel is 4590 m.
4. A bat flying in a cave emits a sound and receives its echo 0.1 s later. Show that its distance from the cave wall is 19 m.
5. You watch distant Sally Homemaker driving nails into a front porch at a regular rate of 1 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 the hammering stop. Explain how you calculate that Sally is 340 m away from you.
6. Imagine a Rip van Winkle type who lives in the mountains. Just before going to sleep, he yells, "WAKE UP," and the sound echoes off the nearest mountain and returns 8 hours later. Show that the distance between Rip and the imaginary mountain is nearly 5000 km (about the distance from New York to San Francisco).
7. What beat frequencies are possible with tuning forks of frequencies 256, 259, and 261 Hz?
8. • A grunting porpoise emits sound at 57 Hz. What is the wavelength of this sound in water, where the speed of sound is 1500 m/s?

CHAPTER 20 ONLINE RESOURCES

PhysicsPlace.com™

Interactive Figures

- 20.16, 20.17, 20.18

Videos

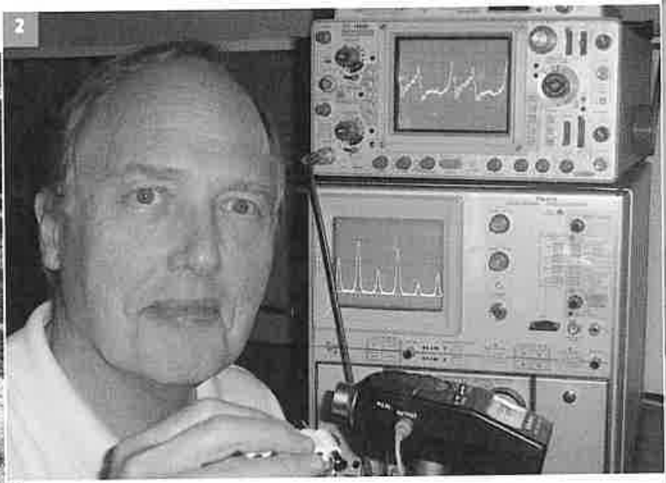
- Refraction of Sound
- Resonance
- Resonance and Bridges
- Interference and Beats

Quizzes

Flashcards

Links

21 Musical Sounds



1 Gracie Hewitt produces soothing tones with her clarinet. 2 Norm Whitlatch shows the first five harmonics, in blue, from a Fourier analysis of sound from a guitar pitch pipe, which is displayed on the upper green oscilloscope trace. 3 Michelle Anna Wong and Miriam Dijamco delight audiences when they draw bows across the strings of their violins.

What does physics have to do with music? PLENTY! Since ancient times, scientists have seen a close connection between music and mathematics. One such mathematician and physicist was Jean Baptiste Joseph Fourier, who was born in France in 1768. He was the son of a tailor and was orphaned at age 10. Fourier showed signs of great brightness, but since not being of "good birth," he was ineligible for a commission he sought in the scientific corps of the army. Instead, he accepted a military lectureship and became a teacher of mathematics.

In his home district, Fourier took a prominent part in promoting the French Revolution. At age 30 he went with Napoleon Bonaparte on his Egyptian expedition and was made governor of Lower Egypt. Cut off from France by the English fleet, he organized the workshops on which the French army relied on for their munitions of war. At that time he also contributed several mathematical papers to the institute that Napoleon founded, the Cairo Institute. After British victories, Fourier made his way back to France, where he conducted experiments on the propagation of heat. He discovered that sums of mathematical trigonometric functions greatly simplified the study of heat propagation.

Fourier discovered a mathematical regularity to the component parts of any type of periodic wave motion. He found that even the most complex periodic waves can be disassembled into simple sine waves that add together. What he discovered in 1822 is today called Fourier analysis. In this chapter let's see how this applies to musical sounds.

Noise and Music

Most of the sounds we hear are noises. The impact of a falling object, the slamming of a door, the roaring of a motorcycle, and most of the sounds from traffic in city streets are noises. Noise corresponds to an irregular vibration of the eardrum produced by some irregular vibration in our surroundings, a jumble of wavelengths and amplitudes. *White noise* is a mixture of a variety of frequencies of sound, just as white light is a mixture of all the frequencies of light. We describe the sound of surf, rustling leaves, or bubbling water in a brook as white noise.

Music is the art of sound and has a different character. Musical sounds have periodic tones—or musical *notes*. Although noise doesn't have these characteristics, the line that separates music and noise can be thin and subjective. To some contemporary composers, it is nonexistent. Some people consider contemporary music and music from other cultures to be noise. Differentiating these types of music from noise becomes a problem of aesthetics. However, differentiating traditional music—that is, Western classical music and most types of popular music—from noise presents no problem. A person with total hearing loss could distinguish between these by using an oscilloscope, as Norm Whitlatch shows in the opening photo. When an electrical signal from a microphone is fed into an oscilloscope, patterns of air-pressure variations with time are nicely displayed that make it easy to distinguish between noise and traditional music (Figure 21.1).

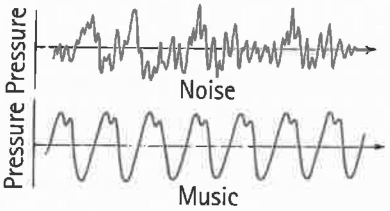


FIGURE 21.1
Graphical representations of noise and music.

Musicians usually speak of musical tones in terms of three principal characteristics: pitch, loudness, and quality.

CHECK POINT

A thud makes noise. Can a series of thuds be musical?

Check Your Answer

Yes, especially when they are periodic—think of a drum solo.

Pitch

Music is organized on many different levels. Most noticeable are musical notes. You may remember these in your earlier school years as "do, re, mi, fa, sol, la, ti, and do." Each note has its own **pitch.** We can describe pitch by frequency. Rapid vibrations of the sound source (high frequency) produce sound of a high pitch, whereas slow vibrations (low frequency) produce a low pitch. We often speak of the pitch of a sound in terms of its position on the musical scale. Musicians give different pitches different letter names: A, B, C, D, E, F, G. When A, called concert A, is struck on a piano, a hammer strikes two or three strings, each of which vibrates 440 times in 1 second. The pitch of concert A corresponds to 440 hertz.[1] Notes A

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[1] Interestingly, concert A varies from as low as 436 Hz to as high as 448 Hz in frequency.

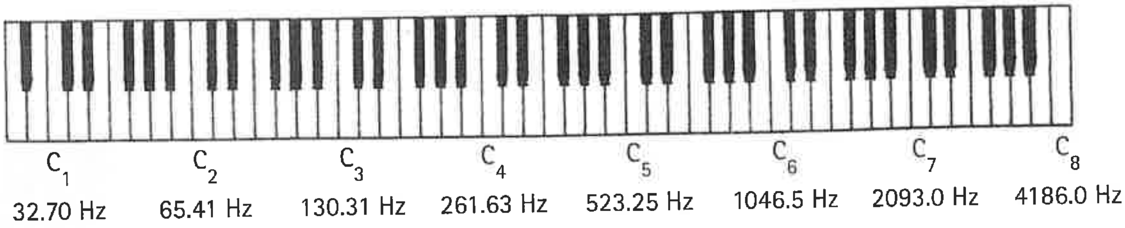

FIGURE 21.2

Piano keyboard. Low C (C_1) is 32.70 Hz and successive overtones of C keep doubling in frequency. The 261.63-Hz C is called middle C.

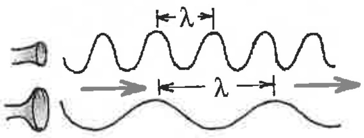

FIGURE 21.3

Both sound waves travel at the same speed. The one with the shorter wavelength λ reaches the listener's ear more frequently. It therefore has a higher frequency and is heard as a higher pitch.

through G are all notes within one octave. Multiply the frequency on any note by 2, and you have the same note at a higher pitch in the next octave. A piano keyboard covers a little more than seven octaves (Figure 21.2).

Different musical notes are obtained by changing the frequency of the vibrating sound source. This is usually done by altering the size, the tightness, or the mass of the vibrating object. A guitarist or violinist, for example, adjusts the tightness, or tension, of the strings when tuning them. Then different notes can be played by altering the length of each string by "stopping" it with the fingers. In wind instruments, the length of the vibrating air column can be altered (trombone and trumpet) or holes in the side of the tube can be opened and closed in various combinations (saxophone, clarinet, flute) to change the pitch of the note produced.

High-pitched sounds used in music are most often less than 4000 Hz, but the average human ear can hear sounds with frequencies up to 18,000 Hz. Some people and most dogs can hear tones of higher pitch than this. In general, the upper limit of hearing in people gets lower as they grow older. A high-pitched sound is often inaudible to an older person and yet may be clearly heard by a younger one. This is due to aging of the sensitive hairs on the organ of Corti in the ear. The sense of hearing, especially of higher frequencies, decreases as we grow older.

CHECK POINT

The sound emitted by bats is extremely intense. Why cannot humans hear them?

Check Your Answer

The pitch of sound emitted by bats is higher than humans can hear. Otherwise the sound of bats would drive people batty!

Sound Intensity and Loudness

The **intensity** of sound depends on the amplitude of pressure variations within the sound wave. (And, as with all waves, intensity is directly proportional to the square of the wave amplitude.) Intensity is measured in units of watts/square meter. The human ear responds to intensities covering the enormous range from 10^{-12} W/m^2 (the threshold of hearing) to more than 1 W/m^2 (the threshold of pain). Because the range is so great, intensities are scaled by factors of 10, with the barely audible 10^{-12} W/m^2 as a reference intensity—called 0 *bel* (a unit named after Alexander Graham Bell). A sound 10 times more intense has an intensity of 1 bel (10^{-11} W/m^2) or 10 *decibels*. Table 21.1 lists typical sounds and their intensities. A sound of 10 decibels is 10 times as intense as 0 decibels, the threshold of hearing. Accordingly, 20 decibels is 100, or 10^2, times the intensity of the threshold of hearing, 30 decibels is 10^3 times the threshold of hearing, and 40 decibels is 10^4 times. So 60 decibels represents sound intensity a million times (10^6) greater than 0 decibels. Can you see that 80 decibels represents sound 10^2 times as intense as 60 decibels?[2]

Physiological hearing damage begins at exposure to 85 decibels, the degree of damage depending on the length of exposure and on frequency characteristics. Damage from loud sounds can be temporary or permanent, depending on whether the nerve ending on the organ of Corti, the receptor organ in the inner ear, is impaired or destroyed. A single burst of sound can produce vibrations in the organ intense enough to tear it apart. Less intense, but severe, noise can interfere with cellular processes in the organ and cause its eventual breakdown. Unfortunately, the cells of the organ do not regenerate.

Sound intensity is a purely objective and physical attribute of a sound wave, and it can be measured by various acoustical instruments (and the oscilloscope in Figure 21.4). **Loudness,** on the other hand, is a physiological sensation. The ear senses some frequencies much better than others. A 3500-Hz sound at 80 decibels, for example, sounds about twice as loud to most people as a 125-Hz sound at 80 decibels; humans are more sensitive to the 3500-Hz range of frequencies. The loudest sounds we can tolerate have intensities a trillion times greater than the faintest sounds. The difference in perceived loudness, however, is much less than this amount.

Ear plugs typically reduce noise by about 30 dB.

FIGURE 21.4

James displays a sound signal on an oscilloscope.

TABLE 21.1

Common Sources and Sound Intensities

Source of Sound	Intensity (W/m²)	Sound Level (dB)
Jet airplane 30 m away	10^{2}	140
Air-raid siren, nearby	1	120
Disco music, amplified	10^{-1}	110
Riveter	10^{-3}	90
Busy street traffic	10^{-5}	70
Conversation in home	10^{-6}	60
Quiet radio in home	10^{-8}	40
Whisper	10^{-10}	20
Rustle of leaves	10^{-11}	10
Threshold of hearing	10^{-12}	0

fyi

- The Blue Whale emits the loudest sounds, greater than 180 db in water, but pitched too low for humans to detect without sensitive equipment.

CHECK POINT

Is hearing permanently impaired when attending concerts, clubs, or functions that feature very loud music?

Check Your Answer

Yes, depending on how loud, how long, how near, and how often. Some music groups have emphasized loudness over quality. Tragically, as hearing becomes more and more impaired, members of the group (and their fans) require louder and louder sounds for stimulation. Hearing loss caused by sounds is particularly common in the frequency range of 2000–5000 Hz. Recall that human hearing is normally most sensitive around 3000 Hz. (Looking for a career? Consider becoming an audiologist—you'll be busy!)

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[2] The decibel scale is called a logarithmic scale. The decibel rating is proportional to the logarithm of the intensity.

Quality

We have no trouble distinguishing between the tone from a piano and a tone of the same pitch from a clarinet. Each of these tones has a characteristic sound that differs in **quality,** the "color" of a tone—*timbre.* Timbre describes all of the aspects of a musical sound other than pitch, loudness, or length of tone. Timbre is described subjectively as heavy, light, murky, thin, smooth, or transparently clear. Sound from a viola, for example, has a noticeably "deeper" sound, while the violin has a noticeably "brighter" sound.

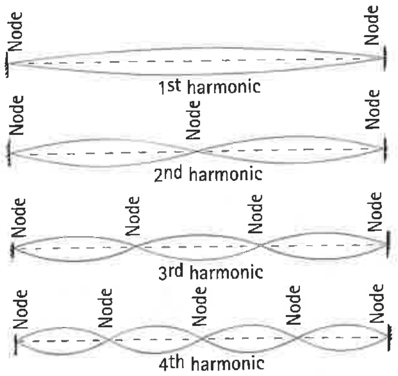


FIGURE 21.5

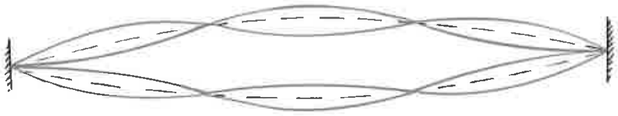
Modes of vibration of a guitar string.

Most musical sounds are composed of a superposition of many tones differing in frequency. The various tones are called **partial tones,** or simply *partials.* The lowest frequency, called the **fundamental frequency,** determines the pitch of the note. A partial tone whose frequency is a whole-number multiple of the fundamental frequency is called a **harmonic.** Different harmonics have different pitches. A tone that has twice the frequency of the fundamental is the second harmonic; a tone with 3 times the fundamental frequency is the third harmonic; and so on (Figure 21.5).[3] It is the variety of partial tones that gives a musical note its characteristic quality. So we see that musical instruments have characteristic timbres, each with their own "color."

Thus, if we strike middle C on the piano, we produce a fundamental tone with a pitch of about 262 Hz and also a blending of partial tones of two, three, four, five, and so on, times the frequency of middle C. The number and relative loudness of the partial tones determine the quality of sound associated with the piano. Sound from practically every musical instrument consists of a fundamental and partials. Pure tones, those having only one frequency, can be produced electronically. Electronic synthesizers produce pure tones, and mixtures of these tones, to give a vast variety of musical sounds.

FIGURE 21.6

A composite vibration of the fundamental mode and the third harmonic.



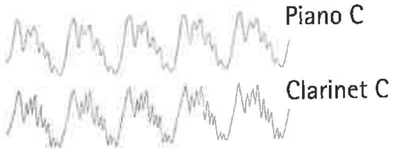


FIGURE 21.7

Sounds from the piano and clarinet differ in quality.

The quality of a tone is determined by the presence and relative intensity of the various partials. The sound produced by a certain tone from the piano and a clarinet of the same pitch have different qualities that the ear can recognize because their partials are different. A pair of tones of the same pitch with different qualities have either different partials or a difference in the relative intensity of the partials.

CHECK POINT

The pitch and loudness of two people's voices may be the same, but we easily distinguish between them. Why?

Check Your Answer

The voice of each person has a characteristic mixture of partial tones. We say each person's voice has its own timbre—its own special "color."

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[3] In the terminology often used in music, the second harmonic is called the *first overtone,* the third harmonic is called the *second overtone,* and so on. Not all partial tones present in a complex tone are integer multiples of the fundamental. Unlike the harmonics of woodwinds and brasses, stringed instruments, such as pianos, produce "stretched" partial tones that are nearly, but not quite, harmonics. This is an important factor in tuning pianos, and it occurs because the stiffness of the strings adds a little bit of restoring force to the tension.

Musical Instruments

Conventional musical instruments can be grouped into one of three classes: those in which the sound is produced by vibrating strings, those in which the sound is produced by vibrating air columns, and those in which the sound is produced by *percussion*—as with the vibrating of a two-dimensional surface.

In a stringed instrument, the vibration of the strings is transferred to a sounding board and then to the air, but with low efficiency. To compensate for this, we find relatively large string sections in orchestras. A smaller number of the high-efficiency wind instruments sufficiently balances a much larger number of violins.

In a wind instrument, the sound is a vibration of an air column in the instrument. There are various ways to set air columns into vibration. In brass instruments, such as trumpets, French horns, and trombones, air is blown into the instrument's mouthpiece at or near one end of the tube and exits at the other end. Vibrations of the player's lips interact with standing waves that are set up by acoustic energy reflected within the instrument by the flared bell at the end of the instrument. Sound from wind instruments depends mostly on the size and shape of the tube that the air moves through. The lengths of the vibrating air columns are manipulated by pushing valves that add or subtract extra segments[4] or by extending the length of the tube, as in a slide trombone. In woodwinds, such as clarinets, oboes, and saxophones, a stream of air produced by the musician sets a reed vibrating, whereas in fifes, flutes, and piccolos, the musician blows air against the edge of a hole to produce a fluttering stream that sets the air column into vibration.

In percussion instruments such as drums and cymbals, a two-dimensional membrane or elastic surface is struck to produce sound. The fundamental tone produced depends on the geometry, the elasticity, and, in some cases, the tension of the surface. Changes in pitch result from changing the tension in the vibrating surface; depressing the edge of a drum membrane with the hand is one way of accomplishing this. A variety of modes of vibration can be set up by striking the surface in different places. In the kettledrum, for example, the shape of the kettle changes the frequency of the drum. As in all musical sounds, the quality depends on the number and relative loudness of the partial tones.

Electronic musical instruments differ markedly from conventional musical instruments. Instead of strings that must be bowed, plucked, or struck, or reeds over which air must be blown, or diaphragms that must be tapped to produce sounds, some electronic instruments use electrons to generate the signals that produce musical sounds. Others start with sound from an acoustical instrument and then modify it. Electronic music demands of the composer and player an expertise beyond the knowledge of musicology. It brings a powerful new tool to the hands of the musician.

CHECK POINT

Sound from a guitar comes from vibrating strings. What vibrates to produce sound from a bugle?

Check Your Answer

In a bugle the players lips vibrate against each other and against the rim of the mouthpiece. More than depending on brass metal, brass instruments depend on the vibrating reeds or lips at the mouthpiece.

---

[4] A bugle has neither valves nor variable length. A bugler must be adept in creating various overtones to get various notes.

Fourier Analysis

Did you ever look closely at the grooves in an old phonograph record, the kind that provided music for Grandma and Grandpa? Variations in the width of the grooves, seen in Figure 21.8, cause the phonograph needle (stylus) to vibrate as it rides in the moving groove. These mechanical vibrations, in turn, are transformed into electrical vibrations to produce sound. Isn't it remarkable that all the distinct vibrations made by the various pieces of an orchestra are captured and then converted to a single sound signal?

Parrots, like humans, use their tongues to craft and shape sound. Tiny changes in the position of a parrot's tongue produce big differences in the sound first produced in the parrot's syrinx, a voice-box organ nestled between the trachea and the lungs.

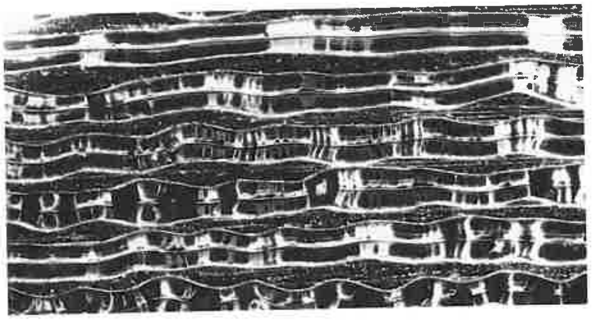
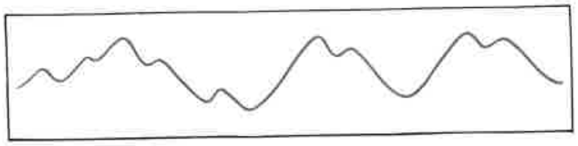


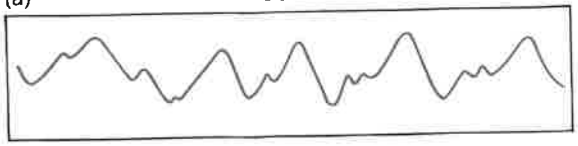
FIGURE 21.8

A microscopic view of the grooves in a phonograph record.

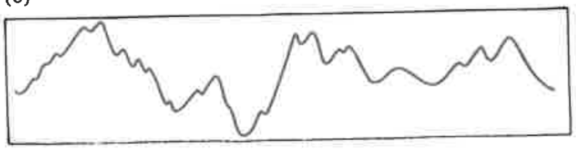
The sound of an oboe displayed on the screen of an oscilloscope looks like Figure 21.9a. This wave corresponds to the vibrations in the oboe. It also corresponds to the amplified signal that activates the speaker of the sound system and to the amplitude of air vibrating against the eardrum. Figure 21.9b shows the wave appearance of a clarinet. When oboe and clarinet are sounded together, the principle of superposition is evident as their individual waves combine to produce the waveform shown in Figure 21.9c.



(a) Oboe



(b) Clarinet



(c) Oboe and clarinet together

FIGURE 21.9

Waveforms of (a) an oboe, (b) a clarinet, and (c) the oboe and clarinet sounded together.

The shape of the wave in Figure 21.9c is the net result of shapes a and b superposing (interfering). If we know a and b, it is a simple thing to create c. But it is a far different problem to discern in c the shapes of a and b that make it up. Looking only at shape c, we cannot unscramble the oboe from the clarinet. But if we listen to a recording of the music, our ears will at once distinguish what instruments are being played, what notes they are playing, and what their relative loudness is. Our ears break the overall signal into its component parts automatically.

As mentioned at the beginning of this chapter, the French mathematician Joseph Fourier discovered a mathematical regularity to the component parts of periodic wave motion. He found that even the most complex periodic wave motion can be disassembled into simple sine waves that add together. Recall that a sine wave is the simplest of waves, having a single frequency (Figure 21.10). Fourier found that all periodic waves may be broken down into constituent sine waves of different amplitudes and frequencies. The mathematical operation for performing this is called **Fourier analysis.** We will not explain the mathematics here but simply point out that, by such analysis, one can find the pure sine waves that add to compose the tone of, say, a violin. When these pure tones are sounded together, as by striking a number of tuning forks or by selecting the proper keys on an electric organ, they combine to give the tone of the violin. The lowest-frequency sine wave is the fundamental and determines the pitch of the note. The higher-frequency sine waves are the partials that give the characteristic quality. Thus, the waveform of any musical sound is no more than a sum of simple sine waves.

Since the waveform of music is a multitude of various sine waves, to duplicate sound accurately by any of the means by which sound is recorded, we should process as large a range of frequencies as possible. The notes of a piano keyboard range from 27 Hz to 4200 Hz, but, to duplicate the music of a piano composition accurately, the sound system must have a range of frequencies up to 20,000 Hz. The greater the range of the frequencies of an electrical sound system, the closer the musical output approximates the original sound, and hence the wide range of frequencies in the best of sound systems.

Our ear performs a sort of Fourier analysis automatically. It sorts out the complex jumble of air pulsations that reach it and transforms them into pure tones composed of sine waves. We recombine various groupings of these pure tones when we listen. What combinations of tones we have learned to focus our attention on determines what we hear when we listen to a concert. We can direct our attention to the sounds of the various instruments and discern the faintest tones from the loudest; we can delight in the intricate interplay of instruments and still detect the extraneous noises of others around us. This is a most incredible feat.

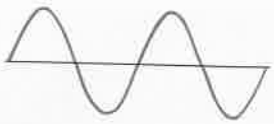


FIGURE 21.10

A sine wave.

FIGURE 21.11

Does each listener hear the same music?

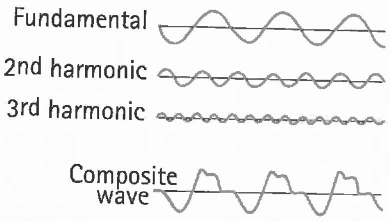


FIGURE 21.12

The fundamental and its harmonics combine to produce a composite wave.

Digital Versatile Discs (DVDs)

The phonograph records of old utilized a conventional stylus that vibrated in the squiggly groove of a disc more than twice the diameter of today's CDs (compact discs) and DVDs (first called digital video discs, and now digital versatile discs). The output of phonograph records was signals like those shown in Figure 21.9. This type of continuous waveform is called an *analog* signal. The analog signal can be changed to a *digital* signal by measuring the numerical value of its amplitude during each split second (Figure 21.13). This numerical value is expressed in the number system that is convenient for computers, called *binary*. In the binary code, any number can be expressed as a succession of 1s and 0s; for example, the number 1 is 1, 2 is 10, 3 is 11, 4 is 100, 5 is 101, 17 is 10001, and so forth. So the shape of the analog waveform is expressed as a series of "on" and "off" pulses that corresponds to a series of 1s and 0s in binary code.

Who better appreciates music—one knowledgeable about it, or the casual listener?

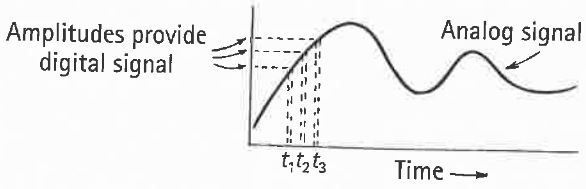


FIGURE 21.13

The amplitude of the analog waveform is measured at successive split seconds to provide digital information that is recorded in binary form on the reflective surface of the CD.

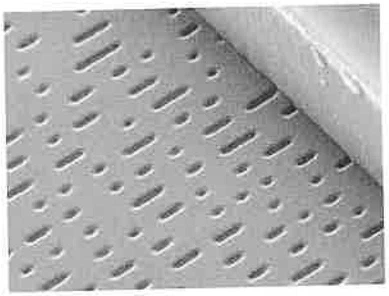


FIGURE 21.14

A microscopic view of the pits on a laser disc.

Microscopic pits about one-thirtieth the diameter of a strand of human hair are imbedded in the CD or DVD (Figure 21.14). The pits are of two types, short and long, with short corresponding to 0 and long to 1. A laser beam reads these pits. When the beam falls on a short pit on the reflective surface, it is reflected directly into the player's optical system and registers a 0. When the beam is incident upon a passing longer pit, the optical sensor registers a 1. Hence the beam reads the 1 and 0 digits of the binary code.

On a CD, the rate at which these tiny pits are sampled is 44,100 times per second. If you could gather all these pits together without overlapping they would be the size of the period at the end of this sentence. Billions of bits of information are encoded on the reflective surface, which is covered with a protective layer of clear lacquer.

Single-layer digital versatile discs (DVDs) have about 6 times the information-carrying or information-storage capacity of CDs, 4.37 GB versus 700 MB. DVD discs have smaller pits, which, in effect, make the length of the spiral track more than twice as long as that of a CD. The smaller pits of the DVD are read with laser light of shorter wavelength and also by way of a more powerful focusing lens. Whereas the pits on a CD lie on a single reflecting surface, a DVD can have multiple layers, storing even more information on a disk. By precision focusing, laser light reads the pits in the desired layer.

Now we have the 25-GB Blu-ray™ DVD player. The even shorter-wavelength blue light reads even more pits stored on a disc. More information (up to 50 GB) means higher resolution, so this feature is responsible for the incredibly sharp pictures on high-definition Blu-ray™ DVDs.

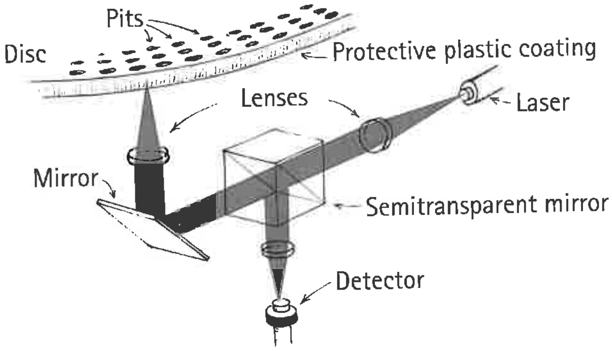


FIGURE 21.15

A tightly focused laser beam reads digital information represented by a series of pits on the laser disc.

SUMMARY OF TERMS

Pitch The "highness" or "lowness" of a tone, as on a musical scale, which is principally governed by frequency. A high-frequency vibrating source produces a sound of high pitch; a low-frequency vibrating source produces a sound of low pitch.

Intensity The power per square meter carried by a sound wave, often measured in decibels.

Loudness The physiological sensation directly related to sound intensity or volume.

Quality The characteristic timbre of a musical sound, which is governed by the number and relative intensities of partial tones.

Partial tone Single-frequency component sound wave of a complex tone. When the frequency of a partial tone is an integer multiple of the lowest frequency, it is referred to as a *harmonic*.

Fundamental frequency The lowest frequency of vibration, or first harmonic, in a musical tone.

Harmonic A partial tone whose frequency is an integer multiple of the fundamental frequency. The second harmonic has twice the frequency of the fundamental, the third harmonic 3 times the frequency, and so on in sequence.

Fourier analysis A mathematical method that disassembles any periodic waveform into a combination of simple sine waves.

REVIEW QUESTIONS

Noise and Music

1. Distinguish between noise and music.
2. What are the three principal characteristics of musical tones?

Pitch

3. How does a high-pitch musical note compare with a low one in terms of frequency?
4. How does the highest pitch one can hear vary with age?

Sound Intensity and Loudness

5. What is a decibel, and how many decibels correspond to the lowest-intensity sound we can hear?
6. Is the sound of 30 dB 30 times greater than the threshold of hearing, or 10^3 (a thousand) times greater?
7. Distinguish between sound intensity and loudness.
8. How do the loudest sounds we can tolerate compare with the faintest sounds?

Quality

9. What is it that determines the pitch of a note?
10. If the fundamental frequency of a note is 200 Hz, what is the frequency of the second harmonic? The third harmonic?
11. What exactly determines the musical quality of a note?
12. Why do the same notes plucked on a banjo and on a guitar have distinctly different sounds?

Musical Instruments

13. What are the three principal classes of musical instruments?
14. Why do orchestras generally have a greater number of stringed instruments than wind instruments?

Fourier Analysis

15. What did Fourier discover about complex periodic wave patterns?
16. A high-fidelity sound system may have a frequency range that extends up to or beyond 20,000 Hz. What is the purpose of this extended range?

Digital Versatile Discs (DVDs)

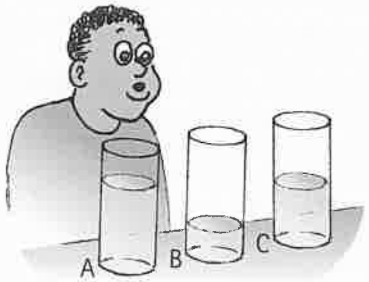
17. How was the sound signal captured on phonograph records of the 20th century? How is the sound signal captured on a CD?
18. Why does the use of blue light allow more information on a DVD?

PROJECTS

1. Test to see which ear has the better hearing by covering one ear and finding how far away your open ear can hear the ticking of a clock; repeat for the other ear. Notice also how the sensitivity of your hearing improves when you cup your ears with your hands.
2. Make the lowest-pitched sound you are capable of; then keep doubling the pitch to see how many octaves your voice can span. If you are a singer, what is your range?
3. On a sheet of graph paper, construct one full cycle (one period of the fundamental) of the composite wave of Figure 21.12 by superposing various vertical displacements of the fundamental and first two partial tones. Your instructor can show you how this is done. Then find the composite waves of partial tones of your own choosing.

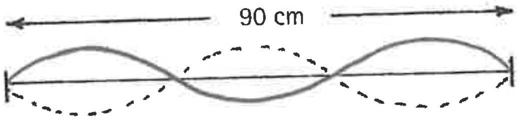
RANKING

1. Consider three notes: A, 220 Hz; B, 440 Hz; and C, 660 Hz. Rank them from highest to lowest for
   a. pitch.
   b. frequency.
   c. wavelength.
2. You blow across the mouths of identical bottles A, B, and C, each containing a different amount of water, as shown. From highest to lowest, rank the pitch of sound for each.

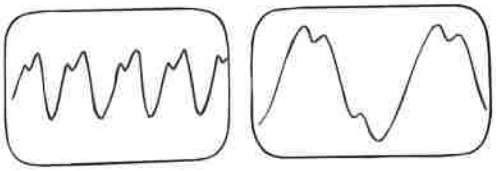


EXERCISES

1. Your friend says that frequency is a quantitative measure of pitch. Do you agree or disagree?
2. As the pitch of sound increases, what happens to the frequency?
3. Your classmate says that timbre refers to the quality of a steady musical sound composed of a mixture of harmonics of different intensities. Do you agree or disagree?
4. The yellow-green light emitted by streetlights matches the yellow-green color to which the human eye is most sensitive. Consequently, such a 100-W streetlight emits light that is better seen at night. Similarly, the monitored sound intensities of TV commercials are louder than the sound of regular programming, yet don't exceed the regulated intensities. At what frequencies do advertisers concentrate the commercial's sound?
5. Why should guitars be played offstage before they are brought onstage for a concert? (*Hint:* Think thermally.)
6. A guitar and a flute are in tune with each other. Explain how a change in temperature could alter this situation.
7. If sound becomes louder, which wave characteristic is likely increasing—frequency, wavelength, amplitude, or speed?
8. Explain how you can lower the pitch of a note on a guitar by altering the string's (a) length, (b) tension, or (c) thickness or mass.
9. Does the pitch of a note depend on sound frequency, loudness, quality, or on all of these?
10. When a guitar string is struck, a standing wave is produced that causes the sounding board to oscillate with a large sustained amplitude, pushing back and forth against the surrounding air to generate sound. How does the frequency of the resulting sound compare with the frequency of the standing wave in the string?
11. The strings on a harp are of different lengths and produce different notes. How are different notes produced on a guitar, where all strings have the same length?
12. If a vibrating string is made shorter (as by holding a finger on it), how does this affect the frequency of vibration and pitch?
13. A nylon guitar string vibrates in a standing-wave pattern, as shown below. What is the wavelength of the wave?



14. Why do tuning forks with long tines vibrate at a lower frequency than short-tined forks? (*Hint:* This question could have been asked back in Chapter 8.)
15. Why is the thickness greater for the bass strings of a guitar than for the treble strings?
16. Will the thicker or thinner of two guitar strings of the same tension and length vibrate at the higher frequency?
17. Why does a vibrating guitar string not sound as loud when it is mounted on a work bench as it does when mounted on the guitar?
18. Would a plucked guitar string vibrate for a longer time or a shorter time if the instrument had no sounding board? Why?
19. If you very lightly touch a guitar string at its midpoint, you can hear a tone that is one octave above the fundamental for that string. (An octave is a factor of 2 in frequency.) Explain.
20. If a guitar string vibrates in two segments, where can a tiny piece of folded paper be supported without flying off? How many pieces of folded paper could similarly be supported if the waveform were of three segments?
21. Your classmate says that a harmonic series of frequencies includes the fundamental frequency and integral multiples of the fundamental frequency. Do you agree or disagree?
22. Why do the same notes on a trumpet and on a saxophone sound different when both are played with the same pitch and loudness?
23. The amplitude of a transverse wave in a stretched string is the maximum displacement of the string from its equilibrium position. What does the amplitude of a longitudinal sound wave in air correspond to?
24. Which of the two musical notes displayed one at a time on an oscilloscope screen has the higher pitch?



25. In the oscilloscopes shown above, which screen displays the louder sound (assuming detection by equivalent microphones)?
26. Tom Senior makes music by setting small columns of air into vibration by blowing across the ends of drinking straws of various lengths. Which straws, the short ones or the long ones, produce lower pitch? What would you expect of the pitch produced by the much larger musical instrument behind Tom that uses resonant air columns excited by striking the ends of the tubes with paddles?

27. Which is a more objective measurement—sound intensity or loudness? Defend your answer.
28. One person has a threshold of hearing of 5 dB, and another of 10 dB. Which person has the more acute hearing?
29. How is an electronic organ able to imitate the sounds of various musical instruments?
30. After inhaling helium gas, a person talks with a high-pitched voice. One of the reasons for this is the higher speed of sound in helium than in air. Why does sound travel faster in helium?
31. Why does your voice sound fuller in the shower?
32. The frequency range for a telephone is between 500 Hz and 4000 Hz. Why does a telephone not do a very good job of transmitting music?
33. How many octaves does normal human hearing span? How many octaves are on a common piano keyboard? (If you're not sure, look and see.)

34. The note middle C on a piano has a fundamental frequency of about 262 Hz. What is the frequency of the second harmonic of this note?

35. If the fundamental frequency of a guitar string is 220 Hz, what is the frequency of the second harmonic? Of the third harmonic?

36. If the fundamental frequency of a violin string is 440 Hz, what is the frequency of the second harmonic? Of the third harmonic?

37. How many nodes, not including the endpoints, are in a standing wave three wavelengths long? How many nodes are in a standing wave four wavelengths long?

38. How can you tune the note A_3 on a piano to its proper frequency of 220 Hz with the aid of a tuning fork whose frequency is 440 Hz?

39. At an outdoor concert, the pitch of musical tones is *not* affected on a windy day. Explain.

40. A trumpet has keys and valves that permit the trumpeter to change the length of the vibrating air column and the position of the nodes. A bugle has no such keys and valves, yet it can sound various notes. How do you think the bugler achieves different notes?

41. The human ear is sometimes called a Fourier analyzer. What does this mean, and why is it an appropriate description?

42. The width of a laser beam is significant in reading CDs and DVDs. The thinner the beam, the closer the series of pits can be. Why will blue laser light allow closer pits than red laser light?

43. Do all the people in a group hear the same music when they listen attentively as in Figure 21.11? Do all see the same sight when viewing a painting? Do all taste the same flavor when sipping the same wine? Do all perceive the same aroma when smelling the same perfume? 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?

44. Why is it a safe prediction that you, presently reading this, will have a significantly greater loss of hearing in your later years than your grandparents experienced?

45. Make up a multiple-choice question that distinguishes between any of the terms listed in the Summary of Terms.

PROBLEMS

1. The highest frequency humans can hear is about 20,000 Hz. What is the wavelength of sound in air at this frequency? What is the wavelength of the lowest sounds we can hear, about 20 Hz?

2. A violin string playing the note "A" oscillates at 440 Hz. What is the period of the string's oscillation?

3. The string of a cello playing the note C oscillates at 264 Hz. What is the period of the string's oscillation?

4. How much more intense than the threshold of hearing is a sound of 10 dB? 30 dB? 60 dB?

5. How much more intense is sound at 40 dB than sound at 0 dB?

6. How much more intense is a sound of 40 dB than a sound of 30 dB?

7. A certain note has a frequency of 1000 Hz. What is the frequency of a note one octave above it? Two octaves above it? One octave below it? Two octaves below it?

• **8.** Starting with a fundamental tone, how many harmonics are between the first and second octaves? Between the second and third octaves? (See Figure 21.5 to get started.)

CHAPTER 21 ONLINE RESOURCES

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Flashcards

PART FOUR MULTIPLE-CHOICE PRACTICE EXAM

Choose the BEST answer to the following:

1. You swing to and fro on a playground swing. If you stand rather than sit, the time for a to-and-fro swing is
   (a) lengthened.
   (b) shortened.
   (c) unchanged.
2. The time it takes for a pendulum swinging to and fro refers to its
   (a) frequency.
   (b) period.
   (c) wavelength.
   (d) amplitude.
3. The period of a 10-Hz wave is
   (a) 1/10 s.
   (b) 1.0 s.
   (c) 10 s.
   (d) None of these.
4. A wave transfers
   (a) amplitude.
   (b) wavelength.
   (c) frequency.
   (d) energy.
5. Find the speed of a wave by multiplying its frequency by its
   (a) period.
   (b) wavelength.
   (c) amplitude.
   (d) None of these.
6. The vibrations in a transverse wave move in a direction
   (a) along the wave.
   (b) perpendicular to the wave.
   (c) Both of these.
   (d) Neither of these.
7. The vibrations in a longitudinal wave move in a direction
   (a) along and parallel to the wave.
   (b) perpendicular to the wave.
   (c) Both of these.
   (d) Neither of these.
8. Interference is characteristic of
   (a) sound waves.
   (b) light waves.
   (c) water waves.
   (d) All of these.
9. Standing waves are the result of
   (a) interference.
   (b) waves overlapping in phase and out of phase.
   (c) waves reflecting upon themselves.
   (d) All of these.
10. The Doppler effect occurs when a source of sound moves
    (a) toward you.
    (b) away from you.
    (c) Both of these.
    (d) None of these.
11. Compared with the sound you hear from the siren of a stationary fire engine, its sound when it approaches you has an increased
    (a) speed.
    (b) frequency.
    (c) Both of these.
    (d) Neither of these.
12. Bow waves are produced by waves of water
    (a) overlapping one another.
    (b) constructively interfering.
    (c) moving slower than the source producing them.
    (d) All of these.
13. Shock waves are produced by waves of sound
    (a) overlapping one another.
    (b) constructively interfering.
    (c) moving slower than the source producing them.
    (d) All of these.
14. During the time an aircraft produces a sonic boom, the aircraft is
    (a) breaking the sound barrier.
    (b) pulling out of a subsonic dive.
    (c) flying faster than sound.
    (d) All of these.
15. The sound waves that most humans cannot hear are
    (a) infrasonic.
    (b) ultrasonic.
    (c) Both of these.
    (d) Neither of these.
16. Sound travels in air by a series of
    (a) compressions.
    (b) rarefactions.
    (c) Both of these.
    (d) Neither of these.
17. The compressions and rarefactions in sound normally travel
    (a) in the same direction.
    (b) in opposite directions.
    (c) at right angles to each other.
    (d) None of these.
18. Sound travels in
    (a) solids.
    (b) liquids.
    (c) gases.
    (d) All of these.
19. The speed of sound is slightly greater on a
    (a) cold day.
    (b) hot day.
    (c) day with steady temperature.
    (d) None of these.
20. Sound will travel fastest in
    (a) a steel beam.
    (b) a wooden plank.
    (c) ocean water.
    (d) air in a balloon.
21. The loudness of a sound is most closely related to its
    (a) frequency.
    (b) period.
    (c) wavelength.
    (d) amplitude.
22. Your friend states that under all conditions, any radio wave travels faster than any sound wave. You
    (a) agree with your friend.
    (b) disagree with your friend.
23. When you tap a piece of wood it will produce a characteristic sound related to its
    (a) wavelength.
    (b) amplitude.
    (c) period.
    (d) natural frequency.
24. When an object is set vibrating by a wave that has a matching frequency, what occurs is
    (a) forced vibration.
    (b) resonance.
    (c) refraction.
    (d) amplitude reduction.
25. Noise-canceling devices make use of sound
    (a) destruction.
    (b) interference.
    (c) resonance.
    (d) amplification.
26. The phenomenon of beats is the result of sound
    (a) destruction.
    (b) interference.
    (c) resonance.
    (d) amplification.
27. A 1134-Hz tuning fork is sounded at the same time a piano note is struck. You hear 3 beats per second. The frequency of the piano string is
    (a) 1131 Hz.
    (b) 1134 Hz.
    (c) 1137 Hz.
    (d) More information is needed.
28. The pitch of a sound is mostly related to its
    (a) intensity.
    (b) frequency.
    (c) amplitude.
    (d) speed.
29. Compared with a sound of 60 decibels, a sound of 80 decibels has an intensity
    (a) 10 times greater.
    (b) 100 times greater.
    (c) 1000 times greater.
    (d) more than 1000 time greater.
30. Compared with a fundamental tone, the frequency of its second harmonic is
    (a) half as much.
    (b) twice as much.
    (c) the same.
    (d) 4 times as much.

After you have made thoughtful choices, and discussed them with your friends, find the answers on page 681.