16

Sound and Music

▶Sounds are all around us. Some are pleasant, and some irritate and distract us. How do the sounds of music differ from those sounds we call noise, and why do musicians use different-sized instruments?

(See page 346 for the answer to this question.)

Jake Rajs/Stone/Getty

A military marching band at a ticker-tape parade in New York City.

WHEN we think of sound, we generally think of signals traveling through the air to our ears. But sound is more than this. Sound also travels through other media. For instance, old-time Westerns showed cowboys and Indians listening for the "iron horse" by putting their ears to the rails or the ground; two rocks clapped together underwater are easily heard by swimmers below the surface; a fetus inside a mother's womb can be examined with ultrasound; and the voices of people talking in the next room are often heard through the walls. Sounds can be soothing and musical, but they can also be irritating or even painful.

Sound is a wave phenomenon. For example, we talk of the pitch, or frequency, of sounds, which is definitely a wave characteristic. But what other evidence do we have? The conclusive evidence is that sound exhibits superposition, something that we know distinguishes waves from particles.

Sound

A vibrating object produces disturbances in the surrounding air. When the surface moves outward, the air molecules are pushed away, creating a *compression*. When its surface moves in the opposite direction, a partial void, or *rarefaction,* is created near the object. Pressure differences cause the air molecules to rush back into the region only to get pushed out again. Thus, the air molecules vibrate back and forth near the object's surface as illustrated by the tuning fork in Figure 16-1. The compressions and rarefactions travel away from the vibrating surface as a sound wave. Because the vibrations of the air molecules are along the same direction as the motion of the wave, sound is a longitudinal wave.

sound is a longitudinal wave ▶

As with all waves, it is energy—not mass—that is transported. The individual molecules of the air are not moving from one place to another; they simply vibrate back and forth. It is the disturbance that moves across the room when you talk. This disturbance, or wave, moves with a certain speed.

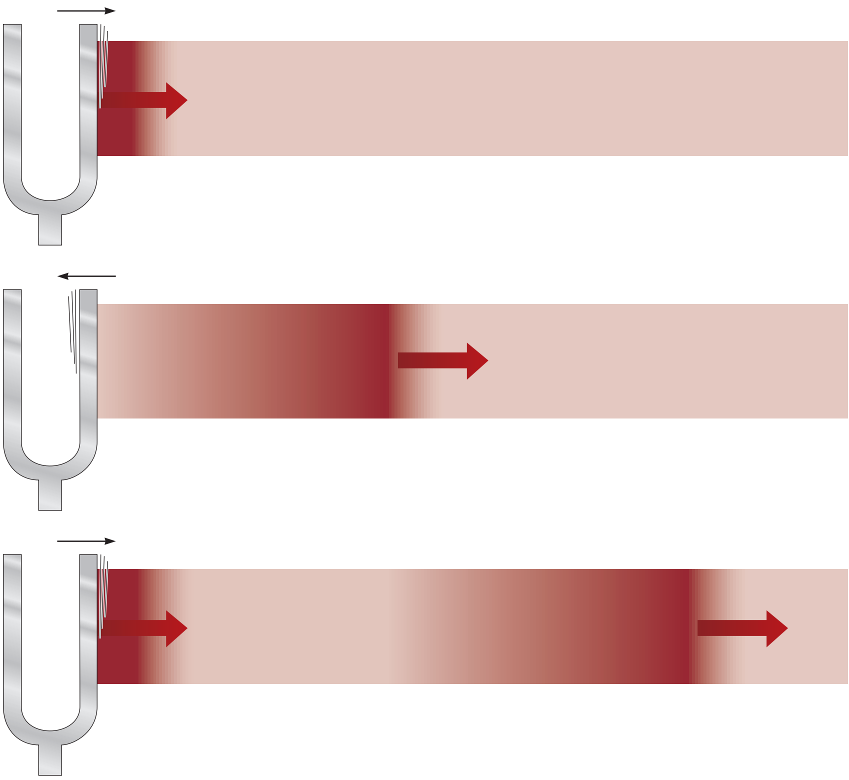


Figure 16-1 Sound is a longitudinal wave in which the air molecules vibrate along the direction the wave is traveling, producing compressions and rarefactions that travel through the air.

Speed of Sound

◀ Extended presentation available in the *Problem Solving* supplement

Echoes demonstrate that sound waves reflect off surfaces and that they move with a finite speed. You can use this phenomenon to measure the speed of sound in air. If you know the distance to the reflecting surface and the time it takes for the echo to return, you can calculate the speed of sound. The speed of sound is 343 meters per second (1125 feet per second), or 1235 kilometers per hour (767 miles per hour), at room temperature.

◀ **speed of sound = 343 m/s**

Experiments have shown that the speed of sound does not depend on the pressure, but it does depend on the temperature and the type of gas. Sound is slower at lower temperatures. At the altitude of jet airplanes, where the temperature is typically −40°C (−40°F), the speed of sound drops to 310 meters per second, or 1020 kilometers per hour (690 miles per hour). The speed is higher for gases with molecules that have smaller masses. The speed of sound in pure helium at room temperature is three times that in air.

FLAWED REASONING

Heidi and Russell are discussing the speed of sound in air:

Heidi: "A sound wave travels through air via collisions of air molecules. If the air is compressed, the molecules are closer together. The sound wave should speed up because each molecule does not need to travel as far to collide with its neighbor."

Russell: "The textbook claims that the speed of sound in air depends only on the temperature of the air, not on its pressure."

Find the error in Heidi's reasoning.

ANSWER Imagine a relay race in which every runner runs *exactly* 5 mph. If one of the teams has twice as many runners (spaced half as far apart), the race still ends in a tie. Each runner on the smaller team runs twice as far before passing the baton, but there are half as many baton transfers. Similarly, each molecule in the compressed gas reaches its neighbor in less time, but more neighbors are involved. The air temperature determines the average molecular speed, and this determines how quickly the wave travels.

Knowing the speed of sound in air allows you to calculate your distance from a lightning bolt. Because the speed of light is very fast, the time light takes to travel from the lightning to you is negligible. Therefore, the time delay between the arrival of the light flash and the sound of the thunder is essentially all due to the time it takes the sound to travel the distance. Given the speed of sound, we can use the definition of speed from Chapter 2 to calculate that sound takes approximately 3 seconds to travel 1 kilometer (5 seconds for a mile).

Sound waves also travel in other media. The speed of sound in water is about 1500 meters per second, much faster than in air. The speed of sound in solids is usually quite a bit higher—as high as 5000 meters per second—and the sound is quite a bit louder. Hearing the sounds of an approaching train through the rails works well because the sound moving through the rail does not spread out like sound waves in air and experiences less scattering along the path. You can easily experience this phenomenon in the classroom. Have a friend scratch one end of a meter stick while you hold the other end next to your ear. The effect is striking.

Sonar (*so*und *na*vigation *r*anging) uses the echoes of sound waves in water to determine the distances to underwater objects. These sonar devices emit sound pulses and measure the time required for the echo to return. Sonar is used to determine the depth of the water, search for schools of fish, and locate submarines.

Q: If it takes the thunder 9 seconds to reach you, how far away is the lightning?

A: Because it takes the thunder 3 seconds to travel a kilometer, the lightning bolt must have been 3 kilometers away (a little less than 2 miles).

Hearing Sounds

Sound perception is a complex phenomenon whose study involves a wide variety of sciences, including physiology, psychology, and the branch of physics called acoustics. Experiments with human hearing, for example, clearly show that our perception is often different from the simple interpretations of the measurements taken by instruments. Our perception of pitch depends mainly on frequency but is also affected by other properties, such as loudness. And loudness depends on the amplitude of the wave (as well as the response of our ears). When our ear–brain systems tell us that one sound is twice as loud as another, instruments show that the power output is nearly eight times as great.

Our ears intercept sound waves from the air and transmit their vibrations through internal bone structures to special hairlike sensors. The ear canal acts as a resonator, greatly amplifying frequencies near 3000 hertz. This amplified sound wave moves the eardrum, which is located at the end of the ear canal, as shown in Figure 16-2. The eardrum is connected to three small bones in the middle ear. When sound reaches the middle ear, it has been transformed from a wave in air to a mechanical wave in the bones. These bones then move a smaller oval window inside the ear. The leverage advantage of the bone structure and the concentration of the pressure vibration onto a smaller window further amplify the sound, increasing our ability to hear faint sounds. The final transformation of mechanical sound waves to nerve impulses takes place in the inner ear. The pressure vibrations in the fluid of the inner ear resonate with different hairlike sensors, depending on the frequency of the sound.

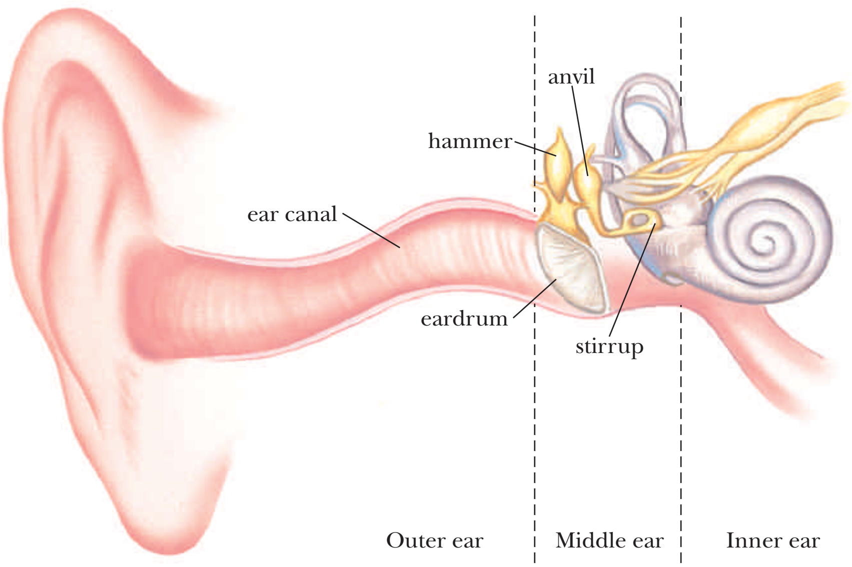


Figure 16-2 The structure of the human ear.

The range of frequencies that we can hear clearly depends on the resonant structures within our ears. When a frequency is too high or too low, the sound wave is not amplified like those within the audible range. The audible range is normally from 20 hertz to 20,000 hertz, although it varies with age and the individual. The sensitivity of our ears varies over this range, with low sensitivity occurring at both ends of the range. As we get older, our ability to hear higher frequencies decreases. However, modern digital hearing aids can be individually programmed to compensate for a person's hearing loss at each frequency.

Courtesy of SENSO Digital Hearing Aid by Widex

Digital hearing aid.

The Recipe of Sounds

Suppose you are in a windowless room but can hear sounds from the outside. You would have no trouble identifying most of the sounds you hear. A bird sounds different from a foghorn, a trumpet different from a baritone. Why is it that you can recognize these different sources of sound? They may be pro-

Everyday Physics | *Animal Hearing*

Animals have different ranges of sensitivity for hearing than humans. Dogs and bats, for example, have hearing ranges that extend to ultrasonic frequencies—frequencies above those that we can hear.

Unlike humans, most animals use their hearing as an aid in gathering food and escaping danger. Bats squeak at ultrasonic frequencies and detect the echoes from small flying insects (Figure A); robins cock their heads in early spring as they listen for the very faint sounds of worms in the ground, and owls have two different types of ears providing them with binocular hearing for finding mice moving through grassy fields.

Animal researchers have found that homing pigeons and elephants hear very low-frequency sounds—infrasonic frequencies. Low-frequency sounds do not attenuate as rapidly and therefore travel much farther than high-frequency sounds. In the case of pigeons, hearing the sounds of skyscrapers swaying in the wind in distant cities may provide them with navigational bearings. There is evidence that elephants communicate with each other over distances of miles using a low-frequency rumble. Figure B displays the frequency ranges that some animals can hear.

1. Are there frequencies that humans can hear, but dogs cannot? Explain.
2. Which animal can hear the greater range in frequencies, a mouse or an elephant? Give evidence for your answer from the graph in Figure B.

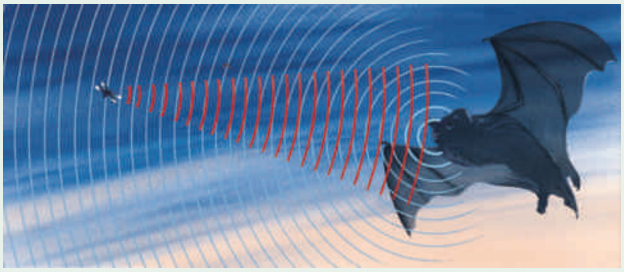


Figure A The bat emits sound waves (shown in blue) that reflect off the insect and return (shown in red) to the bat, giving away the insect's position.

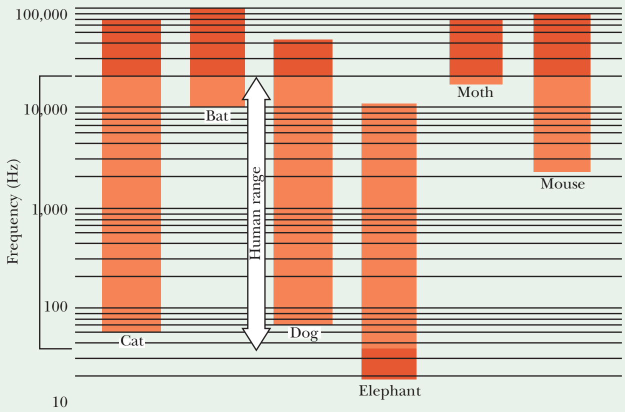


Figure B The frequency ranges of hearing for some animals.

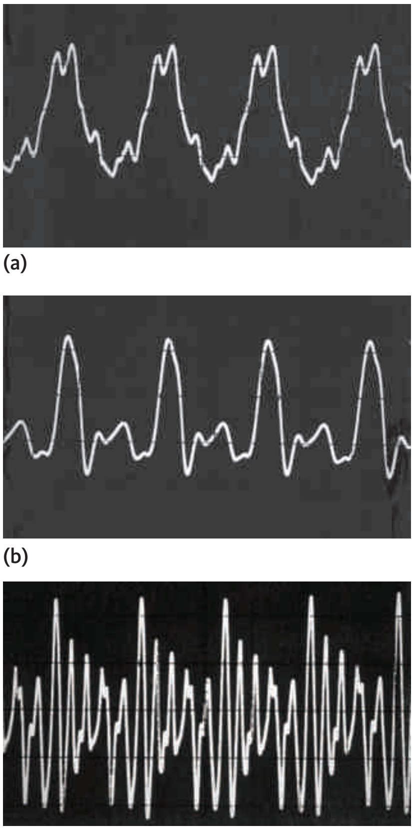


Figure 16-3 Wave patterns of (a) a violin, (b) a trumpet, and (c) a bassoon. These photographs show only general characteristics; the details depend on the placement of the microphone.

ducing different notes; a bird sings much higher than a foghorn. They may make different melodies; some birds have a rather complex sequence of notes in their call, whereas the foghorn produces one continuous note.

What if all the sound makers outside your room are restricted to a single note? Do you suppose that you could still identify the different sources? Most likely. When each source produces the note, it is accompanied by other higher, resonant frequencies. You actually hear a superposition of these frequencies. The reason you can distinguish among the sources is that each sound has a unique combination of intensities of the various harmonics (Chapter 15). One sound may be composed of a strong fundamental frequency and weaker higher harmonics, and another may have a particularly strong second harmonic. Each sound has a particular recipe of resonant frequencies that combine to make the total sound.

The vibrating strings in a piano, violin, guitar, or banjo have their own combinations of the fundamental frequency and higher harmonics. The relative intensities of these harmonics depend primarily on the way the string was initially vibrated and on the vibrational characteristics of the body of the instrument. The initial part of the sound is called the *attack,* and its character is determined, in part, by how the sound is produced. Bowing, for example, produces a sound different from plucking or striking. The manner in which the various components of the sound decay also differs from one instrument to another. The wave patterns produced by various sounds are illustrated in Figure 16-3.

Our voices have the same individual character. We recognize different voices because of their particular recipe of harmonics. Research has shown that this recipe changes under emotional stress. Some people have suggested that these changes in the recipe of sound of a voice can be used in lie detection. Electronic devices can decompose the composite waveform—the superposition of all the harmonics—and evaluate the relative strength of each harmonic. This technique spots changes in higher harmonics that are virtually undetectable in the composite waveform.

How does music differ from other sounds? This question is difficult because what is music to one person may be noise to you. In general, music can be defined as that collection of periodic sounds that is pleasing to the ear.

Most cultures divide the totality of musical frequencies into groups known as octaves. A note in one octave has twice the frequency of the corresponding note in the next lower octave. For example, the pitches labeled C in ascending adjacent octaves have frequencies of 262, 524, and 1048 hertz, respectively. In Western cultures most music is based on a scale that divides the octave into 12 steps. It may seem strange that an octave spans 12 notes, because the word *octave* derives from the Latin word meaning "eight." An octave contains 7 natural notes and 5 sharps and flats. Indian and Chinese music have different divisions within their octaves.

Through the years, people have created instruments to produce sounds that were pleasing to them. Nearly all of these instruments involve the production of standing waves. Although there is an enormous variety of instruments, most of them can be classified as string, wind, or percussion instruments.

Stringed Instruments

When a string vibrates, it moves the air around it, producing sound waves. Because the string is quite thin, not much air is moved, and consequently the sound is weak. In acoustic stringed instruments, this lack of volume is solved by mounting the vibrating string on a larger body. The vibrations are transmitted to the larger body, which can move more air and produce a louder

Everyday Physics | *Loudest and Softest Sounds*

The intensity of sound is measured in terms of the sound energy that crosses 1 square meter of area in 1 second and is measured by a sound level meter. At a reference value of 1000 hertz, the faintest sounds that can be heard by the human ear have intensities a little less than one-trillionth (10^{-12}) of a watt per square meter. This results from a variation in pressure of about 0.3 billionth of an atmosphere and corresponds to a displacement of the air molecules of approximately one-billionth of a centimeter, which is less than the diameter of a molecule! The ear is a very sensitive instrument.

On the loud side, the ear cannot tolerate sound intensities much greater than 1 watt per square meter without experiencing pain. This corresponds to a variation in pressure of about one-thousandth of an atmosphere, 1 million times as big as for sounds that can be barely heard. The displacements of the molecules are also 1 million times as large.


Erwin C. "Bud" Nielsen/Visuals Unlimited

A source of sound that is transmitting at 100 watts in a spherically symmetric pattern is painful to our ears at a distance of 1 meter and theoretically audible at about 3000 kilometers (2000 miles!), if we assume no losses in moving through the air. Psychoacoustic scientists report that when the intensity of sound is increased about eight times, people report a doubling in the loudness of the sound.

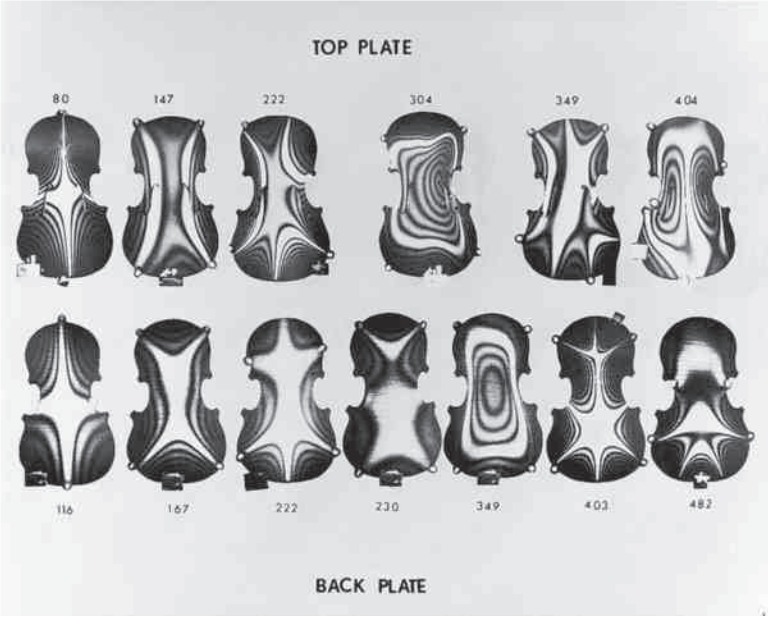
Because of the large range of sensitivity of the ear as well as our perceptual scale, the scale scientists use to distinguish different sound levels is based on multiples of 10. A sound that has 10 times as much intensity as another sound has a level of 10 decibels, or 10 dB (pronounced "dee bee"), higher than the first sound. Because every increase of 10 decibels corresponds to a factor-of-10 increase in intensity, an increase of 20 decibels means that the intensity increases by $10 \times 10 = 100$ times. Sound-level meters use this same nonlinear scale. The table gives some representative values of sound intensity.

A sound level of 85 decibels is safe for unlimited exposure. However, a sound level of 100 decibels is safe for only 2 hours, and an increase to 110 decibels reduces the safe period to 30 minutes. Note that a typical rock concert has an intensity 10 times as large as this. It is also interesting to note that 75% of hearing losses are due to exposure to loud noises and not due to aging. Earplugs typically reduce sound levels by 20–30 decibels and should be used whenever sound levels exceed safe limits.

1. By what factor do earplugs reduce the intensity of sound if they reduce the sound level by 30 dB?
2. The sound intensity from a typical rock concert (not the Vienna Boy's Choir) is greater than the sound intensity of a screaming baby by what factor?

Decibel Levels for Some Common Sounds

Source	Decibels	Energy Relative to Threshold	Sensation
Nearby jet taking off	150	1 quadrillion	
Jackhammer	130	10 trillion	
Rock concert, automobile horn	120	1 trillion	Pain
Police siren, video arcade	110	100 billion	
Power lawn mower, loud music	100	10 billion	
Screaming baby	90	1 billion	Endangers hearing
Traffic on a busy street, alarm clock	80	100 million	Noisy
Vacuum cleaner	70	10 million	
Conversation	60	1 million	
Library	40	10,000	Quiet
Whisper	30	1000	Very quiet
Breathing	10	10	Just audible
	0	1	Hearing threshold



Catgut Acoustical Society, Inc.

Figure 16-4 The vibrations in the body of the violin are made visible by holographic techniques.

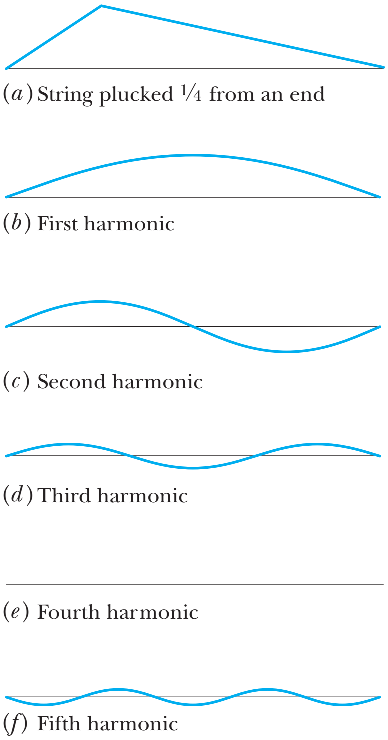


Figure 16-5 The shape of the plucked string (a) is the superposition of the first five harmonics (b–f). Note that the fourth harmonic does not contribute to this particular shape.

sound. Figure 16-4 shows a variety of vibrations produced in a violin's body by its vibrating strings. The design of the instrument produces variations in the instrument's vibrational patterns and thus changes the character of the sound produced. There was something special about the way Antonio Stradivari made his violins that made their sound more pleasing than others.

Modern electric guitars do not use the body of the instrument to transmit the vibrations of the strings to the air. The motions of the vibrating strings are converted to oscillating electric signals by pickup coils mounted under the strings. This signal is then amplified and sent to the speakers.

Whether acoustic or electric, plucking a guitar string creates vibrations. This initial distortion causes waves to travel in both directions along the string and reflect back and forth from the fixed ends. The initial shape of the string is equivalent to a unique superposition of many harmonic waves. Figure 16-5 shows the shape of a plucked string at the moment of release and the contributions of the first five harmonics. (For this particular shape, the fourth harmonic is zero everywhere and does not contribute.)

These harmonic waves travel back and forth on the string, creating standing waves with nodes at the two ends of the string. The first three standing waves are shown in Figure 16-6. Because the distance between nodes is one-half the wavelength, the wavelength of the fundamental, or first harmonic (a), is twice as long as the string, or $\lambda_1 \times 2L$. The wavelength of the second harmonic (b) is $\lambda_2 = L$, the length of the string, and therefore half as long as that of the fundamental. The wavelength of the third harmonic (c) is $\lambda_3 = \frac{2}{3}L$, one-third of the fundamental wavelength.

harmonic wavelengths $\lambda_1, \frac{\lambda_1}{2}, \frac{\lambda_1}{3}, \ldots$ ▶

Are You On the Bus?

Q: What is the wavelength corresponding to the third harmonic on a 60-centimeter-long wire?

A: It must be one-third the length of the fundamental wavelength. Because the fundamental wavelength is twice the length of the string, we obtain 2(60 centimeters)/3 = 40 centimeters.

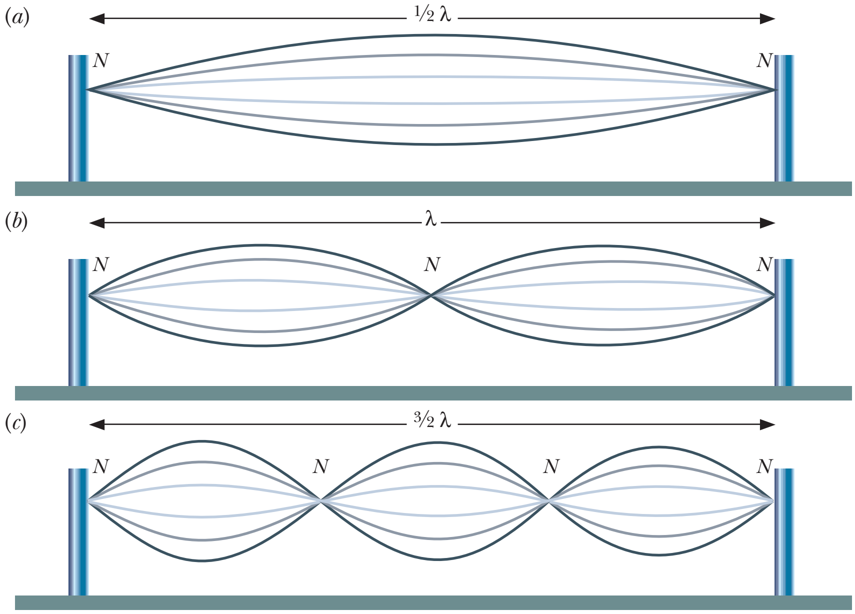


Figure 16-6 The first three standing waves on a guitar string. The wavelengths of these harmonics are $2L$, L, and $\frac{2}{3}L$, respectively.

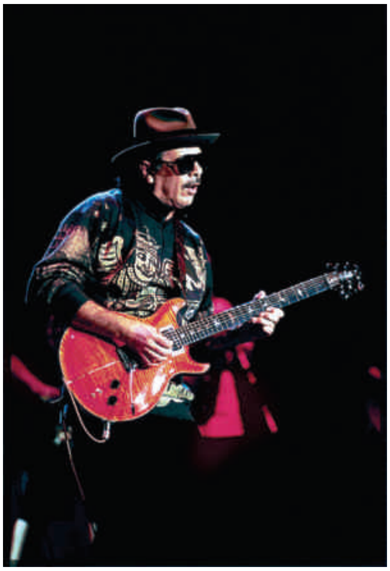
The frequencies of the various harmonics can be obtained from the relationship for the wave's speed, $v = \lambda f$. As long as the vibrations are small, the speeds of the different waves on the plucked string are all the same. Therefore, $v = \lambda_1 f_1 = \lambda_2 f_2 = \lambda_3 f_3 = \ldots$ Because the second harmonic has half the wavelength, it must have twice the frequency. The third harmonic has one-third the wavelength and three times the frequency. The harmonic frequencies are whole-number multiples of the fundamental frequency.

◀ harmonic frequencies $f_1, 2f_1, 3f_1, \ldots$

There is a simple way to verify that more than one standing wave is present on a vibrating string. By lightly touching the string in certain places, particular standing waves can be damped out and thus make others more obvious. For example, suppose you touch the center of the vibrating guitar string. We can see from Figure 16-6(a) that the fundamental will be damped out because it has an antinode at the middle. The second harmonic, however, has a node at the middle [Figure 16-6(b)], so it is unaffected by your touch. The third harmonic is damped because it also has an antinode at the middle of the string. In fact, all odd-numbered harmonics are damped out, and all even-numbered ones remain.

When you do this experiment, you hear a shift in the lowest frequency. With the initial pluck, the fundamental is the most prominent frequency. After touching the middle of the string, the fundamental is gone, so the lowest frequency is now that of the second harmonic, a frequency twice the original frequency. In musical terms we say that the note shifts upward by one octave. You can find the higher harmonics by plucking the string again and gently touching it $\frac{1}{3}, \frac{1}{4}, \frac{1}{5}, \ldots$ of the way from one end.

Music, of course, consists of many notes. The string we have been discussing can play only one note at a time because the fundamental frequency determines the musical note. Instruments must be able to play many different frequencies to be useful. To play other notes, we must have more strings or a simple way of changing the vibrational conditions on the string. Most stringed instruments use similar methods for achieving different notes. Pianos, harps, and harpsichords have many strings. Striking or plucking different strings produces different notes.



Guitarist Carlos Santana changes notes by pushing the strings against the frets to shorten the lengths that vibrate.

Q: What are the different ways to increase the fundamental frequency of a note played on a guitar string?

A: To increase the fundamental frequency of a note on a guitar string, you can increase the tension, finger the string, or use a string with less mass per unit length.

Figure 16-7 The note played by this one-string bass is changed by varying the tension (and thus the wave speed) in the string.

A guitar usually has six strings, some more massive than others to extend the range of frequencies. Still, only six strings aren't enough to produce many interesting songs. A guitarist must be able to change the note produced by each string. By fingering the string the guitarist shortens the vibrating portion of the string, creating new conditions for standing waves. The new fundamental wavelength is now twice this *shortened* length and therefore smaller than before. This smaller wavelength produces a higher frequency.

The guitarist can change the speed of the waves by changing the tension of the string. An increase in the tension increases the speed and therefore increases the frequency. It takes too long to change the tension in the middle of a song, so changes in tension are only used to tune the instruments. An exception is the "washtub bass" shown in Figure 16-7.

Wind Instruments

Wind instruments—such as clarinets, trumpets, and organ pipes—are essentially containers for vibrating columns of air. Each has an open end that transmits the sound and a method for exciting the air column. With the exception of the organ pipe, wind instruments also have a method for altering the fundamental frequency. In many ways wind instruments are analogous to stringed instruments. A spectrum of initial waves is created by a disturbance. The instrument governs the standing waves that are generated; all other frequencies are quickly damped out. The sound we hear is a combination of the frequencies of these standing waves.

Figure 16-8 A drawing of a longitudinal sound wave. The dark regions represent compressions (high density); the lighter regions represent rarefactions (low density).

But there are three main differences between wind and string instruments. First, unlike vibrating strings, the vibrational characteristics of air cannot be altered to change the speed of the waves. Only the length of the vibrating air column can be changed. Second, a string has a node at each end, but there is an antinode near the open end of the wind instrument. At an antinode the vibration of the air molecules is a maximum. A node occurs at the closed end, where there is no vibration of the air molecules. Finally, the disturbance in wind instruments produces longitudinal waves in the air column instead of the transverse waves of the stringed instruments. A longitudinal wave at a single moment is represented in Figure 16-8.

Drawing longitudinal standing waves is difficult because the movement of the air molecules is along the length of the pipe. If we draw them in this manner for even one period, crests and troughs overlap and produce a confusing drawing. When illustrating longitudinal waves in a windpipe, we normally draw them as if the air movements were transverse. This should not be overly confusing as long as you remember that these drawings are basically graphs of the displacements of the air molecules versus position. In Figure 16-9 two curves are drawn to represent the range of displacement of the standing waves. Note that the curves meet at the closed end of the pipe. There is a node at that spot, indicating that the air molecules near the wall do not move.

Consider a closed organ pipe—one that is closed at one end and open at the other. The largest wavelength that produces a node at the closed end and an antinode at the open end is four times the length of the pipe, or $4L$. This is

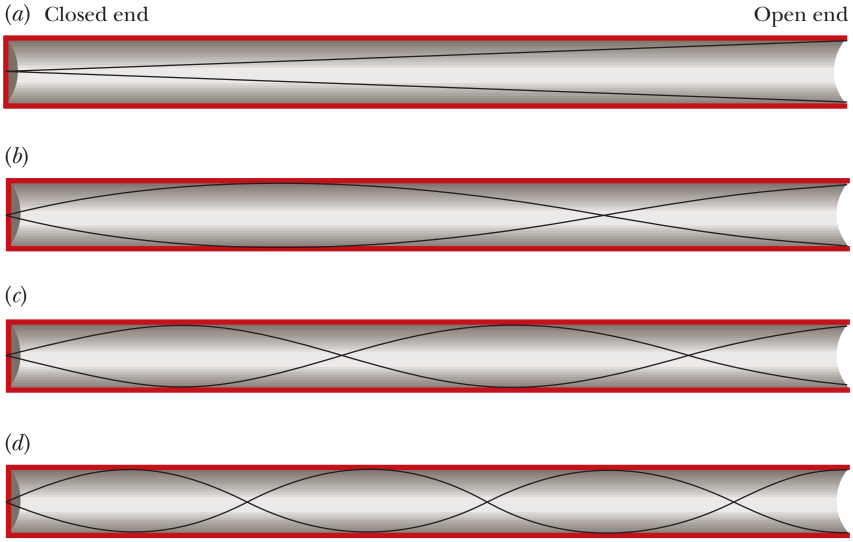


Figure 16-9 Graphs of the first four standing waves in a closed organ pipe. Note that there is a node at the closed end and an antinode at the open end.

illustrated in Figure 16-9(a). The next-smaller wavelength [Figure 16-9(b)] is four-thirds the length of the pipe, or $\frac{4}{3}L$; and the wavelength in Figure 16-9(c) is four-fifths the length of the pipe, or $\frac{4}{5}L$.

As with the stringed instruments, we can generate a relationship among the various frequencies by examining the relationship between the wave's speed, its wavelength, and its frequency: $v = \lambda f$. The possible wavelengths are 1, $\frac{1}{3}$, $\frac{1}{5}$, $\frac{1}{7}$, . . . times the fundamental wavelength. Because the wave speeds are constant, the corresponding frequencies are 1, 3, 5, 7, . . . times the fundamental frequency.

Q: What is the wavelength corresponding to the fifth harmonic in a 50-centimeter-long closed organ pipe?

A: It must be one-fifth the length of the fundamental wavelength. Because the fundamental wavelength is four times the length of the pipe, we obtain 4(50 centimeters)/5 = 40 centimeters.

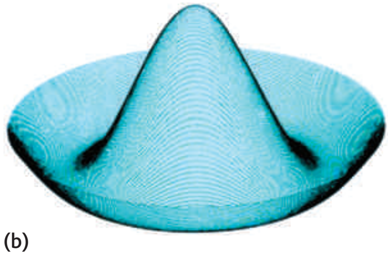
The closed organ pipe does not have resonant frequencies that are 2, 4, 6, . . . times the fundamental frequency; the even-numbered harmonics are missing because these frequencies would not produce a node at the closed end and an antinode at the open end. On the other hand, the open organ pipe (one that is open at both ends) has all harmonics.

Percussion Instruments

Percussion instruments are characterized by their lack of the harmonic structure of the string and wind instruments. Percussionists employ a wide range of instruments, including drums, cymbals, bells, triangles, gongs, and xylophones. Although all of these resonate at a variety of frequencies, the higher frequencies are not whole-number multiples of the lowest frequency.

Each of the percussion instruments behaves in a different way. The restoring force in a drum is provided by the tension in the drumhead. The two-dimensional standing-wave patterns are produced by the reflection of transverse waves from the edges of the drum and are characterized by nodal lines. These

(a)



(b)

(c)

(d)

Figure 16-10 A circular drumhead can vibrate in many different modes with nonharmonic frequencies.

WORKING IT OUT *Organ Pipe*

An organ pipe is found to produce resonances at 150 Hz and 250 Hz but at no frequency in between. Is this an open pipe or a closed pipe? What is the pipe's length?

There is no formula to answer the first part of this question. What we have to ask is whether this appears to be part of a series of all multiples of a single frequency or just the odd multiples. The highest frequency that goes evenly into both values is 50 Hz. An open pipe with a 50-Hz fundamental would produce 100 Hz, 150 Hz, 200 Hz, 250 Hz, and so on. Even though it would produce the two required frequencies, it would also produce a resonance at 200 Hz, which we know doesn't exist in this pipe. A closed pipe would produce 50 Hz, 150 Hz, 250 Hz, 350 Hz, and so on, as required. This is therefore a closed organ pipe with a fundamental frequency of 50 Hz. To find the tube's length, we begin by using the wave equation to find the wavelength:

$$\lambda = v/f$$

$$\lambda = \frac{343 \text{ m/s}}{50 \text{ Hz}} = 6.86 \text{ m}$$

At the fundamental frequency, only one-quarter of a wavelength fits in the pipe, so the length of the organ pipe must be

$$L = \lambda/4 = 1.7 \text{ m}$$

nodal lines are the two-dimensional analogs of the nodal points in vibrating strings.

The nodal lines for a circular membrane are either along a diameter or circles about the center; there is always a nodal line around the edge of the drumhead. Figure 16-10(a) shows the fundamental mode, in which the center of the drumhead moves up and down symmetrically. Figure 16-10(c) shows a mode with an antinodal line along a diameter. When one-half of the drumhead is up, the other half is down. This mode has a frequency 1.593 times that of the fundamental frequency. The second symmetric mode is shown in Figure 16-10(b) and has a frequency 2.295 times the fundamental frequency.

Beats

When we listen to two steady sounds with nearly equal frequencies, we hear a periodic variation in the volume. This effect is known as **beats** and should not be confused with the rhythm of the music that you may dance to; beats are the result of the superposition of the two waves. Because the two waves have different frequencies, there are times when they are in step and add together and times when they are out of step and cancel. The result is a periodic cancellation and reinforcement of the waves that is heard as a periodic variation in the loudness of the sound.

This is illustrated by the drawings in Figure 16-11. It is important to realize that these drawings do not represent strobe pictures of the waves. The horizontal line represents time, not position. The drawings represent the variation in the amplitude of the sound at a single location—for instance, as it reaches one of your ears. Figures 16-11(a) and (b) show each wave by itself, and Figure 16-11(c) shows the superposition of these two waves. Your ears hear a frequency that is the average of the two frequencies, and that varies in amplitude with a beat frequency.

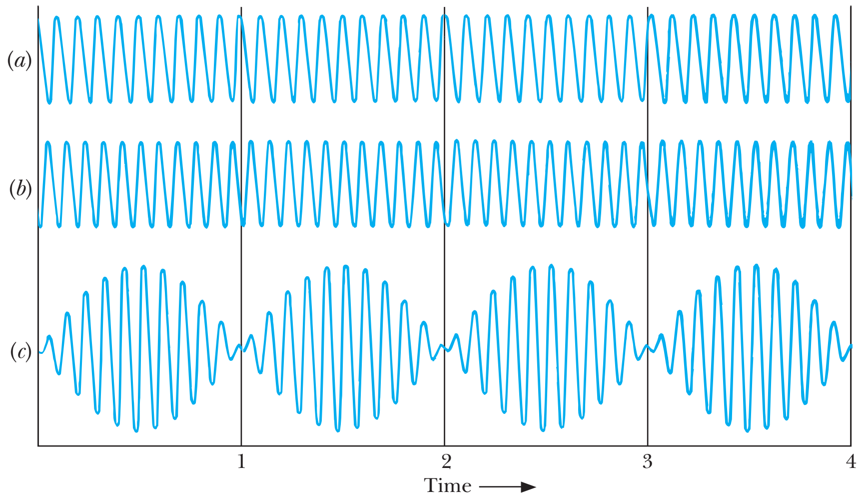


Figure 16-11 The superposition of two sound waves of different frequencies produces a sound wave (c) that varies in amplitude.

We can obtain the beat frequency by examining Figure 16-11. If the time between vertical lines is 1 second, wave (a) has a frequency of 10 hertz and wave (b) 11 hertz. At the beginning of a second, a crest from wave (a) cancels a trough from wave (b), and the sound level is zero. Wave (a) has a lower frequency and continually falls behind. At the end of 1 second, it has fallen an entire cycle behind, and the waves once again cancel. The difference of 1 hertz in their frequencies shows up as a variation in the sound level that has a frequency of 1 hertz. This same process is valid for any frequencies that differ by 1 hertz. For example, the beat frequency produced when two sound waves of 407 hertz and 408 hertz are combined is also 1 hertz.

If the frequencies differ by 2 hertz, it takes only $\frac{1}{2}$ second for the lower-frequency wave to fall one cycle behind. Therefore, this pattern happens two times per second, or with a beat frequency of 2 hertz. This reasoning can be generalized to show that the beat frequency is equal to the difference in the two frequencies.

◀ beat frequency = Δf

Piano tuners employ this beat phenomenon when tuning pianos. The tuner produces the desired frequency by striking a tuning fork and then adjusts the piano wire's tension until the beats disappear. Modern electronics have now made it possible for a tone-deaf person to make a living tuning pianos.

WORKING IT OUT *Beats*

You play an unknown tuning fork alongside a 440-Hz tuning fork. The resulting sound has a beat frequency of 3 Hz. You then play the unknown alongside a 445-Hz tuning fork and hear a beat frequency of 8 Hz. What is the frequency of the unknown tuning fork?

We can reason the solution based on the idea that the beat frequency is the difference in the two source frequencies. From the first experiment we know that the unknown tuning fork must be different from 440 Hz by 3 Hz. The choices are 437 Hz and 443 Hz. Clearly, the first experiment does not provide enough information to answer the question. The second experiment tells us that the unknown tuning fork must be different from 445 Hz by 8 Hz. The choices are 437 Hz and 453 Hz. The choice that is consistent with both experiments is 437 Hz.

Q: Why don't we hear beats when adjacent keys on a piano are hit at the same time?

A: The beats do exist, but the beat frequency is too high for us to notice.

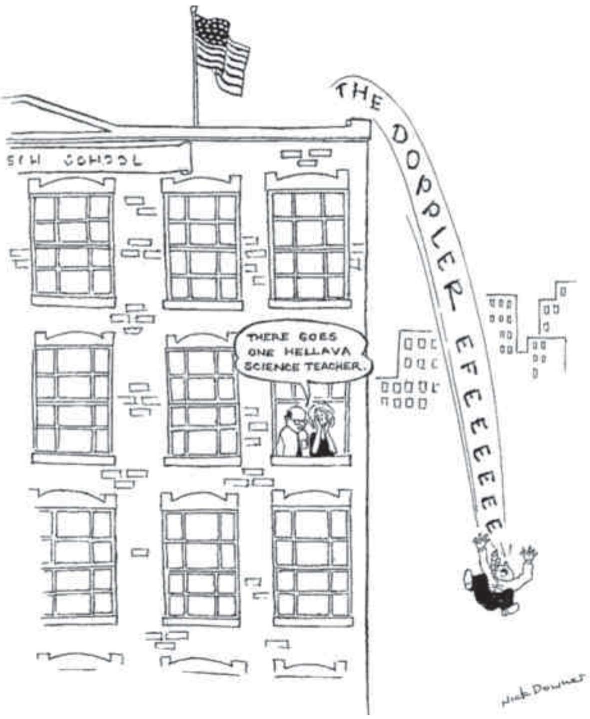
Doppler Effect

What we hear is not necessarily the sound that was originally produced, even when only a single source is involved. Recall the sound of a car as it passes you. This variation in sound is especially noticeable with race cars and some motorcycles because they emit distinctive roars. Imagine standing by the side of a road as a car passes you with its horn blasting constantly. Two things about the horn's sound change. First, as the car approaches, its sound gets progressively louder; as it leaves, the sound gets quieter. The volume changes simply because the wave spreads out as it moves away from the source. If you are far from the source, the energy of the sound waves intercepted by your ears each second is smaller.

The second change in the sound of the horn may not be as obvious. The frequency *that you hear* is not the same as the frequency that is actually emitted by the horn. The frequency you hear is higher as the car approaches you and lower as the car recedes from you. This shift in frequency due to the motion is called the **Doppler effect,** after the Austrian physicist and mathematician Christian Doppler.

The pitch of the sound we hear is determined by the frequency with which crests (or troughs) hit our ears. Our ears are sensitive to the frequency of a wave, not to the wavelength. Figure 16-12 shows a two-dimensional drawing of sound waves leaving a tuning fork. A small portion of the sound is intercepted by the ear. If the tuning fork and the ear are stationary relative to each other, the frequency heard is the same as that emitted.

When the tuning fork is moving, the listener hears a different frequency. Because the tuning fork moves during the time between the generation of one crest and the next, the sound waves crowd together in the forward direction and spread out in the backward direction, as shown in Figure 16-13. If the tun-



Q: If you were flying a model airplane on a wire so that it traveled in circles about you, would you hear a Doppler shift?

A: Because the airplane is not moving toward or away from you, you would not hear a Doppler shift. However, someone standing off to the side watching you would hear a Doppler shift.

Are You On the Bus?

ing fork moves toward the listener, the ear detects the sound waves that are crowded together. The frequency with which the waves hit the ear is therefore higher than was actually emitted by the source. Similarly, if the tuning fork moves away from the listener, the observed frequency is lower.

Notice, however, that in both Figures 16-12 and 16-13 the spacings do not change with the separation of the source and receiver. Because the shift does not depend on the distance, the Doppler-shifted frequency does not change as the source gets closer or farther away.

We will see in later chapters that the Doppler effect also occurs for light. The observation that the light from distant galaxies is shifted toward lower frequencies (their colors are *redshifted*) tells us that they are moving away from our Galaxy and that the universe is expanding.

The Doppler effect also occurs when the receiver moves and the source is stationary. If the listener moves toward a stationary tuning fork, her ear intercepts wave crests at a higher rate, and she hears a higher frequency. If she recedes from the tuning fork, the crests must continually catch up with her ear, which therefore intercepts the crests at a reduced rate, and she consequently hears a lower frequency. Notice that the shift in the frequency is still constant over time as long as the velocities are constant. Of course, the loudness of the signal decreases as the distance to the tuning fork increases.

When a wave bounces off a moving object, it experiences a similar Doppler shift in frequency due to successive crests (or troughs) having longer or shorter distances to travel before reflecting. By monitoring these frequency shifts, we can determine the speed of objects toward or away from the original source. Because the Doppler effect occurs for all kinds of waves, this technique is used in many situations, such as catching speeding motorists using radar (an electromagnetic wave) and monitoring the movement of dolphins using sound waves in water.

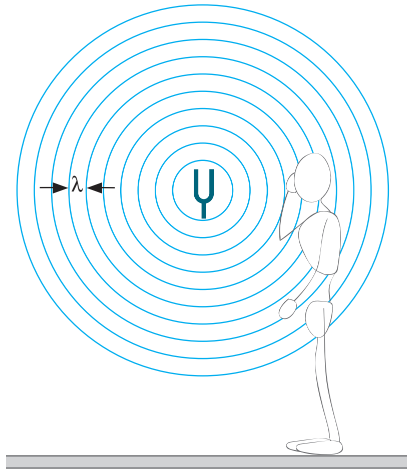


Figure 16-12 If the source and the ear are stationary relative to each other, the ear hears the same frequency as emitted by the source.

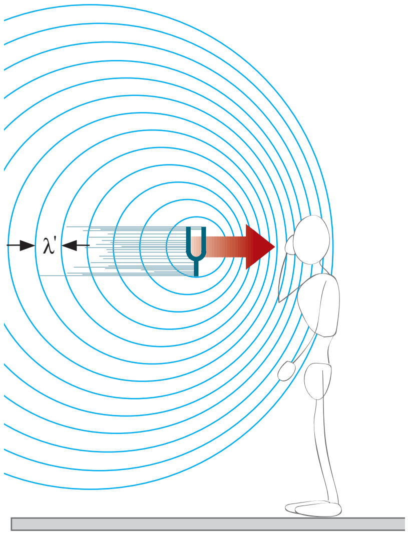


Figure 16-13 If the source of sound moves toward the right, the waves bunch up on the right-hand side and spread out on the left-hand side. The person hears a frequency that is higher than that emitted by the source.

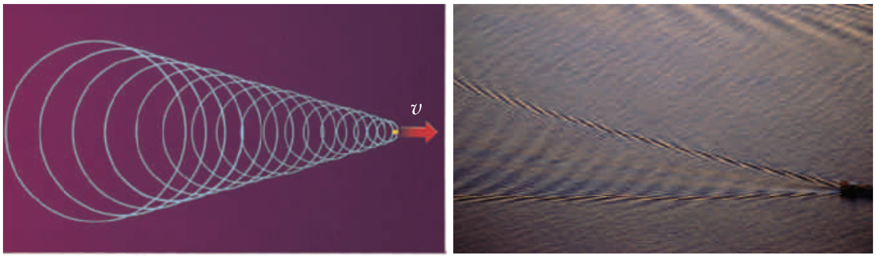
FLAWED REASONING

The following question appears on the final exam: "You and a friend are standing a city block apart. An ambulance with its siren blaring drives down the street toward you and away from your friend. The ambulance passes you and continues down the street at a constant speed. Is the frequency that you hear higher than, lower than, or the same as the frequency your friend hears?"

Matt gives the following answer to this question: "According to the Doppler shift, as the siren gets farther away, the wavelengths get farther apart. The longer the wavelength, the lower the frequency. I will therefore hear a higher frequency than my friend."

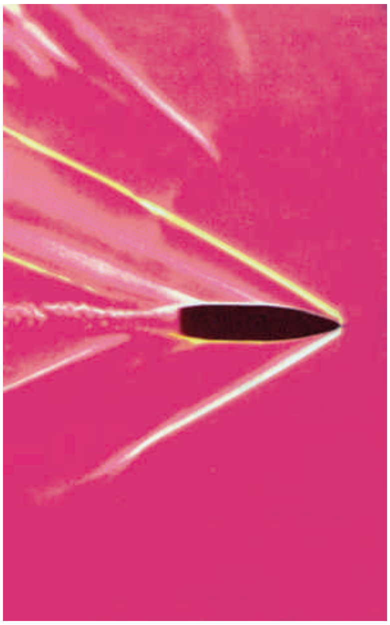
What is wrong with Matt's reasoning, and what is the correct answer to the exam question?

ANSWER The Doppler shift does not depend on the distance to the source. The shift in frequency depends only on the velocity of the source relative to the observer. The ambulance is moving away from both of you with the same speed. Therefore, both of you will hear the same lower frequency, but the siren will be louder to you.



(a) (b)

Figure 16-14 (a) When the source moves faster than the speed of sound, the waves form a cone known as the shock wave. (b) The presence of the bow wave (analogous to a shock wave) indicates that the canoe is traveling faster than the speed of the water waves.



A stroboscopic photograph of a bullet traveling through the hot air above a candle. The formation of the shock wave tells us that the bullet was traveling faster than the speed of sound.

Shock Waves

When a source of waves moves faster than the speed of the waves in the medium, the next crest is generated in front of the leading edge of the previous crest. This causes the expanding waves to superimpose and form the conical pattern shown in Figure 16-14(a). The amplitude along the cone's edge can become very large because the waves add together with their crests lined up. The edge of the cone is known as a **shock wave** because it arrives suddenly and with a large amplitude.

Shock waves are common in many media. When speedboats go much faster than the speed of the water waves, they create shock waves commonly known as wakes. The Concorde, a supersonic plane, travels much faster than the speed of sound in air and therefore produces shock waves. Some people are concerned about the effects of the sonic boom when the edge of the pressure cone reaches the ground.

The return of a space shuttle to Earth produces a double sonic boom. The nose produces one boom, and the engine housings near the rear of the spacecraft produce the other. Listen for this the next time you watch a television broadcast of a shuttle returning.

Are You On the Bus?

Q: Would you expect a spacecraft traveling to the Moon to produce a shock wave during its entire trip?

A: No. Because there is no air in most of the space between Earth and the Moon, the spacecraft would not produce any sound.

Summary

Sound is a longitudinal wave that travels through a variety of media. The speed of sound is 343 meters per second in air at room temperature, four times as fast in water, and more than ten times as fast in solids. In a gas the speed of sound depends on the temperature (slower at lower temperatures) and the type of gas (faster in molecules with less mass).

Ears detect sound waves and send electric signals to the brain. The range of frequencies that can be detected depends on the resonant structures in the animals' ears. The audible range in humans is roughly 20–20,000 hertz, although it varies with age and the individual.

You can recognize different sources of sound because each source produces a unique combination of intensities of the various harmonics—its own recipe of harmonics.

Music generally differs from other sounds in its periodicity. Nearly all musical instruments—string, wind, or percussion—involve the production of stand-