### Differentiated Instruction

<table>
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<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Level 1 activities should be appropriate for students with learning difficulties.</td>
</tr>
<tr>
<td>L2</td>
<td>Level 2 activities should be within the ability range of all students.</td>
</tr>
<tr>
<td>L3</td>
<td>Level 3 activities are designed for above-average students.</td>
</tr>
</tbody>
</table>

### Section/Objectives

**Chapter Opener**

See page 14T for a key to the standards.

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<th>Section/Objectives</th>
<th>Standards</th>
<th>Lab and Demo Planning</th>
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<td><strong>Section 15.1</strong></td>
<td>UCP.1, UCP.2, UCP.3, A.1, A.2, B.6, C.3, C.6, D.3, D.4, E.1, F.1, F.6, G.1, G.3</td>
<td><strong>Student Lab:</strong> Launch Lab, p. 403: stemmed glasses of assorted thickness and stem height, tumblers, water. <strong>Additional Mini Lab,</strong> p. 406: penny, nickel, dime, quarter. <strong>Teacher Demonstration:</strong> Quick Demo, p. 408: foam ball, electronic buzzer (oscillator), batteries.</td>
</tr>
<tr>
<td>1. Demonstrate the properties that sound shares with other waves.</td>
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<tr>
<td>2. Relate the physical properties of sound waves to our perception of sound.</td>
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<tr>
<td>3. Identify some applications of the Doppler effect.</td>
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<td><strong>Section 15.2</strong></td>
<td>UCP.1, UCP.2, UCP.3, A.1, A.2, B.6, D.4, E.1, E.2</td>
<td><strong>Student Lab:</strong> Mini Lab, p. 418: wind instrument, meter measuring tape, frequency generator. <strong>Physics Lab,</strong> pp. 420–421: three tuning forks of known frequencies, graduated cylinder (1000-mL), water, tuning fork mallet, metric ruler, thermometer (nonmercury), glass tube (approximately 40 cm in length and 3.5 cm in diameter). <strong>Teacher Demonstration:</strong> Quick Demo, p. 415: 50- to 200-cm length of 10- to 15-mm-diameter aluminum rod, rosin.</td>
</tr>
<tr>
<td>4. Describe the origin of sound.</td>
<td></td>
<td></td>
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<tr>
<td>5. Demonstrate an understanding of resonance, especially as applied to air columns and strings.</td>
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<tr>
<td>6. Explain why there are variations in sound among instruments and among voices.</td>
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</table>
### Reproducible Resources and Transparencies

**FAST FILE Chapters 11–15 Resources, Chapter 15**
- Transparency 15-1 Master, p. 157
- Transparency 15-2 Master, p. 159
- Study Guide, pp. 145–150
- Section 15-1 Quiz, p. 151

**Teaching Transparency 15-1**

**Teaching Transparency 15-2**

**Connecting Math to Physics**

### Technology

**TeacherWorks™ includes:** Interactive Teacher Edition ■ Lesson Planner with Calendar ■ Access to all Blacklines ■ Correlation to Standards ■ Web links

### Fast File Chapters 11–15 Resources, Chapter 15

**FAST FILE Chapters 11–15 Resources, Chapter 15**
- Transparency 15-3 Master, p. 161
- Transparency 15-4 Master, p. 163
- Transparency 15-5 Master, p. 165
- Study Guide, pp. 145–150
- Reinforcement, pp. 153–154
- Enrichment, pp. 155–156
- Section 15-2 Quiz, p. 152
- Mini Lab Worksheet, p. 139
- Physics Lab Worksheet, pp. 141–144

**Teaching Transparency 15-3**

**Teaching Transparency 15-4**

**Teaching Transparency 15-5**

**Connecting Math to Physics**

**Laboratory Manual, pp. 77–84**

**Probeware Laboratory Manual, pp. 29–32**

### Technology

- **Interactive Chalkboard CD-ROM:** Section 15.1 Presentation
- **TeacherWorks™ CD-ROM**
- **Problem of the Week at physicspp.com**

### Assessment Resources

**FAST FILE Chapters 11–15 Resources, Chapter 15**
- Chapter Assessment, pp. 167–172
- Additional Challenge Problems, p. 15
- Physics Test Prep, pp. 29–30
- Pre-AP/Critical Thinking, pp. 29–30
- Supplemental Problems, pp. 29–30

**Technology**
- **Interactive Chalkboard CD-ROM:** Chapter 15 Assessment
- **ExamView® Pro Testmaker CD-ROM**
- **Vocabulary PuzzleMaker**
- **TeacherWorks™ CD-ROM**
- **physicspp.com**
Chapter Overview

Sound is a pressure variation that travels as a longitudinal wave. This chapter examines sound characteristics, such as direction, pitch, loudness, and speed. The chapter then links physics and music by discussing resonance in air columns and on strings. The chapter closes with a discussion of sound quality, sound reproduction, and noise.

Think About This

Musical instruments generate sound in a variety of ways. Wind instruments produce sound by causing a column of air to vibrate, percussion instruments make a surface vibrate, and, in a stringed instrument, both the strings and a resonating surface vibrate. For more details, see p. 411. The differences in the sounds made by the instruments are related to the pattern of the sound waves they form. For more details, see pp. 415 to 417.

Key Terms

- sound wave, p. 404
- pitch, p. 406
- loudness, p. 406
- sound level, p. 406
- decibel, p. 406
- Doppler effect, p. 407
- closed-pipe resonator, p. 412
- open-pipe resonator, p. 412
- fundamental, p. 417
- harmonics, p. 417
- dissonance, p. 418
- consonance, p. 418
- beat, p. 418

What You’ll Learn

- You will describe sound in terms of wave properties and behavior.
- You will examine some of the sources of sound.
- You will explain properties that differentiate between music and noise.

Why It’s Important

Sound is an important means of communication and, in the form of music, cultural expression.

Musical Groups A small musical group might contain two or three instruments, while a marching band can contain 100 or more. The instruments in these groups form sounds in different ways, but they can create exciting music when they are played together.

Think About This

How do the instruments in a musical group create the sounds that you hear? Why do various instruments sound different even when they play the same note?

Purpose
to introduce the production of sound waves by a vibrating edge

Materials stemmed glasses of assorted thickness and stem height, tumblers, water

Teaching Strategies

- Allow students time to practice; initially not everyone will be able to make the glass vibrate.

CAUTION: Glass is fragile and should be handled with care.
15.1 Properties and Detection of Sound

Sound is an important part of existence for many living things. Animals can use sound to hunt, attract mates, and warn of the approach of predators. In humans, the sound of a siren can heighten our awareness of our surroundings, while the sound of music can soothe and relax us. From your everyday experiences, you already are familiar with several of the characteristics of sound, including volume, tone, and pitch. Without thinking about it, you can use these, and other characteristics, to categorize many of the sounds that you hear; for example, some sound patterns are characteristic of speech, while others are characteristic of a musical group. In this chapter, you will study the physical principles of sound, which is a type of wave.

In Chapter 14, you learned how to describe waves in terms of speed, frequency, wavelength, and amplitude. You also discovered how waves interact with each other and with matter. Knowing that sound is a type of wave allows you to describe some of its properties and interactions. First, however, there is a question that you need to answer: exactly what type of wave is sound?

**Objectives**
- Demonstrate the properties that sound shares with other waves.
- Relate the physical properties of sound waves to our perception of sound.
- Identify some applications of the Doppler effect.

**Vocabulary**
- sound wave
- pitch
- loudness
- sound level
- decibel
- Doppler effect

**Expected Results**

Stemmed glasses will vibrate very well and produce ringing tones. Flat-bottomed glasses probably will not produce tones because they rest directly on the counter, which absorbs vibrational energy. Students will find that their fingers alternately slip and stick along the rim, setting up a standing wave in the glass.

**Analysis**

Students should indicate that the stemmed glasses produce a ringing tone. Various factors will affect the tones, including the speed at which the finger moves around the rim, the diameter of the glass, the length of the stem, and the amount of water in the glass. Additionally, the quality of the glass will affect the tone produced. Pressed glass will not ring.

**Critical Thinking**

Students will find that pouring a little water into the glasses will raise the pitch of the sound slightly, because that changes the size of the vibrating material. Students might suggest varying the thickness of the glass, the shapes of the bowls, and the heights of the stems.
Before the bell is struck, the air around it is a region of average pressure (a). Once the bell is struck, however, the vibrating edge creates regions of high and low pressure. The dark areas represent regions of higher pressure; the light areas represent regions of lower pressure (b). For simplicity, the diagram shows the regions moving in one direction; in reality, the waves move out from the bell in all directions.

Sound Waves

Put your fingers against your throat as you hum or speak. Can you feel the vibrations? Have you ever put your hand on the loudspeaker of a boom box? Figure 15-1 shows a vibrating bell that also can represent your vocal cords, a loudspeaker, or any other sound source. As it moves back and forth, the edge of the bell strikes the particles in the air. When the edge moves forward, air particles are driven forward; that is, the air particles bounce off the bell with a greater velocity. When the edge moves backward, air particles bounce off the bell with a lower velocity.

The result of these velocity changes is that the forward motion of the bell produces a region where the air pressure is slightly higher than average. The backward motion produces slightly below-average pressure. Collisions among the air particles cause the pressure variations to move away from the bell in all directions. If you were to focus at one spot, you would see the value of the air pressure rise and fall, not unlike the behavior of a pendulum. In this way, the pressure variations are transmitted through matter.

Describing sound

A pressure variation that is transmitted through matter is a sound wave. Sound waves move through air because a vibrating source produces regular variations, or oscillations, in air pressure. The air particles collide, transmitting the pressure variations away from the source of the sound. The pressure of the air oscillates about the mean air pressure, as shown in Figure 15-2. The frequency of the wave is the number of oscillations in pressure each second. The wavelength is the distance between successive regions of high or low pressure. Because the motion of the particles in air is parallel to the direction of the wave’s motion, sound is a longitudinal wave.

The speed of sound in air depends on the temperature, with the speed increasing by about 0.6 m/s for each 1°C increase in air temperature. At room temperature (20°C), sound moves through air at sea level at a speed of 343 m/s. Sound also travels through solids and liquids. In general, the speed of sound is greater in...
solids and liquids than in gases. Table 15-1 lists the speeds of sound waves in various media. Sound cannot travel in a vacuum because there are no particles to collide.

Sound waves share the general properties of other waves. For example, they reflect off hard objects, such as the walls of a room. Reflected sound waves are called echoes. The time required for an echo to return to the source of the sound can be used to find the distance between the source and the reflective object. This principle is used by bats, by some cameras, and by ships that employ sonar. Two sound waves can interfere, causing dead spots at nodes where little sound can be heard. As you learned in Chapter 14, the frequency and wavelength of a wave are related to the speed of the wave by the equation \( v = f \lambda \).

Detection of Pressure Waves

Sound detectors convert sound energy—the kinetic energy of the vibrating air particles—into another form of energy. A common detector is a microphone, which converts sound waves into electrical energy. A microphone consists of a thin disk that vibrates in response to sound waves and produces an electrical signal. You will learn about this transformation process in Chapter 25, during your study of electricity and magnetism.

**The human ear** As shown in Figure 15-3, the human ear is a detector that receives pressure waves and converts them to electrical impulses. Sound waves entering the auditory canal cause vibrations of the tympanic membrane. Three tiny bones then transfer these vibrations to fluid in the cochlea. Tiny hairs lining the spiral-shaped cochlea detect certain frequencies in the vibrating fluid. These hairs stimulate nerve cells, which send impulses to the brain and produce the sensation of sound.

The ear detects sound waves over a wide range of frequencies and is sensitive to an enormous range of amplitudes. In addition, human hearing can distinguish many different qualities of sound. Knowledge of both physics and biology is required to understand the complexities of the ear. The interpretation of sounds by the brain is even more complex, and it is not totally understood.

Identifying Misconceptions

**Pitch and Intensity**

**Relationship Demo** Ask students how they think the pitch of a tuning fork may change if its loudness decreases. Some student responses may reveal the misconception that the pitch will decrease. Address this misconception by first matching the frequency of a struck tuning fork with that of a tone generator. Next, strike the tuning fork and decrease the intensity of the tone generator so that it matches the tuning fork as the fork’s intensity fades. Students should notice that the pitch does not decrease.

**Reinforcement**

**Properties of Longitudinal Waves** Have students diagram how the motion of the particles of the medium through which a sound wave moves indicates that it is a longitudinal wave. The particles move back and forth, parallel to the direction of the wave.

| Table 15-1 Speed ofSound in Various Media |
|-------------------------------|------------------|
| **Medium** | **m/s** |
| Air (0°C) | 331 |
| Air (20°C) | 343 |
| Helium (0°C) | 972 |
| Water (25°C) | 1493 |
| Seawater (25°C) | 1533 |
| Copper (25°C) | 3560 |
| Iron (25°C) | 5130 |

**Pressure-Time Graphs** Point out that a sound wave is a pressure variation that is transmitted through matter and that the definition implies that pressure varies with time. Illustrate this implication by drawing a pressure-time graph representing the wave as a sine curve. Emphasize that the graph is like a movie of how the pressure varies at a single point along the path of the sound wave. Ask students what term describes the time interval for the movie to repeat itself, period. Show that a pressure-time graph yields the period of a sound wave.
Sound Characteristics

Purpose  to recognize physical factors that determine the sounds of dropped coins

Materials penny, nickel, dime, quarter

Procedure

1. With students in teams, have one lab partner drop each coin in any order.
2. Have the other student try to identify the sound of each coin with his or her eyes closed.

The dime has the highest-pitched sound and the quarter has the lowest-pitched sound. Each coin produces a characteristic sound.

Assessment  Have students compare physical factors that might affect the frequency of the sound made by each coin, such as geometry, material, and size.

Critical Thinking

Negative Sound Levels  Ask students to explain what a negative sound level, such as –10 dB, is. Start with 0 dB. Because decibels are measured relative to another sound, a measurement of 0 dB occurs when sound pressure is equal to the reference level. A negative sound level has a pressure that is smaller than the reference pressure.

Perceiving Sound

Pitch  Marin Mersenne and Galileo first determined that the pitch we hear depends on the frequency of vibration. Pitch can be given a name on the musical scale. For instance, the middle C note has a frequency of 262 Hz. The ear is not equally sensitive to all frequencies. Most people cannot hear sounds with frequencies below 20 Hz or above 16,000 Hz. Older people are less sensitive to frequencies above 10,000 Hz than are young people. By age 70, most people cannot hear sounds with frequencies above 8000 Hz. This loss affects the ability to understand speech.

Loudness  Frequency and wavelength are two physical characteristics of sound waves. Another physical characteristic of sound waves is amplitude. Amplitude is the measure of the variation in pressure along a wave. In humans, sound is detected by the ear and interpreted by the brain. The loudness of a sound, as perceived by our sense of hearing, depends primarily on the amplitude of the pressure wave.

The human ear is extremely sensitive to pressure variations in sound waves, which is the amplitude of the wave. Recall from Chapter 13 that 1 atm of pressure equals 1.01 × 10⁵ Pa. The ear can detect pressure-wave amplitudes of less than one-billionth of an atmosphere, or 2 × 10⁻⁵ Pa. At the other end of the audible range, pressure variations of approximately 20 Pa or greater cause pain. It is important to remember that the ear detects only pressure variations at certain frequencies. Driving over a mountain pass changes the pressure on your ears by thousands of pascals, but this change does not take place at audible frequencies.

Because humans can detect a wide range in pressure variations, these amplitudes are measured on a logarithmic scale called the sound level. The unit of measurement for sound level is the decibel (dB). A sound level depends on the ratio of the pressure variation of a given sound wave to the pressure variation in the most faintly heard sound, 2 × 10⁻⁵ Pa. Such an amplitude has a sound level of 0 dB. A sound with a pressure amplitude ten times larger (2 × 10⁻⁴ Pa) is 20 dB. A pressure amplitude ten times larger than this is 40 dB. Most people perceive a 10-dB increase in sound level as about twice as loud as the original level. Figure 15-4 shows the sound level for a variety of sounds. In addition to pressure variations, power and intensity of sound waves can be described by decibel scales.

Exposure to loud sounds, in the form of noise or music, has been shown to cause the ear to lose its sensitivity, especially to high frequencies. The longer a person is exposed to loud sounds, the greater the effect. A person can recover from short-term exposure in a period of hours, but the effects...
of long-term exposure can last for days or weeks. Long exposure to 100-dB or greater sound levels can produce permanent damage. Many rock musicians have suffered serious hearing loss, some as much as 40 percent. Hearing loss also can result from loud music being transmitted to stereo headphones from personal radios and CD players. In some cases, the listeners are unaware of just how high the sound levels really are. Cotton earplugs reduce the sound level only by about 10 dB. Special ear inserts can provide a 25-dB reduction. Specifically designed earmuffs and inserts as shown in Figure 15-5, can reduce the sound level by up to 45 dB.

Loudness, as perceived by the human ear, is not directly proportional to the pressure variations in a sound wave. The ear’s sensitivity depends on both pitch and amplitude. Also, perception of pure tones is different from perception of a mixture of tones.

The Doppler Effect

Have you ever noticed that the pitch of an ambulance, fire, or police siren changed as the vehicle sped past you? The pitch was higher when the vehicle was moving toward you, then it dropped to a lower pitch as the source moved away. This frequency shift is called the Doppler effect and is shown in Figure 15-6. The sound source, $S$, is moving to the right with a speed of $v_s$. The waves that it emits spread in circles centered on the source at the time it produced the waves. As the source moves toward the sound detector, Observer A in Figure 15-6a, more waves are crowded into the space between them. The wavelength is shortened to $\lambda_A$. Because the speed of sound is not changed, more crests reach the ear per second, which means that the frequency of the detected sound increases. When the source is moving away from the detector, Observer B in Figure 15-6a, the wavelength is lengthened to $\lambda_B$ and the detected frequency is lower. Figure 15-6b illustrates the Doppler effect for a moving source of sound on water waves in a ripple tank.

A Doppler shift also occurs if the detector is moving and the source is stationary. In this case, the Doppler shift results from the relative velocity of the sound waves and the detector. As the detector approaches the stationary source, the relative velocity is larger, resulting in an increase in the wave crests reaching the detector each second. As the detector recedes from the source, the relative velocity is smaller, resulting in a decrease in the wave crests reaching the detector each second.

Using Figure 15-6

Ask students how the wavelength of the sound wave detected by Observer A compares to the wavelength of the sound wave detected by Observer B. It is shorter. Have students relate the wavelength to the frequency of the sound wave striking each observer’s ear. Observer A detects a higher frequency than Observer B does. How does the pitch perceived by each observer compare to the pitch that would be heard if the same sound source were at rest? The pitch is higher for Observer A than when the sound source is at rest and is lower for Observer B. L2

Concept Development

Range of the Doppler Shift

Emphasize that the Doppler shift is used to measure the velocity of a source of either mechanical waves, such as sound, or electromagnetic waves, such as light, over a wide range of scale, from atoms to autos to galaxies.

Pressure-Position Graphs

Point out that the definition of a sound wave also implies that pressure varies with location. Illustrate this implication by drawing a pressure-position graph representing the wave as a sine curve, perhaps starting with an amplitude other than zero. Point out that this graph is a “snapshot” of the pressure along the path of the wave at one instant. Ask students what term describes the distance between locations that have identical snapshots. wavelength Show that a pressure-position graph yields the wavelength of a sound wave. L2
Doppler effect.

The source is an example of the Doppler effect caused by motion of the sound wave. The difference in pitch perceived by a detector is higher when the source is traveling toward the students than when it is traveling away.

Because the pitch of a sound wave is lower when the source is at rest once it is caught. Because the pitch is lower, they catch the ball. Point out that there is a slight decrease in the pitch as the ball is traveling away from the detector.

Procedure

Before the demonstration, assemble the buzzer and batteries. Hollow out the foam ball so that the buzzer and batteries fit snugly within. Turn on the buzzer and place it inside the ball. Toss the ball to a student and have the student note any changes in pitch as the ball is traveling toward or away from them. Students should note a slight decrease in the pitch as the ball is traveling away from the detector.

Materials

- Foam ball
- Electronic buzzer (oscillator)
- Batteries

Estimated Time

15 minutes

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Chapters 11–15 Resources

For both a moving source and a moving observer, the frequency that the observer hears can be calculated using the equation below.

\[
\text{Doppler Effect } \quad f_{d} = f_{s} \left( \frac{v - v_{d}}{v - v_{s}} \right)
\]

The frequency perceived by a detector is equal to the velocity of the detector relative to the velocity of the wave, divided by the velocity of the source relative to the velocity of the wave, multiplied by the wave’s frequency.

In the Doppler effect equation, \( v \) is the velocity of the sound wave, \( v_{d} \) is the velocity of the detector, \( v_{s} \) is the velocity of the sound’s source, \( f_{s} \) is the frequency of the wave emitted by the source, and \( f_{d} \) is the frequency received by the detector. This equation applies when the source is moving, when the observer is moving, and when both are moving.

As you solve problems using the above equation, be sure to define the coordinate system so that the positive direction is from the source to the detector. The sound waves will be approaching the detector from the source, so the velocity of sound is always positive. Try drawing diagrams to confirm that the term \( (v - v_{d})/(v - v_{s}) \) behaves as you would predict based on what you have learned about the Doppler effect. Notice that for a source moving toward the detector (positive direction, which results in a smaller denominator compared to a stationary source) and for a detector moving toward the source (negative direction and increased numerator compared to a stationary detector), the detected frequency, \( f_{d} \), increases. Similarly, if the source moves away from the detector or if the detector moves away from the source, then \( f_{d} \) decreases. Read the Connecting Math to Physics feature below to see how the Doppler effect equation reduces when the source or observer is stationary.

Reducing Equations

When an element in a complex equation is equal to zero, the equation might reduce to a form that is easier to use.

<table>
<thead>
<tr>
<th>Stationary detector, source in motion: ( v_{d} = 0 )</th>
<th>Stationary source, detector in motion: ( v_{s} = 0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{d} = f_{s} \left( \frac{v}{v - v_{s}} \right) )</td>
<td>( f_{d} = f_{s} \left( \frac{v}{v - v_{d}} \right) )</td>
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<tr>
<td>( = f_{s} \left( \frac{v}{v - v_{s}} \right) )</td>
<td>( = f_{s} \left( \frac{v}{v - v_{d}} \right) )</td>
</tr>
<tr>
<td>( = f_{s} \left( \frac{1}{1 - \frac{v_{d}}{v}} \right) )</td>
<td>( = f_{s} \left( \frac{1}{1 - \frac{v_{s}}{v}} \right) )</td>
</tr>
<tr>
<td>( = f_{s} \left( \frac{1}{1 - \frac{v_{d}}{v}} \right) )</td>
<td>( = f_{s} \left( \frac{1}{1 - \frac{v_{s}}{v}} \right) )</td>
</tr>
</tbody>
</table>

Early Warning System

The Chinese used pottery jars to detect the sounds of an advancing army. Leather membranes were stretched over the mouths of empty, 80-L pottery jars. The jars were lowered into deep shafts that were dug a few paces apart, and soldiers with good hearing were stationed near these shafts. Not only could the soldiers hear the sounds of an approaching army, but by listening to the different sounds from the shafts, they could judge from which direction the enemy was coming and from how far away. They could do this because the vibrations from the feet of the moving soldiers transferred to the earth and radiated in all directions, including to the pottery jars and their leather caps, which in turn vibrated and created sound.
The Doppler Effect A trumpet player sounds C above middle C (524 Hz) while traveling in a convertible at 24.6 m/s. If the car is coming toward you, what frequency would you hear? Assume that the temperature is 20°C.

1. **Analyze and Sketch the Problem**
   - Sketch the situation.
   - Establish a coordinate axis. Make sure that the positive direction is from the source to the detector.
   - Show the velocities of the source and detector.

   **Known:**
   - $v_s = +343$ m/s
   - $v_d = +24.6$ m/s
   - $v_d = 0$ m/s
   - $f_s = 524$ Hz

   **Unknown:**
   - $f_d = ?$

2. **Solve for the Unknown**
   Use $f_d = f_s \frac{v - v_d}{v - v_s}$ with $v_d = 0$ m/s.

   $f_d = f_s \left( \frac{1}{1 - \frac{v_d}{v}} \right)$

   $f_d = 524 \frac{1}{1 - \frac{24.6}{343}}$

   Substitute $v = +343$ m/s, $v_s = +24.6$ m/s, and $f_s = 524$ Hz

   $f_d = 564$ Hz

3. **Evaluate the Answer**
   - **Are the units correct?** Frequency is measured in hertz.
   - **Is the magnitude realistic?** The source is moving toward you, so the frequency should be increased.

---

**Practice Problems**

6. Repeat Example Problem 1, but with the car moving away from you. What frequency would you hear?

7. You are in an auto traveling at 25.0 m/s toward a pole-mounted warning siren. If the siren’s frequency is 365 Hz, what frequency do you hear? Use 343 m/s as the speed of sound.

8. You are in an auto traveling at 55 mph (24.6 m/s). A second auto is moving toward you at the same speed. Its horn is sounding at 475 Hz. What frequency do you hear? Use 343 m/s as the speed of sound.

9. A submarine is moving toward another submarine at 9.20 m/s. It emits a 3.50-MHz ultrasound. What frequency would the second sub, at rest, detect? The speed of sound in water is 1482 m/s.

10. A sound source plays middle C (262 Hz). How fast would the source have to go to raise the pitch to C sharp (271 Hz)? Use 343 m/s as the speed of sound.

---

**Sonic Booms** As can be seen in Figure 15-6 on page 407, the motion of a sound source distorts the sound wave leading it. When the sound source is moving faster than the speed of sound (supersonic speeds), a conical wave front called a shock wave is produced. The energy of the shock wave is concentrated at the surface of the cone and is the cause of a jet plane’s sonic boom. At a much smaller scale, the crack of a whip is also a sonic boom because the tip of the whip is moving faster than the speed of sound.
Because the Doppler shift occurs with light as well as sound, astronomers can note the change in the wavelength of light emitted by a distant, moving source. As a galaxy moves away from Earth, the apparent frequency of the light it emits decreases, and the wavelength increases. This is referred to as a redshift. The equivalent phenomenon in sound is more easily observed as a decrease in pitch.

The Doppler effect occurs in all wave motion, both mechanical and electromagnetic. It has many applications. Radar detectors use the Doppler effect to measure the speed of baseballs and automobiles. Astronomers observe light from distant galaxies and use the Doppler effect to measure their speeds and infer their distances. Physicians can detect the speed of the moving heart wall in a fetus by means of the Doppler effect in ultrasound. Bats use the Doppler effect to detect and catch flying insects. When an insect is flying faster than a bat, the reflected frequency is lower, but when the bat is catching up to the insect, as in Figure 15-7, the reflected frequency is higher. Not only do bats use sound waves to navigate and locate their prey, but they often must do so in the presence of other bats. This means they must discriminate their own calls and reflections against a background of many other sounds of many frequencies. Scientists continue to study bats and their amazing abilities to use sound waves.

15. Early Detection In the nineteenth century, people put their ears to a railroad track to get an early warning of an approaching train. Why did this work?

16. Bats A bat emits short pulses of high-frequency sound and detects the echoes.

a. In what way would the echoes from large and small insects compare if they were the same distance from the bat?

b. In what way would the echo from an insect flying toward the bat differ from that of an insect flying away from the bat?

17. Critical Thinking Can a trooper using a radar detector at the side of the road determine the speed of a car at the instant the car passes the trooper? Explain.
15.2 The Physics of Music

In the middle of the nineteenth century, German physicist Hermann Helmholtz studied sound production in musical instruments and the human voice. In the twentieth century, scientists and engineers developed electronic equipment that permits not only a detailed study of sound, but also the creation of electronic musical instruments and recording devices that allow us to listen to music whenever and wherever we wish.

Sources of Sound

Sound is produced by a vibrating object. The vibrations of the object create particle motions that cause pressure oscillations in the air. A loudspeaker has a cone that is made to vibrate by electrical currents. The surface of the cone creates the sound waves that travel to your ear and allow you to hear music. Musical instruments such as gongs, cymbals, and drums are other examples of vibrating surfaces that are sources of sound.

The human voice is produced by vibrations of the vocal cords, which are two membranes located in the throat. Air from the lungs rushing through the throat starts the vocal cords vibrating. The frequency of vibration is controlled by the muscular tension placed on the vocal cords.

In brass instruments, such as the trumpet and tuba, the lips of the performer vibrate, as shown in Figure 15-8a. Reed instruments, such as the clarinet and saxophone, have a thin wooden strip, or reed, that vibrates as a result of air blown across it, as shown in Figure 15-8b. In flutes and organ pipes, air is forced across an opening in a pipe. Air moving past the opening sets the column of air in the instrument into vibration.

In stringed instruments, such as the piano, guitar, and violin, wires or strings are set into vibration. In the piano, the wires are struck; in the guitar, they are plucked; and in the violin, the friction of the bow causes the strings to vibrate. Often, the strings are attached to a sounding board that vibrates with the strings. The vibrations of the sounding board cause the pressure oscillations in the air that we hear as sound. Electric guitars use electronic devices to detect and amplify the vibrations of the guitar strings.

1 FOCUS

Bellringer Activity
Straw Flutes Distribute a plastic soda straw to each student. Have students cut one end of the straw to a point and flatten this end by chewing on it gently. (This will result in a reedlike end on the straw.) With a little practice, students can blow on the reed and produce a musical tone. Have several students cut their straws shorter and then compare the tones they make with others in the class. Have students discuss how the straw might produce a sound and how the pitch of the sound relates to the length of the straw.

Tie to Prior Knowledge
Sound in Music Students apply their understanding of sound waves to the concept of resonance and to the properties of standing waves in air columns and on strings.
2 TEACH

Discussion

Question Ask students to classify musical instruments as closed-pipe or open-pipe resonators and to explain why.

Answer Although many instruments can be difficult to classify, the trumpet and flute are examples of open pipe resonators because both ends of these instruments are open, and the sound waves reflect off an open end and are inverted. A lip reed instrument, such as the clarinet, is a closed-pipe resonator because only one end of this instrument is open to air, while the reed end is (almost) closed to air. In these instruments, the closed end has a much smaller cross-section than the open end, which is enough to cause a reflection like that from a completely closed end. The pan pipe and didjeridu are other closed-pipe resonators. One of the oldest closed-pipe instruments is the conch shell. Playing a closed-pipe resonator is like blowing air into a bottle at the correct angle.

Identifying Misconceptions

Pipes and Air Columns Remind students that the standing waves in pipes occur in the column of air within the pipe and not in the material of which the pipe is made. Explain that the sound moves through the air because the vibrating source, such as a reed of an instrument, produces the regular oscillations in the air pressure. With every cycle of the wave, air rushes in and out of the ends of the pipe to create the compression and rarefaction for the wave.

Resonance in Air Columns

If you have ever used just the mouthpiece of a brass or reed instrument, you know that the vibration of your lips or the reed alone does not make a sound with any particular pitch. The long tube that makes up the instrument must be attached if music is to result. When the instrument is played, the air within this tube vibrates at the same frequency, or in resonance, with a particular vibration of the lips or reed. Remember that resonance increases the amplitude of a vibration by repeatedly applying a small external force at the same natural frequency. The length of the air column determines the frequencies of the vibrating air that will be set into resonance. For many instruments, such as flutes, saxophones, and trombones, changing the length of the column of vibrating air varies the pitch of the instrument. The mouthpiece simply creates a mixture of different frequencies, and the resonating air column acts on a particular set of frequencies to amplify a single note, turning noise into music.

A tuning fork above a hollow tube can provide resonance in an air column, as shown in Figure 15-9. The tube is placed in water so that the bottom end of the tube is below the water surface. A resonating tube with one end closed to air is called a closed-pipe resonator. The length of the air column is changed by adjusting the height of the tube above the water. If the tuning fork is struck with a rubber hammer and the length of the air column is varied as the tube is lifted up and down in the water, the sound alternately becomes louder and softer. The sound is loud when the air column is in resonance with the tuning fork. A resonating air column intensifies the sound of the tuning fork.

Standing pressure wave How does resonance occur? The vibrating tuning fork produces a sound wave. This wave of alternate high- and low-pressure variations moves down the air column. When the wave hits the water surface, it is reflected back up to the tuning fork, as indicated in Figure 15-10a. If the reflected high-pressure wave reaches the tuning fork at the same moment that the fork produces another high-pressure wave, then the emitted and returning waves reinforce each other. This reinforcement of waves produces a standing wave, and resonance is achieved.

An open-pipe resonator is a resonating tube with both ends open that also will resonate with a sound source. In this case, the sound wave does not reflect off a closed end, but rather off an open end. The pressure of the reflected wave is inverted; for example, if a high-pressure wave strikes the open end, a low-pressure wave will rebound, as shown in Figure 15-10b.

Resonance lengths A standing sound wave in a pipe can be represented by a sine wave, as shown in Figure 15-11. Sine waves can represent either the air pressure or the displacement of the air particles. You can see that standing waves have nodes and antinodes. In the pressure graphs, the nodes are regions of mean atmospheric pressure, and at the antinodes, the pressure oscillates between its maximum and minimum values.

Graphing Sound Waves Suggest that students use sound display equipment to show pressure-time representations of the sound waves of pure tones. The equipment might include a graphing calculator with CLB, oscilloscope tracings, or computer interfacing. Sources of pure tones might include tuning forks, tone generators, or certain toys. Have students analyze the graphs for period and frequency. Urge students to post the analyzed graphs in the classroom for classmates to inspect.
In the case of the displacement graph, the antinodes are regions of high displacement and the nodes are regions of low displacement. In both cases, two antinodes (or two nodes) are separated by one-half wavelength.

**Resonance frequencies in a closed pipe** The shortest column of air that can have an antinode at the closed end and a node at the open end is one-fourth of a wavelength long, as shown in Figure 15-12. As the frequency is increased, additional resonance lengths are found at half-wavelength intervals. Thus, columns of length \(\lambda/4, 3\lambda/4, 5\lambda/4, 7\lambda/4\), and so on will all be in resonance with a tuning fork.

In practice, the first resonance length is slightly longer than one-fourth of a wavelength. This is because the pressure variations do not drop to zero exactly at the open end of the pipe. Actually, the node is approximately 0.4 pipe diameters beyond the end. Additional resonance lengths, however, are spaced by exactly one-half of a wavelength. Measurements of the spacing between resonances can be used to find the velocity of sound in air, as shown in the next Example Problem.

\[
\begin{align*}
\lambda_1 &= 4L \\
\lambda_2 &= \frac{3}{4} L \\
\lambda_3 &= \frac{4}{3} L \\
\lambda_4 &= \frac{4}{5} L \\
\lambda_5 &= \frac{5}{4} L \\
f_1 &= \frac{v}{\lambda_1} = \frac{v}{4L} \\
f_2 &= \frac{3v}{4L} = 3f_1 \\
f_3 &= \frac{3v}{4L} = 3f_1 \\
f_4 &= \frac{3v}{4L} = 5f_1
\end{align*}
\]

Figure 15-12 A closed pipe resonates when its length is an odd number of quarter wavelengths.
Piano Whisper  Allow students access to a piano with an open lid. Arrange students into small groups. While a student in the group depresses the damper (right) pedal of the piano, have another student loudly hum a tone for a short time. When the student has stopped humming, have the others listen intently and they will discern that a string in the piano is producing a similar pitch. Let other groups repeat the activity. Have students relate the effect to resonance between the frequency of the sound wave they produce by humming and the fundamental frequency of the string.  L1 Auditory-Musical

Critical Thinking
Differences in Standing Waves
Point out that a 1.00-m-long brass rod held in the middle can be made to resonate with a longitudinal standing wave that has a wavelength of 2.00 m and a fundamental frequency of 1750 Hz. The rod acts the way an open pipe or a string does, with resonant frequencies at whole-number multiples of f, so that f = v/2L and \( \lambda = 2L \). On the other hand, for a closed pipe, f = v/4L, and a 1.00-m-long closed pipe produces a standing wave with an equal wavelength but a fundamental frequency of only 85.8 Hz. Ask students what other quantity differs between the two “pipes.” The speed of sound differs. The fundamental frequency of a standing wave on a brass rod is greater because the speed of longitudinal waves in brass is greater than the speed of the longitudinal waves in air.  L2 Logical-Mathematical

Resonance frequencies in an open pipe  The shortest column of air that can have nodes at both ends is one-half of a wavelength long, as shown in Figure 15-13. As the frequency is increased, additional resonance lengths are found at half-wavelength intervals. Thus, columns of length \( \lambda/2, \lambda, 3\lambda/2 \), and so on will be in resonance with a tuning fork.

If open and closed pipes of the same length are used as resonators, the wavelength of the resonant sound for the open pipe will be half as long as that for the closed pipe. Therefore, the frequency will be twice as high for the open pipe as for the closed pipe. For both pipes, resonance lengths are spaced by half-wavelength intervals.

Hearing resonance  Musical instruments use resonance to increase the loudness of particular notes. Open-pipe resonators include flutes and saxophones. Clarinets and the hanging pipes under marimbas and xylophones are examples of closed-pipe resonators. If you shout into a long tunnel, the booming sound you hear is the tunnel acting as a resonator. The seashell in Figure 15-14 acts as a closed-pipe resonator.

Resonance on Strings
Although the waveforms on vibrating strings vary in shape, depending upon how they are produced, such as by plucking, bowing, or striking, they have many characteristics in common with standing waves on springs and ropes, which you studied in Chapter 14. A string on an instrument is clamped at both ends, and therefore, the string must have a node at each end when it vibrates. In Figure 15-15, you can see that the first mode of vibration has an antinode at the center and is one-half of a wavelength long. The next resonance occurs when one wavelength fits on the string, and additional standing waves arise when the string length is \( 3\lambda/2, 2\lambda, 5\lambda/2 \), and so on. As with an open pipe, the resonant frequencies are whole-number multiples of the lowest frequency.

The speed of a wave on a string depends on the tension of the string, as well as its mass per unit length. This makes it possible to tune a stringed instrument by changing the tension of its strings. The tighter the string, the faster the wave moves along it, and therefore, the higher the frequency of its standing waves.

Pitch It  Have students work in small groups to construct a pair of instruments out of common items, such as soda bottles, rods, and rubber bands. Together, the instruments have to sound some standard musical interval, which must be identified by the use of a tuned instrument, such as a piano, or a tone generator. Have students sketch pressure-time graphs of the waves produced by each instrument and the superposition of the waves when both instruments are played simultaneously. That is, they must show the total amplitude of the vibrations from both instruments. Allow the groups to demonstrate their instruments and explain their graphs to other groups.  L2 Auditory-Musical
Section 15.2 The Physics of Music

Sound Quality

A tuning fork produces a soft and uninteresting sound. This is because its tines vibrate like simple harmonic oscillators and produce the simple sine wave shown in Figure 15-16a. Sounds made by the human voice and musical instruments are much more complex, like the wave in Figure 15-16b. Both waves have the same frequency, or pitch, but they sound very different. The complex wave is produced by using the principle of superposition to add waves of many frequencies. The shape of the wave depends on the relative amplitudes of these frequencies. In musical terms, the difference between the two waves is called timbre, tone color, or tone quality.

Reinforcement

Standing Pressure Waves

Have students explain why Figures 15-13 (on page 414) and 15-15 are pressure-position graphs. Both show the pressure variation from one location to another along a medium.

Resonance in Rods

Estimated Time 10 minutes

Materials 50- to 200-cm length of 10- to 15-mm-diameter aluminum rod, rosin

Procedure Hold the rod securely at its center with the thumb and forefinger of one hand. Place some rosin on the thumb and forefinger of the other hand. Run your thumb and forefinger briskly along the rod until it starts to vibrate. Adjust the pressure of the fingers until the rod starts to vibrate loudly. Have students note the pitch. Repeat the demonstration. When the rod is sounding, grab the midpoint of the vibrating portion with your free hand. A rod can produce a longitudinal standing wave. Because you supported the rod at its midpoint, the center of the rod was a node and \( \lambda_1 = 2L \). When you grabbed the midpoint of the vibrating portion of the rod, you eliminated an antinode, and the rod stopped vibrating.

Visual Impaired

Allow students with visual impairment to examine musical instruments in the band room or those that students bring in. Have students determine the location of the source of the sound waves (such as lips, string, reed) and a means of controlling the fundamental frequency (such as length of air column, tension and length of a string). Have students also investigate how pitch, loudness, and tone quality are controlled with each instrument.

Auditory-Visual

Activity

Visually Impaired  Allow students with visual impairment to examine musical instruments in the band room or those that students bring in. Have students determine the location of the source of the sound waves (such as lips, string, reed) and a means of controlling the fundamental frequency (such as length of air column, tension and length of a string). Have students also investigate how pitch, loudness, and tone quality are controlled with each instrument.

Auditory-Visual
A 440-Hz tuning fork is held above a closed pipe. Find the spacing between the resonances when the air temperature is 20°C.

A 440-Hz tuning fork is used with a resonating column to determine the velocity of sound in helium gas. If the spacings between resonances are 110 cm, what is the velocity of sound in helium gas?

The frequency of a tuning fork is unknown. A student uses an air column at 27°C and finds resonances spaced by 20.2 cm. What is the frequency of the tuning fork? Use the speed calculated in Example Problem 2 for the speed of sound in air at 27°C.

A bugle can be thought of as an open pipe. If a bugle were straightened out, it would be 2.65 m long.

a. If the speed of sound is 343 m/s, find the lowest frequency that is resonant for a bugle (ignoring end corrections).

b. Find the next two resonant frequencies for the bugle.

Finding the Speed of Sound Using Resonance When a tuning fork with a frequency of 392 Hz is used with a closed-pipe resonator, the loudest sound is heard when the column is 21.0 cm and 65.3 cm long. What is the speed of sound in this case? Is the temperature warmer or cooler than normal room temperature, which is 20°C? Explain your answer.

Math Handbook Order of Operations page 843

Critical Thinking Pitch and Temperature Have students explain why woodwind instruments tend to “go sharp” (pitch of notes rises), but stringed instruments “go flat” as temperature rises. As temperature increases, the velocity of sound increases, but the length of the woodwind instrument, which determines the wavelength, changes little. Thus, the frequency varies only with the velocity of sound. On the other hand, a string expands, causing the tension to decrease and, in turn, lower the frequency.

A pipe organ has an open pipe with a resonating height of 9.75 m. Ignoring end corrections, what is the frequency of the longest sound wave produced by this pipe? Assume the speed of sound is 343 m/s.

Obtain the resonance length of the lowest note using $L = \lambda/2$, then use $v = \lambda f$ to solve for $f, 17.6$ Hz.

Audiograms are graphical representations of one’s hearing. They are similar to sound spectra because they are plots of intensity versus frequency. Audiograms are used in audiometry, which is a medical testing procedure for hearing loss. A patient is exposed randomly to sounds at frequencies of 250 Hz, 500 Hz, 750 Hz, 1000 Hz, 2000 Hz, 4000 Hz, 6000 Hz, and 8000 Hz, one ear at a time, through earphones. The minimum intensity at which the patient perceives the sound is recorded. The resulting audiogram is analyzed against norms to determine the extent of hearing loss.

18. 0.39 m
19. 970 m/s
20. 859 Hz
21. a. 64.7 Hz
b. 129 Hz and 194 Hz
The sound spectrum: fundamental and harmonics The complex sound wave in Figure 15-16b was made by a clarinet. Why does the clarinet produce such a sound wave? The air column in a clarinet acts as a closed pipe. Look back at Figure 15-12, which shows three resonant frequencies for a closed pipe. Because the clarinet acts as a closed pipe, for a clarinet of length $L$, the lowest frequency, $f_1$, that will be resonant is $v/4L$. This lowest frequency is called the fundamental. A closed pipe also will resonate at $3f_1$, $5f_1$, and so on. These higher frequencies, which are odd-number multiples of the fundamental frequency, are called harmonics. It is the addition of these harmonics that gives a clarinet its distinctive timbre.

Some instruments, such as an oboe, act as open-pipe resonators. Their fundamental frequency, which is also the first harmonic, is $f_1 = v/2L$ with subsequent harmonics at $2f_1$, $3f_1$, $4f_1$, and so on. Different combinations and amplitudes of these harmonics give each instrument its own unique timbre. A graph of the amplitude of a wave versus its frequency is called a sound spectrum. The spectra of three instruments are shown in Figure 15-17.

**CHALLENGE PROBLEM**

1. The wavelength of the fundamental in a closed pipe is equal to $4L$, so the frequency is $f = \frac{v}{4L}$. The wavelength of the fundamental on a string is equal to $2L$, so the frequency of the string is $f = \frac{v}{2L}$, where $u$ is the speed of the wave on the string; $u = \sqrt{\frac{F_T}{\mu}}$.
   
   The mass per unit length of the string is $\mu = m/L$. Squaring the frequencies and setting them equal gives
   
   $$\frac{v^2}{16L^2} = \frac{u^2}{4L^2} = \frac{F_T}{4L^2\mu}$$
   
   Finally, rearranging for the tension gives
   
   $$F_T = \frac{mv^2}{4L}$$

2. For a string of mass 1.0 g and length 0.40 m, the tension is
   
   $$F_T = \frac{mv^2}{4L} = \frac{(0.0010 \text{ kg})(343 \text{ m/s})^2}{4(0.400 \text{ m})} = 74 \text{ N.}$$

**DIFFERENTIATED INSTRUCTION**

**Hearing Impaired** For activities in which students must discern differences in the sound intensities, use a lamp that has an inline dimmer switch to model changes in sound intensity. For example, in the Physics Lab on pp. 420–421, pair a hearing-impaired student with a hearing student facilitator. While the hearing-impaired student manipulates the apparatus, the facilitator can use the lamp to indicate increases in sound level by brightening the lamp as the experimenter approaches resonance length. By dimming the lamp, the facilitator can indicate decreasing sound intensity as the experimenter passes the resonance length. **Visual-Spatial**
Sounds Good

See page 141 of FAST FILE

Chapters 11–15 Resources for the accompanying Mini Lab Worksheet.

Purpose to model a musical instrument as an open- or closed-pipe resonator

Materials wind instrument, meter measuring tape, frequency generator

Expected Results Bugles, saxophones, flutes, and oboes act as open-pipe resonators; clarinets act as closed-pipe resonators.

Analyze and Conclude

4. Using the frequency and speed of sound, students can determine the wavelength of the fundamental and then compare it to the length of the instrument. For example, if they discover that \( \lambda = 4L \), then the instrument acted as a closed-pipe resonator.

5. Students should determine the appropriate ratio of frequencies, such as 1:2 for an octave and 2:3 for a perfect fifth.

Consonance and dissonance When sounds that have two different pitches are played at the same time, the resulting sound can be either pleasant or jarring. In musical terms, several pitches played together are called a chord. An unpleasant set of pitches is called dissonance. If the combination is pleasant, the sounds are said to be in consonance.

What makes a sound pleasant to listen to? Different cultures have different definitions, but most Western cultures accept the definitions of Pythagoras, who lived in ancient Greece. Pythagoras experimented by plucking two strings at the same time. He noted that pleasing sounds resulted when the strings had lengths in small, whole-number ratios, for example 1:2, 2:3, or 3:4. This means that their pitches (frequencies) will also have small, whole-number ratios.

Musical intervals Two notes with frequencies related by the ratio 1:2 are said to differ by an octave. For example, if a note has a frequency of 440 Hz, a note that is one octave higher has a frequency of 880 Hz. The fundamental and its harmonics are related by octaves; the first harmonic is one octave higher than the fundamental, the second is two octaves higher, and so on. The sum of the fundamental and the first harmonic is shown in Figure 15-18a. It is the ratio of two frequencies, not the size of the interval between them, that determines the musical interval.

In other musical intervals, two pitches may be close together. For example, the ratio of frequencies for a “major third” is 4:5. A typical major third is made up of the notes C and E. The note C has a frequency of 262 Hz, so E has a frequency of \( \frac{5}{4} \times 262 \text{ Hz} = 327 \text{ Hz} \). In the same way, notes in a “fourth” (C and F) have a frequency ratio of 3:4, and those in a “fifth” (C and G) have a ratio of 2:3. Graphs of these pleasant sounds are shown in Figure 15-18. More than two notes sounded together also can produce consonance. The three notes called do, mi, and sol make a major chord. For at least 2500 years, this has been recognized as the sweetest of the three-note chords; it has the frequency ratio of 4:5:6.

Beats

You have seen that consonance is defined in terms of the ratio of frequencies. When the ratio becomes nearly 1:1, the frequencies become very close. Two frequencies that are nearly identical interfere to produce high and low sound levels, as illustrated in Figure 15-19. This oscillation of wave amplitude is called a beat. The frequency of a beat is the magnitude of difference between the frequencies of the two waves, \( f_{\text{beat}} = \left| f_A - f_B \right| \).

When the difference is less than 7 Hz, the ear detects this as a pulsation of loudness. Musical instruments often are tuned by sounding one against another and adjusting the frequency of one until the beat disappears.

Piano Strings Have students determine the lengths of the longest and shortest strings in a piano if they atypically had the same tension and mass per unit length (assume frequency of lowest-pitched tone = 275 Hz; frequency of highest-pitched tone = 4190 Hz; sound velocity = 343 m/s). In this case, the pitch (frequency) of each note alone determines string length. Knowing that the longest string generates the lowest pitch, and that wavelength = speed/frequency, the wavelength of the longest string is \( \lambda = \frac{343 \text{ m/s}}{275 \text{ Hz}} = 1.25 \text{ m} \). Then, \( L_{\text{longest}} = \frac{\lambda}{2} \). Since \( n = 1 \), representing the standing wave pattern, \( L_{\text{shortest}} = 12.5 \text{ m/2} = 6.24 \text{ m or 20.5 ft} \). Since the shortest string has the highest frequency, its length \( L_{\text{shortest}} = \frac{343 \text{ m/s}}{4190 \text{ Hz}} = 0.0819 \text{ m} \). L_{\text{shortest}} = 0.0819/2 = 0.0409 \text{ m or 1.61 in.}
Sound Reproduction and Noise

How often do you listen to music produced directly by a human voice or musical instrument? Most of the time, the music has been recorded and played through electronic systems. To reproduce the sound faithfully, the system must accommodate all frequencies equally. A good stereo system must keep the amplitudes of all frequencies between 20 and 20,000 Hz the same to within 3 dB.

A telephone system, on the other hand, needs only to transmit the information in spoken language. Frequencies between 300 and 3000 Hz are sufficient. Reducing the number of frequencies present helps reduce the noise. A noise wave is shown in Figure 15-20. Many frequencies are present with approximately the same amplitude. While noise is not helpful in a telephone system, some people claim that listening to noise has a calming effect. For this reason, some dentists use noise to help their patients relax.

15.2 Section Review

22. Origins of Sound What is the vibrating object that produces sounds in each of the following?
   a. a human voice
   b. a clarinet
   c. a tuba
   d. a violin
23. Resonance in Air Columns Why is the tube from which a tube is made much longer than that of a cornet?
24. Resonance in Open Tubes How must the length of an open tube compare to the wavelength of the sound to produce the strongest resonance?
25. Resonance on Strings A violin sounds a note of F sharp, with a pitch of 370 Hz. What are the frequencies of the next three harmonics produced with this note?

26. Resonance in Closed Pipes One closed organ pipe has a length of 2.40 m.
   a. What is the frequency of the note played by this pipe?
   b. When a second pipe is played at the same time, a 1.40-Hz beat note is heard. By how much is the second pipe too long?
27. Timbre Why do various instruments sound different even when they play the same note?
28. Beats A tuning fork produces three beats per second with a second, 392-Hz tuning fork. What is the frequency of the first tuning fork?
29. Critical Thinking Strike a tuning fork with a rubber hammer and hold it at arm’s length. Then press its handle against a desk, a door, a filing cabinet, and other objects. What do you hear? Why?

Using Models

Beat Period Demo Construct two similar pendulums with lengths of 0.4 m and 0.6 m. Arrange the pendulums so that they align vertically and the bobs can be released directly behind each other. Release the bobs and have students observe that both bobs reach their starting point in tandem about every eight seconds. This time interval is the period of the beat, \( T_{\text{beat}} \). Have students determine the beat frequency:

\[ f_{\text{beat}} = \frac{1}{T_{\text{beat}}} = 0.1 \text{ Hz}. \]

Logical-Mathematical

3 ASSESS

Check for Understanding

Pipe Harmonics Have students draw pressure-position representations of standing waves in closed- and open-pipe resonators. Ask them how the wavelengths of standing waves are related to the length of each pipe. 

- closed-pipe resonator: \( \lambda = 4L \)
- open-pipe resonator: \( \lambda = 2L \)

Visual-Spatial

Extension

So That’s Timbre Urge students to listen to The Young Person’s Guide to the Orchestra, Opus 34, by Benjamin Britten. Have them respond by writing a brief paragraph describing differences in timbre among the woodwind, brass, string, and percussion families of instruments.

Logical-Mathematical

Auditory-Musical

greatly when it is pressed against other objects because they resonate like sounding boards. They sound different because they resonate with different harmonics, therefore having different timbres.
**Speed of Sound**

If a vibrating tuning fork is held above a closed pipe of the proper length, the air in the pipe will vibrate at the same frequency, \( f \), as the tuning fork. By placing a glass tube in a large, water-filled graduated cylinder, the length of the glass tube can be changed by raising or lowering it in the water. The shortest column of air that will resonate occurs when the tube is one-fourth of a wavelength long. This resonance will produce the loudest sound, and the wavelength at this resonance is described by \( \lambda = 4L \), where \( L \) is the length from the water to the open end of the pipe. In this lab, you will determine \( L \), calculate \( \lambda \), and calculate the speed of sound.

**QUESTION**

How can you use a closed-pipe resonator to determine the speed of sound?

**Alternatives CBL instructions** can be found on the Web site: physicspp.com

**Objectives**
- Collect and organize data to obtain resonant points in a closed pipe.
- Measure the length of a closed-pipe resonator.
- Analyze the data to determine the speed of sound.

**Safety Precautions**
- Immediately wipe up any spilled liquids.
- Glass is fragile. Handle with care.

**Materials**
- three tuning forks of known frequencies
- graduated cylinder (1000-mL)
- water
- tuning fork mallet

**Materials**
- metric ruler
- thermometer (non-mercury)
- glass tube (approximately 40 cm in length and 3.5 cm in diameter)

**Objectives**

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<th>Trial</th>
<th>Temperature (°C)</th>
<th>Accepted Speed of Sound (m/s)</th>
<th>Experimental Speed of Sound (m/s)</th>
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<td>24</td>
<td>345</td>
<td>320</td>
</tr>
<tr>
<td>2</td>
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<td>345</td>
<td>316</td>
</tr>
<tr>
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<td>345</td>
<td>326</td>
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**Data Table 1**

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<th>Trial</th>
<th>Tuning Fork Frequency (Hz)</th>
<th>Diameter (m)</th>
<th>Length of Tube Above Water (m)</th>
<th>Calculated Wavelength (m)</th>
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**Data Table 2**

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<th>Accepted Speed of Sound (m/s)</th>
<th>Corrected Calculated Wavelength (m)</th>
<th>Corrected Experimental Speed of Sound (m/s)</th>
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<tbody>
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<td>1</td>
<td>480</td>
<td>345</td>
<td>0.722</td>
<td>346</td>
</tr>
<tr>
<td>2</td>
<td>493.9</td>
<td>345</td>
<td>0.694</td>
<td>342</td>
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<tr>
<td>3</td>
<td>320</td>
<td>345</td>
<td>1.074</td>
<td>343</td>
</tr>
</tbody>
</table>

**Data Table 3**
Data Table 1

<table>
<thead>
<tr>
<th>Trial</th>
<th>Temperature (°C)</th>
<th>Accepted Speed of Sound (m/s)</th>
<th>Experimental Speed of Sound (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
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<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Data Table 2

<table>
<thead>
<tr>
<th>Trial</th>
<th>Tuning Fork Frequency (Hz)</th>
<th>Diameter (m)</th>
<th>Length of Tube Above Water (m)</th>
<th>Calculated Wavelength (m)</th>
</tr>
</thead>
<tbody>
<tr>
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</table>

Data Table 3

<table>
<thead>
<tr>
<th>Trial</th>
<th>Tuning Fork Frequency (Hz)</th>
<th>Accepted Speed of Sound (m/s)</th>
<th>Corrected Calculated Wavelength (m)</th>
<th>Corrected Experimental Speed of Sound (m/s)</th>
</tr>
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<tbody>
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<tr>
<td>3</td>
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</tr>
</tbody>
</table>

Analyze

1. Calculate the accepted speed of sound using the relationship \( v = 331 \text{ m/s} + 0.607T \), where \( v \) is the speed of sound at temperature \( T \), and \( T \) is the air temperature in degrees Celsius. Record this as the accepted speed of sound in Data Tables 1 and 3 for all the trials.

2. Since the first resonant point is located when the tube is one-fourth of a wavelength above the water, use the measured length of the tube to determine the calculated wavelength for each trial. Record the calculated wavelengths in Data Table 2.

3. Multiply the values in Data Table 2 of wavelength and frequency to determine the experimental speed of sound and record this in Data Table 1 for each of the trials.

4. **Error Analysis** For each trial in Data Table 1, determine the relative error between the experimental and accepted speed of sound. Use the same formula that you used in step 4, above.

5. **Critique** To improve the accuracy of your calculations, the tube diameter must be taken into consideration. The following relationship provides a more accurate calculation of wavelength: \( \lambda = 4(L + 0.4d) \), where \( \lambda \) is the wavelength, \( L \) is the length of the tube above the water, and \( d \) is the inside diameter of the tube. Using the values in Data Table 1 for length and diameter, recalculate \( \lambda \) and record it in Data Table 3 as the corrected wavelength. Calculate the corrected experimental speed of sound by multiplying the tuning fork frequency and corrected wavelength and record the new value for the corrected experimental speed of sound in Data Table 3.

6. **Error Analysis** For each trial in Data Table 3, determine the relative error between the corrected experimental speed and the accepted speed of sound. Use the same formula that you used in step 4, above.

Conclude and Apply

1. Infer In general, the first resonant point occurs when the tube length \( = \lambda/4 \). What are the next two lengths where resonance will occur?

2. Think Critically If you had a longer tube, would it be possible to locate another position where resonance occurs? Explain your answer.

Going Further

Which result produced the more accurate speed of sound?

Real-World Physics

Explain the relationship between the size of organ pipes and their resonant frequencies.

PhysicalsOnline

To find out more about the properties of sound waves, visit the Web site: physicspp.com

ALTERNATIVE INQUIRY LAB

To Make this Lab an Inquiry Lab: Have students investigate how the resonant point in a closed-pipe resonator varies with the frequency of sound. Students can determine the materials needed for the procedure they develop. Encourage them to closely observe the results and to record questions that arise. This activity can assist students in understanding how the human ear acts as a closed-pipe resonator.

Analyze

1. See Tables 1 and 3.
2. See Table 2.
3. See Table 1.
4. Errors of 10–20% are not unusual.
5. See Table 3.
6. Errors should be 5 percent or less.

Conclude and Apply

1. Lengths: \( 3\lambda/4, 5\lambda/4 \)
2. Yes; provided the length of the pipe is at least \( 3\lambda/4 \), the next resonant point should be obtainable.

Going Further

The analysis technique using corrected values for wavelength should be better.

Real-World Physics

The resonant frequency decreases with pipe length.
Background
While standing waves on a string can be modeled by sine and cosine functions, sound waves in the Sun are fit to spherical harmonics. These orthogonal functions are used to match the measured surface waves and predict the behavior of sound waves inside the Sun.

Teaching Strategies
- The artwork shows a cutaway of the Sun that indicates one possible path for a sound wave in the Sun. Sound waves do not penetrate the radiative zone or the core, which has a density about ten times that of lead. There are many sound waves generated in the convective zone, but only waves with particular period and wavelength combinations interfere constructively to form standing waves.
- Even if the sound waves in the Sun could propagate to Earth, we could not hear them because the frequencies of the waves are far too low. The Sun's sounds can be played so that we hear them, but the frequency of the waves needs to be multiplied by about 42,000. If they are interested, students can research such audio files, along with more information about helioseismology.

Activity
Standing Waves Students can see standing waves by setting a coffee cup half full of water or oil in a sink and turning on a noisy garbage disposal. Notice that liquids with different viscosities have different standing wave patterns. Ask students to test several different liquids and indicate whether they could detect any differences in the waves produced.

The motion of the surface of the Sun is measured by observing Doppler shifts in sunlight. The measured vibrations are a complicated pattern that equals the sum of all of the standing waves present in the Sun. Just like a ringing bell, many overtones are present in the Sun. Through careful analysis, the individual standing waves in the Sun and their intensities can be calculated.

Sound Waves in the Sun
The study of wave oscillations in the Sun is called helioseismology. Naturally occurring sound waves (p waves), gravity waves, and surface gravity waves all occur in the Sun. All of these waves are composed of oscillating particles, but different forces cause the oscillations.

For sound waves, pressure differences cause the particles to oscillate. In the Sun, sound waves travel through the convective zone, which is just under the surface, or photosphere. The sound waves do not travel in a straight line, as shown in the image.

Ringing like a Bell The sound waves in the Sun cause the surface of the Sun to vibrate in the radial direction, much like a ringing bell vibrates. When a bell is rung, a clapper hits the bell in one place and standing waves are created. The surface of the Sun does have standing waves, but they are not caused by one large event. Instead, scientists hypothesize that many smaller disruptions in the convective zone start most of the sound waves in the Sun. Just like boiling water in a pot can be noisy, bubbles that are larger than the state of Texas form on the surface of the Sun and start sound waves.

Unlike a pot of boiling water, the sound coming from the Sun is much too low for us to hear. The A above middle C on the piano has a period of $0.00277 \text{s}$ ($f = 440 \text{ Hz}$). The middle mode of oscillation of the waves in the Sun has a period of $5 \text{ min}$ ($f = 0.003 \text{ Hz}$).

Because we cannot hear the sound waves from the Sun, scientists measure the motion of the surface of the Sun to learn about its sound waves. Because a sound wave takes $2 \text{ h}$ to travel from one side of the Sun to the other, the Sun must be observed for long time periods. This necessity makes observations from Earth difficult because the Sun is not visible during the night. In 1995, the Solar and Heliospheric Observatory (SOHO) was launched by NASA. This satellite orbits Earth such that it always can observe the Sun.

Results Because composition, temperature, and density affect the propagation of sound waves, the Sun’s wave oscillations provide information about its interior. SOHO results have given insight into the rotation rate of the Sun as a function of latitude and depth, as well as the density and temperature of the Sun. These results are compared to theoretical calculations to improve our understanding of the Sun.

Going Further
1. Hypothesize How do scientists separate the surface motion due to sound waves from the motion due to the rotation of the Sun?
2. Critical Thinking Would sound waves in another star, similar to the Sun but different in size, have the same wavelength as sound waves in the Sun?
### 15.1 Properties and Detection of Sound

#### Vocabulary
- sound wave (p. 404)
- pitch (p. 406)
- loudness (p. 406)
- sound level (p. 406)
- decibel (p. 406)
- Doppler effect (p. 407)

#### Key Concepts
- Sound is a pressure variation transmitted through matter as a longitudinal wave.
- A sound wave has frequency, wavelength, speed, and amplitude. Sound waves reflect and interfere.
- The speed of sound in air at room temperature (20°C) is 343 m/s. The speed increases roughly 0.6 m/s with each 1°C increase in temperature.
- Sound detectors convert the energy carried by a sound wave into another form of energy. The human ear is a highly efficient and sensitive detector of sound waves.
- The frequency of a sound wave is heard as its pitch.
- The pressure amplitude of a sound wave can be measured in decibels (dB).
- The loudness of sound as perceived by the ear and brain depends mainly on its amplitude.
- The Doppler effect is the change in frequency of sound caused by the motion of either the source or the detector. It can be calculated with the following equation.

\[
f_d = f_s \left( \frac{v_d}{v} \right)
\]

### 15.2 The Physics of Music

#### Vocabulary
- closed-pipe resonator (p. 412)
- open-pipe resonator (p. 412)
- fundamental (p. 417)
- harmonics (p. 417)
- dissonance (p. 418)
- consonance (p. 418)
- beat (p. 418)

#### Key Concepts
- Sound is produced by a vibrating object in a material medium.
- Most sounds are complex waves that are composed of more than one frequency.
- An air column can resonate with a sound source, thereby increasing the amplitude of its resonant frequency.
- A closed pipe resonates when its length is \(\frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}\), and so on. Its resonant frequencies are odd-numbered multiples of the fundamental.
- An open pipe resonates when its length is \(\frac{\lambda}{2}, \frac{2\lambda}{2}, \frac{3\lambda}{2}\), and so on. Its resonant frequencies are whole-number multiples of the fundamental.
- A clamped string has a node at each end and resonates when its length is \(\frac{\lambda}{2}, 2\frac{\lambda}{2}, 3\frac{\lambda}{2}\), and so on, just as with an open pipe. The string's resonant frequencies are also whole-number multiples of the fundamental.
- The frequencies and intensities of the complex waves produced by a musical instrument determine the timbre that is characteristic of that instrument.
- The fundamental frequency and harmonics can be described in terms of resonance.
- Notes on a musical scale differ in frequency by small, whole-number ratios. An octave has a frequency ratio of 1:2.
- Two waves with almost the same frequency interfere to produce beats.
Concept Mapping

Mastering Concepts
31. Sound waves can be described by frequency, wavelength, amplitude, and speed.
32. Light travels at $3.00 \times 10^8$ m/s while sound travels at 343 m/s. Officials would see the smoke before they would hear the pistol fire. The times would be less than they actually were if sound were used.
33. pitch—frequency; loudness—amplitude
34. all types of waves
35. Doctors can measure the Doppler shift from sound reflected by the moving blood cells. Because the blood is moving, sound gets Doppler shifted, and the compressions either get piled up or spaced apart. This alters the frequency of the wave.
36. a vibrating object and a material medium
37. The frequency of the note is the same as the natural resonance of the crystal, causing its molecules to increase their amplitude of vibration as energy from the sound is accepted.
38. While marching in step, a certain frequency is established that could resonate the bridge into destructive oscillation. No single frequency is maintained under "route step."
39. Tuning forks produce simple, single-frequency waves. Musical instruments produce complex waves containing many different frequencies. This gives them their timbre.
40. the sound quality or timbre
41. The slide of a trombone varies pitch by changing the length of the resonating column of vibrating air.
42. The speed of sound is $343$ m/s = $0.343$ km/s = $(1/2.92)$ km/s; or, sound travels approximately 1 km in 3 s. Therefore, divide the number of seconds by three. For miles, sound travels approximately 1 mi in 5 s. Therefore, divide the number of seconds by five.
43. a. There is no change in frequency.

Applying Concepts
42. Estimation To estimate the distance in kilometers between you and a lightning flash, count the seconds between the flash and the thunder and divide by 3. Explain how this rule works. Devise a similar rule for miles.
43. The speed of sound increases by about 0.6 m/s for each degree Celsius when the air temperature rises. For a given sound, as the temperature increases, what happens to the following?
   a. the frequency
   b. the wavelength
44. Movies In a science-fiction movie, a satellite blows up. The crew of a nearby ship immediately hears and sees the explosion. If you had been hired as an advisor, what two physics errors would you have noticed and corrected?
45. The Redshift Astronomers have observed that the light coming from distant galaxies appears redder than light coming from nearer galaxies. With the help of Figure 15-22, which shows the visible spectrum, explain why astronomers conclude that distant galaxies are moving away from Earth.
47. If the pitch of sound is increased, what are the changes in the following?
   a. the frequency
   b. the wavelength
   c. the wave velocity
   d. the amplitude of the wave

48. The speed of sound increases with temperature. Would the pitch of a closed pipe increase or decrease when the temperature of the air rises? Assume that the length of the pipe does not change.

49. Marching Bands Two flutists are tuning up. If the conductor hears the beat frequency increasing, are the two flute frequencies getting closer together or farther apart?

50. Musical Instruments A covered organ pipe plays a certain note. If the cover is removed to make it an open pipe, is the pitch increased or decreased?

51. Stringed Instruments On a harp, Figure 15-23a, long strings produce low notes and short strings produce high notes. On a guitar, Figure 15-23b, the strings are all the same length. How can they produce notes of different pitches?

52. You hear the sound of the firing of a distant cannon 5.0 s after seeing the flash. How far are you from the cannon?

53. If you shout across a canyon and hear an echo 3.0 s later, how wide is the canyon?

54. A sound wave has a frequency of 4700 Hz and travels along a steel rod. If the distance between compressions, or regions of high pressure, is 1.1 m, what is the speed of the wave?

55. Bats The sound emitted by bats has a wavelength of 3.5 mm. What is the sound’s frequency in air?

56. Photography As shown in Figure 15-24, some cameras determine the distance to the subject by sending out a sound wave and measuring the time needed for the echo to return to the camera. How long would it take the sound wave to return to such a camera if the subject were 3.00 m away?

57. Sound with a frequency of 261.6 Hz travels through water at 25°C. Find the sound’s wavelength in water. Do not confuse sound waves moving through water with surface waves moving through water.

58. If the wavelength of a 4.40 × 10^3 Hz sound in freshwater is 3.30 m, what is the speed of sound in freshwater?

59. Sound with a frequency of 442 Hz travels through an iron beam. Find the wavelength of the sound in iron.

60. Aircraft Adam, an airport employee, is working near a jet plane taking off. He experiences a sound level of 150 dB.
   a. If Adam wears ear protectors that reduce the sound level to that of a typical rock concert, what decrease in dB is provided?
   b. If Adam then hears something that sounds like a barely audible whisper, what will a person not wearing the ear protectors hear?

61. Rock Music A rock band plays at an 80-dB sound level. How many times greater is the sound pressure from another rock band playing at each of the following sound levels?
   a. 100 dB
   b. 120 dB

62. A coiled-spring toy is shaken at a frequency of 4.0 Hz such that standing waves are observed with a wavelength of 0.50 m. What is the speed of propagation of the wave?

63. A baseball fan on a warm summer day (30°C) sits in the bleachers 152 m away from home plate.
   a. What is the speed of sound in air at 30°C?
   b. How long after seeing the ball hit the bat does the fan hear the crack of the bat?

51. The strings have different tensions and masses per unit length. Thinner, tighter strings produce higher notes than do thicker, looser strings.

Mastering Problems

15.1 Properties and Detection of Sound

52. a. Frequency will increase.
   b. Wavelength will decrease.
   c. Wave velocity will remain the same.
   d. Amplitude will remain the same.

53. A 40-dB sound has sound pressure 100 times greater.

54. Red light has a longer wavelength and, therefore, a lower frequency than other colors. The Doppler shift of their light to lower frequencies indicates that distant galaxies are moving away from us.

55. A 40-dB sound has sound pressures 100 times greater.

56. Bats The sound emitted by bats has a wavelength of 3.5 mm. What is the sound’s frequency in air?

57. The speed of sound increases with temperature. Would the pitch of a closed pipe increase or decrease when the temperature of the air rises? Assume that the length of the pipe does not change.

58. A covered organ pipe plays a certain note. If the cover is removed to make it an open pipe, is the pitch increased or decreased?

59. The frequencies are getting farther apart.

60. The pitch is increased; the frequency will increase.

61. If the pitch of sound is increased, what are the changes in the following?
   a. the frequency
   b. the wavelength
   c. the wave velocity
   d. the amplitude of the wave

62. A 40-dB sound has sound pressures 100 times greater.

63. A 40-dB sound has sound pressure 100 times greater.
64. On a day when the temperature is 15°C, a person stands some distance, d, as shown in Figure 15-25, from a cliff and claps his hands. The echo returns in 2.0 s. How far away is the cliff?

65. Medical Imaging Ultrasound with a frequency of 4.25 MHz can be used to produce images of the human body. If the speed of sound in the body is the same as in salt water, 1.50 km/s, what is the length of a 4.25-MHz pressure wave in the body?

66. Sonar A ship surveying the ocean bottom sends sonar waves straight down into the seawater from the surface. As illustrated in Figure 15-26, the first reflection, off of the mud at the sea floor, is received 1.74 s after it was sent. The second reflection, from the bedrock beneath the mud, returns after 2.36 s. The seawater is at a temperature of 25°C, and the speed of sound in mud is 1875 m/s.
   a. How deep is the water?
   b. How thick is the mud?

67. Determine the variation in sound pressure of a conversation being held at a sound level of 60 dB.

68. A fire truck is moving at 35 m/s, and a car in front of the truck is moving in the same direction at 15 m/s. If a 327-Hz siren blares from the truck, what frequency is heard by the driver of the car?

69. A train moving toward a sound detector at 31.0 m/s blows a 305-Hz whistle. What frequency is detected on each of the following?
   a. a stationary train
   b. a train moving toward the first train at 21.0 m/s
   c. a train moving away from the detector. What frequency is now detected on each of the following?
   a. a stationary train
   b. a train moving away from the first train at a speed of 21 m/s

15.2 The Physics of Music

71. A vertical tube with a tap at the base is filled with water, and a tuning fork vibrates over its mouth. As the water level is lowered in the tube, resonance is heard when the water level has dropped 17 cm, and again after 49 cm of distance exists from the water to the top of the tube. What is the frequency of the tuning fork?

72. Human Hearing The auditory canal leading to the eardrum is a closed pipe that is 3.0 cm long. Find the approximate value (ignoring end correction) of the lowest resonance frequency.

73. If you hold a 1.2-m aluminum rod in the center and hit one end with a hammer, it will oscillate like an open pipe. Antinodes of pressure correspond to nodes of molecular motion, so there is a pressure antinode in the center of the bar. The speed of sound in aluminum is 5150 m/s. What would be the bar's lowest frequency of oscillation?

74. One tuning fork has a 445-Hz pitch. When a second fork is struck, beat notes occur with a frequency of 3 Hz. What are the two possible frequencies of the second fork?

75. Flutes A flute acts as an open pipe. If a flute sounds a note with a 370-Hz pitch, what are the frequencies of the second, third, and fourth harmonics of this pitch?

76. Clarinets A clarinet sounds the same note, with a pitch of 370 Hz, as in the previous problem. The clarinet, however, acts as a closed pipe. What are the frequencies of the lowest three harmonics produced by this instrument?

77. String Instruments A guitar string is 65.0 cm long and is tuned to produce a lowest frequency of 196 Hz.
   a. What is the speed of the wave on the string?
   b. What are the next two higher resonant frequencies for this string?
78. **Musical Instruments** The lowest note on an organ is 16.4 Hz.
   a. What is the shortest open organ pipe that will resonate at this frequency?
   b. What is the pitch if the same organ pipe is closed?
79. **Musical Instruments** Two instruments are playing musical A (440.0 Hz). A beat note with a frequency of 2.5 Hz is heard. Assuming that one instrument is playing the correct pitch, what is the frequency of the pitch played by the second instrument?
80. A flexible, corrugated, plastic tube, shown in Figure 15-27, is 0.85 m long. When it is swung around, it creates a tone that is the lowest pitch for an open pipe of this length. What is the frequency?

81. The tube from the previous problem is swung faster, producing a higher pitch. What is the new frequency?
82. During normal conversation, the amplitude of a pressure wave is 0.020 Pa.
   a. If the area of an eardrum is 0.52 cm², what is the force on the eardrum?
   b. The mechanical advantage of the three bones in the middle ear is 1.5. If the force in part a is transmitted undiminished to the bones, what force do the bones exert on the oval window, the membrane to which the third bone is attached?
   c. The area of the oval window is 0.026 cm². What is the pressure increase transmitted to the liquid in the cochlea?
83. **Musical Instruments** One open organ pipe has a length of 816 mm. A second open pipe should have a pitch that is one major third higher. How long should the second pipe be?
84. As shown in Figure 15-28, a music box contains a set of steel fingers clamped at one end and plucked on the other end by pins on a rotating drum. What is the speed of a wave on a finger that is 2.4 cm long and plays a note of 1760 Hz?

**Mixed Review**

85. An open organ pipe is 1.65 m long. What fundamental frequency note will it produce if it is played in helium at 0°C?
86. If you drop a stone into a well that is 122.5 m deep, as illustrated in Figure 15-29, how soon after you drop the stone will you hear it hit the bottom of the well?

87. A bird on a newly discovered planet flies toward a surprised astronaut at a speed of 19.5 m/s while singing at a pitch of 945 Hz. The astronaut hears a tone of 985 Hz. What is the speed of sound in the atmosphere of this planet?
88. In North America, one of the hottest outdoor temperatures ever recorded is 57°C and one of the coldest is −62°C. What are the speeds of sound at those two temperatures?
89. A ship’s sonar uses a frequency of 22.5 kHz. The speed of sound in seawater is 1533 m/s. What is the speed of sound received on the ship that was reflected from a whale traveling at 4.15 m/s away from the ship? Assume that the ship is at rest.
90. When a wet finger is rubbed around the rim of a glass, a loud tone of frequency 2100 Hz is produced. If the glass has a diameter of 6.2 cm and the vibration contains one wavelength around its rim, what is the speed of the wave in the glass?
91. **History of Science** In 1845, Dutch scientist Christoph Buys-Ballot developed a test of the Doppler effect. He had a trumpet player sound an A note at 440 Hz while riding on a flatcar pulled by a locomotive. At the same time, a stationary trumpet player played the same note. Buys-Ballot heard 3.0 beats per second. How fast was the train moving toward him?

92. a. 68.6 m/s
   b. \[ \nu = \frac{68.6 \text{ m/s}}{1 \text{ h}} \times \frac{1 \text{ mi}}{1609 \text{ m}} = 153 \text{ mph} \]
   No, do not try the experiment.

**Level 3**
93. 180 N
94. 407 Hz

**Thinking Critically**
96. The graph should show a fairly steady frequency above 300 Hz as it approaches and a fairly steady frequency below 300 Hz as it moves away.
97. You could start the watch when you saw the hit and stop the watch when the sound reached you. The speed would be calculated by dividing the distance, 200 m, by the measured time. The measured time would be too large because you could anticipate the impact by sight, but you could not anticipate the sound. The calculated speed would be too small.
98. The Sun must be rotating on its axis in the same manner as Earth. The Doppler shift indicates that the left side of the Sun is coming toward us, while the right side is moving away.

99. Measure the mass and length of the string to determine \( \mu \). Then clamp the string to a table, hang one end over the table edge, and stretch the string by hanging weights on its end to obtain \( F_T \). Calculate the speed of the wave using the formula. Next, pluck the string in its middle and determine the frequency by matching it to a frequency generator, using beats to tune the generator. Multiply the frequency by twice the string length, which is equal to the wavelength, to obtain the speed from the wave equation. Compare the results. Repeat for different tensions and other strings with different mass per unit length. Consider possible causes of error.
92. You try to repeat Buys-Ballot’s experiment from the previous problem. You plan to have a trumpet played in a rapidly moving car. Rather than listening for beat notes, however, you want to have the car move fast enough so that the moving trumpet sounds one major third above a stationary trumpet. 
   a. How fast would the car have to move?
   b. Should you try the experiment? Explain.

93. **Guitar Strings** The equation for the speed of a wave on a string is \( v = \frac{F_x}{\mu T} \), where \( F_x \) is the tension in the string and \( \mu \) is the mass per unit length of the string. **A guitar string has a mass of 3.2 g and is 65 cm long.** What must be the tension in the string to produce a note whose fundamental frequency is 147 Hz?

94. A train speeding toward a tunnel at 37.5 m/s sounds its horn at 327 Hz. **The sound bounces off the tunnel mouth.** What is the frequency of the reflected sound heard on the train? **Hint:** Solve the problem in two parts. First, assume that the tunnel is a stationary source and find the frequency. Then, assume that the tunnel is a stationary source and find the frequency measured on the train.

**Writing in Physics**

100. **Answers will vary. A report on violin construction might include information about the bridge as a link between the strings and body and information about the role of the body in causing air molecules around the violin to vibrate. Students might also discuss the ways in which the woods and finishes used in making violins affect the quality of the sound produced by the instrument.**

101. **Students should discuss the work of Edwin Hubble, the redshift and the expanding universe, spectroscopy, and the detection of wobbles in the motion of planet-star systems.**

**Cumulative Review**

   **b.** 3.6 kg·m/s at 34° north of west; 1.8 m/s at 34° north of west

103. No work because the force and the displacement are perpendicular.

104. The energy to be absorbed is 11 kJ. The force on her is 150 N.

95. **Make and Use Graphs** The wavelengths of the sound waves produced by a set of tuning forks with given frequencies are shown in Table 15-2 below.
   **a.** Plot a graph of wavelength versus the frequency (controlled variable). What type of relationship does the graph show?
   **b.** Plot a graph of wavelength versus the inverse of the frequency \( 1/f \). What kind of graph is this? Determine the speed of sound from this graph.

96. **Make Graphs** Suppose that the frequency of a car horn is 300 Hz when it is stationary. What would the graph of the frequency versus time look like as the car approached and then moved past you? Complete a rough sketch.

**Thinking Critically**

100. **Research the construction of a musical instrument, such as a violin or French horn. What factors must be considered besides the length of the strings or tube? What is the difference between a quality instrument and a cheaper one? How are they tested for tone quality?**

101. **Research the use of the Doppler effect in the study of astronomy. What is its role in the big bang theory? How is it used to detect planets around other stars? To study the motions of galaxies?**

**Cumulative Review**

102. **Ball A, rolling west at 3.0 m/s, has a mass of 1.0 kg. Ball B has a mass of 2.0 kg and is stationary. After colliding with ball B, ball A moves south at 2.0 m/s.** (Chapter 9)
   **a.** Sketch the system, showing the velocities and momenta before and after the collision.
   **b.** Calculate the momentum and velocity of ball B after the collision.

103. **Chris carries a 10-N carton of milk along a level hall to the kitchen, a distance of 3.5 m. How much work does Chris do?** (Chapter 10)

104. **A movie stunt person jumps from a five-story building (22 m high) onto a large pillow at ground level. The pillow cushions her fall so that she feels a deceleration of no more than 3.0 m/s². If she weighs 480 N, how much energy does the pillow have to absorb? How much force does the pillow exert on her?** (Chapter 11)
Multiple Choice
1. How does sound travel from its source to your ear?
   - changes in air pressure
   - vibrations in wires or strings
   - electromagnetic waves
   - infrared waves

2. Paulo is listening to classical music in the speakers installed in his swimming pool. A note with a frequency of 327 Hz reaches his ears while he is under water. What is the wavelength of the sound that reaches Paulo’s ears? Use 1493 m/s for the speed of sound in water.
   - 2.19 nm
   - 2.19 \times 10^{-1} m
   - 4.88 \times 10^{-5} m
   - 4.57 m

3. The sound from a trumpet travels at 351 m/s in air. If the frequency of the note is 298 Hz, what is the wavelength of the sound wave?
   - 9.93 \times 10^{-4} m
   - 1.18 m
   - 0.849 m
   - 1.05 \times 10^{-5} m

4. The horn of a car attracts the attention of a stationary observer. If the car is approaching the observer at 60.0 km/h and the horn has a frequency of 512 Hz, what is the frequency of the sound perceived by the observer? Use 343 m/s for the speed of sound in air.
   - 488 Hz
   - 538 Hz
   - 512 Hz
   - 600 Hz

5. As shown in the diagram below, a car is receding at 72 km/h from a stationary siren. If the siren is wailing at 657 Hz, what is the frequency of the sound perceived by the driver? Use 343 m/s for the speed of sound.
   - 543 Hz
   - 647 Hz
   - 620 Hz
   - 698 Hz

Extended Answer
8. The figure below shows the first resonance length of a closed air column. If the frequency of the sound is 488 Hz, what is the speed of the sound?

\[ L = 16.8 \text{ cm} \]

Extended Answer
6. Reba hears 20 beats in 5.0 s when she plays two notes on her piano. She is certain that one note has a frequency of 262 Hz. What are the possible frequencies of the second note?
   - 242 Hz or 282 Hz
   - 258 Hz or 266 Hz
   - 260 Hz or 264 Hz
   - 270 Hz or 278 Hz

7. Which of the following pairs of instruments have resonant frequencies at each whole-number multiple of the lowest frequency?
   - a clamped string and a closed pipe
   - a clamped string and an open pipe
   - an open pipe and a closed pipe
   - an open pipe and a reed instrument

8. The figure below shows the first resonance length of a closed air column. If the frequency of the sound is 488 Hz, what is the speed of the sound?

\[ v = \frac{488 \text{ Hz} \times 343 \text{ m/s}}{16.8 \text{ cm}} \]

Extended Response

Points Description
4 The student demonstrates a thorough understanding of the physics involved. The response may contain minor flaws that do not detract from the demonstration of a thorough understanding.
3 The student demonstrates an understanding of the physics involved. The response is essentially correct and demonstrates an essential but less than thorough understanding of the physics.
2 The student demonstrates only a partial understanding of the physics involved. Although the student may have used the correct approach to a solution or may have provided a correct solution, the work lacks an essential understanding of the underlying physical concepts.
1 The student demonstrates a very limited understanding of the physics involved. The response is incomplete and exhibits many flaws.
0 The student provides a completely incorrect solution or no response at all.

Write It Down
Most tests ask you a large number of questions in a small amount of time. Write down your work whenever possible. Do math on paper, not in your head. Underline and reread important facts in passages and diagrams—do not try to memorize them.