Objectives
- Calculate the intensity of sound waves.
- Relate intensity, decibel level, and perceived loudness.
- Explain why resonance occurs.

Key Terms
- intensity
- decibel
- resonance

Sound Intensity

When a piano player strikes a piano key, a hammer inside the piano strikes a wire and causes it to vibrate, as shown in Figure 2.1. The wire's vibrations are then transferred to the piano's soundboard. As the soundboard vibrates, it exerts a force on air molecules around it, causing the air molecules to move. Because this force is exerted through displacement of the soundboard, the soundboard does work on the air. Thus, as the soundboard vibrates back and forth, its kinetic energy is converted into sound waves. This is one reason that the vibration of the soundboard gradually dies out.

**Sound Intensity**

Intensity is the rate of energy flow through a given area.

As described in Section 1, sound waves traveling in air are longitudinal waves. As the sound waves travel outward from the source, energy is transferred from one air molecule to the next. The rate at which this energy is transferred through a unit area of the plane wave is called the intensity of the wave. Because power, $P$, is defined as the rate of energy transfer, intensity can also be described in terms of power.

$$\text{intensity} = \frac{\Delta E}{\Delta t} \frac{\text{area}}{} = \frac{P}{\text{area}}$$

The SI unit for power is the watt. Thus, intensity has units of watts per square meter (W/m²). In a spherical wave, energy propagates equally in all directions; no one direction is preferred over any other. In this case, the power emitted by the source ($P$) is distributed over a spherical surface (area = $4\pi r^2$), assuming that there is no absorption in the medium.

**Intensity of a Spherical Wave**

$$\text{intensity} = \frac{P}{4\pi r^2}$$

This equation shows that the intensity of a sound wave decreases as the distance from the source ($r$) increases. This occurs because the same amount of energy is spread over a larger area.

**Differentiated Instruction**

**Below Level**

Some students may have trouble distinguishing between energy and the rate of energy transfer, or power. Briefly review the idea of power (introduced in the chapter “Work and Energy”) to make sure this distinction is clear to students before intensity is introduced.
Intensity of Sound Waves

Sample Problem A  What is the intensity of the sound waves produced by a trumpet at a distance of 3.2 m when the power output of the trumpet is 0.20 W? Assume that the sound waves are spherical.

1. **SOLVE**
   
   **Given:**  \( P = 0.20 \text{ W} \)  \( r = 3.2 \text{ m} \)
   
   **Unknown:**  Intensity = ?

   Use the equation for the intensity of a spherical wave.

   \[
   \text{Intensity} = \frac{P}{4\pi r^2}
   \]

   \[
   \text{Intensity} = \frac{0.20 \text{ W}}{4\pi(3.2 \text{ m})^2}
   \]

   \[
   \text{Intensity} = 1.6 \times 10^{-3} \text{ W/m}^2
   \]

   **Calculator Solution**

   The calculator answer for intensity is 0.0015542. This is rounded to 1.6 \( \times 10^{-3} \) because each of the given quantities has two significant figures.

Practice

1. Calculate the intensity of the sound waves from an electric guitar’s amplifier at a distance of 5.0 m when its power output is equal to each of the following values:
   a. 0.25 W
   b. 0.50 W
   c. 2.0 W

2. At a maximum level of loudness, the power output of a 75-piece orchestra radiated as sound is 70.0 W. What is the intensity of these sound waves to a listener who is sitting 25.0 m from the orchestra?

3. If the intensity of a person’s voice is \( 4.6 \times 10^{-7} \text{ W/m}^2 \) at a distance of 2.0 m, how much sound power does that person generate?

4. How much power is radiated as sound from a band whose intensity is \( 1.6 \times 10^{-3} \text{ W/m}^2 \) at a distance of 15 m?

5. The power output of a tuba is 0.35 W. At what distance is the sound intensity of the tuba \( 1.2 \times 10^{-3} \text{ W/m}^2 \)?

**Problem Solving**

**REALITY CHECK**

Students should recognize that an increase in power means an increase in intensity. Students should also recognize that the farther the wave is from the source, the lower the intensity. The intensity falls with the square of the distance. Therefore, doubling the distance from the source will have a greater effect on the intensity than doubling the power. If both the power and distance were doubled, then the intensity would drop by a half.
Range of Human Hearing

Human hearing depends on both the frequency and the intensity of sound waves. Sounds in the middle of the spectrum of frequencies can be heard more easily (at lower intensities) than those at lower and higher frequencies.

Intensity and frequency determine which sounds are audible.

The frequency of sound waves heard by the average human ranges from 20 to 20,000 Hz. Intensity is also a factor in determining which sound waves are audible. Figure 2.2 shows how the range of audibility of the average human ear depends on both frequency and intensity. Sounds at low frequencies (those below 50 Hz) or high frequencies (those above 12,000 Hz) must be relatively intense to be heard, whereas sounds in the middle of the spectrum are audible at lower intensities.

The softest sounds that can be heard by the average human ear occur at a frequency of about 1000 Hz and an intensity of 1.0 × 10⁻¹² W/m². Such a sound is said to be at the threshold of hearing. The threshold of hearing at each frequency is represented by the lowest curve in Figure 2.2.

For frequencies near 1000 Hz and at the threshold of hearing, the changes in pressure due to compressions and rarefactions are about three ten-billionths of atmospheric pressure. The maximum displacement of an air molecule at the threshold of hearing is approximately 1 × 10⁻¹¹ m. Comparing this number to the diameter of a typical air molecule (about 1 × 10⁻¹⁰ m) reveals that the ear is an extremely sensitive detector of sound waves.

The loudest sounds that the human ear can tolerate have an intensity of about 1.0 W/m². This is known as the threshold of pain because sounds with greater intensities can produce pain in addition to hearing. The highest curve in Figure 2.2 represents the threshold of pain at each frequency. Exposure to sounds above the threshold of pain can cause immediate damage to the ear, even if no pain is felt. Prolonged exposure to sounds of lower intensities can also damage the ear. Note that the threshold of hearing and the threshold of pain merge at both high and low ends of the spectrum.
Relative intensity is measured in decibels.

Just as the frequency of a sound wave determines its pitch, the intensity of a wave approximately determines its perceived loudness. However, loudness is not directly proportional to intensity. The reason is that the sensation of loudness is approximately logarithmic in the human ear.

Relative intensity is the ratio of the intensity of a given sound wave to the intensity at the threshold of hearing. Because of the logarithmic dependence of perceived loudness on intensity, using a number equal to 10 times the logarithm of the relative intensity provides a good indicator for human perceptions of loudness. This measure of loudness is referred to as the decibel level. The decibel level is dimensionless because it is proportional to the logarithm of a ratio. A dimensionless unit called the decibel (dB) is used for values on this scale.

The conversion of intensity to decibel level is shown in Figure 2.3. Notice in Figure 2.3 that when the intensity is multiplied by ten, 10 dB are added to the decibel level. A given difference in decibels corresponds to a fixed difference in perceived loudness. Although much more intensity \((9 \times 10^{-11} \text{ W/m}^2)\) is added between 110 and 120 dB than between 10 and 20 dB \((9 \times 10^{-11} \text{ W/m}^2)\), in each case the perceived loudness increases by the same amount.

**Did YOU Know?**

The original unit of decibel level is the bel, named in honor of Alexander Graham Bell, the inventor of the telephone. The decibel is equivalent to 0.1 bel.

### Figures

**Figure 2.3** CONVERSION OF INTENSITY TO DECIBEL LEVEL

<table>
<thead>
<tr>
<th>Intensity (W/m²)</th>
<th>Decibel level (dB)</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1.0 \times 10^{-12})</td>
<td>0</td>
<td>threshold of hearing</td>
</tr>
<tr>
<td>(1.0 \times 10^{-11})</td>
<td>10</td>
<td>rustling leaves</td>
</tr>
<tr>
<td>(1.0 \times 10^{-10})</td>
<td>20</td>
<td>quiet whisper</td>
</tr>
<tr>
<td>(1.0 \times 10^{-9})</td>
<td>30</td>
<td>whisper</td>
</tr>
<tr>
<td>(1.0 \times 10^{-8})</td>
<td>40</td>
<td>mosquito buzzing</td>
</tr>
<tr>
<td>(1.0 \times 10^{-7})</td>
<td>50</td>
<td>normal conversation</td>
</tr>
<tr>
<td>(1.0 \times 10^{-6})</td>
<td>60</td>
<td>air conditioner at 6 m</td>
</tr>
<tr>
<td>(1.0 \times 10^{-5})</td>
<td>70</td>
<td>vacuum cleaner</td>
</tr>
<tr>
<td>(1.0 \times 10^{-4})</td>
<td>80</td>
<td>busy traffic, alarm clock</td>
</tr>
<tr>
<td>(1.0 \times 10^{-3})</td>
<td>90</td>
<td>lawn mower</td>
</tr>
<tr>
<td>(1.0 \times 10^{-2})</td>
<td>100</td>
<td>subway, power motor</td>
</tr>
<tr>
<td>(1.0 \times 10^{-1})</td>
<td>110</td>
<td>auto horn at 1 m</td>
</tr>
<tr>
<td>(1.0 \times 10^{0})</td>
<td>120</td>
<td>threshold of pain</td>
</tr>
<tr>
<td>(1.0 \times 10^{1})</td>
<td>130</td>
<td>thunderclap, machine gun</td>
</tr>
<tr>
<td>(1.0 \times 10^{3})</td>
<td>150</td>
<td>nearby jet airplane</td>
</tr>
</tbody>
</table>

**Key Models and Analogies**

The decibel scale of loudness is designed similarly to the Richter scale, which measures earthquake intensity, and the pH scale, which measures acidity levels. The values on these scales correspond to the order of magnitude (power of 10) of the original quantities because these quantities span a very large range of values.

**Misconception Alert!**

Some students may confuse decibel level with intensity. Point out that the ratio of one decibel level to another does not give the ratio between the intensities of these sounds because the decibel scale is logarithmic. Work with examples in Figure 2.3 to correct this misconception.

**TEACH FROM VISUALS**

**Figure 2.3** Point out that zero on the decibel scale does not mean zero intensity or that there is no sound but instead that the sound is inaudible.

**Ask** How does the sound intensity of a subway compare with that of a conversation?

**Answer:** At equal distances, noise from a subway brings to our ears 100 000 \((10^{-2}/10^{-7})\) times more energy than a conversation. (Some students may think the answer is twice as much, or the ratio of 100 to 50. Explain why this is not the case.)
**Demonstration**

**Resonance**

**Purpose** Show resonance with tuning forks.

**Materials** several tuning forks (including two of the same frequency), two identical resonance boxes, a rubber mallet

**Procedure** Place the resonance boxes 15 cm apart with the open ends facing each other. Using the two forks that have the same frequency, mount a tuning fork on each box. Strike one fork with the mallet. Students who are listening carefully should begin to hear a faint sound from the second tuning fork when you stop the vibrations of the first tuning fork. Explain that because energy is transferred through air and wood, the second fork picked up these vibrations because its natural frequency matched that of the first fork. Repeat the experiment with forks of different frequencies to show that resonance does not occur in those cases.

**QuickLab**

**Teacher's Notes**

Students should recognize that resonance occurs when the frequency of the applied force (the pumping or pushing) matches the natural frequency of the system (the swing).

**Homework Options** This QuickLab can easily be performed outside of the physics lab room.

**Forced Vibrations and Resonance**

When an isolated guitar string is held taut and plucked, hardly any sound is heard. When the same string is placed on a guitar and plucked, the intensity of the sound increases dramatically. What is responsible for this difference? To find the answer to this question, consider a set of pendulums suspended from a beam and bound by a loose rubber band, as shown in Figure 2.4. If one of the pendulums is set in motion, its vibrations are transferred by the rubber band to the other pendulums, which will also begin vibrating. This is called a forced vibration.

The vibrating strings of a guitar force the bridge of the guitar to vibrate, and the bridge in turn transfers its vibrations to the guitar body. These forced vibrations are called sympathetic vibrations. Because the guitar body has a larger area than the strings do, it enables the strings' vibrations to be transferred to the air more efficiently. As a result, the intensity of the sound is increased, and the strings' vibrations die out faster than they would if they were not attached to the body of the guitar. In other words, the guitar body allows the energy exchange between the strings and the air to happen more efficiently, thereby increasing the intensity of the sound produced.

In an electric guitar, string vibrations are translated into electrical impulses, which can be amplified as much as desired. An electric guitar can produce sounds that are much more intense than those of an unamplified acoustic guitar, which uses only the forced vibrations of the guitar’s body to increase the intensity of the sound from the vibrating strings.

**Vibration at the natural frequency produces resonance.**

As you saw in the chapter on waves, the frequency of a pendulum depends on its string length. Thus, every pendulum will vibrate at a certain frequency, known as its natural frequency. In Figure 2.4, the two blue pendulums have the same natural frequency, while the red and green pendulums have different natural frequencies. When the first blue pendulum is set in motion, the red and green pendulums will vibrate only slightly, but the second blue pendulum will oscillate with a much larger amplitude because its natural frequency matches the frequency of the pendulum that was initially set in motion. This system is said to be in resonance.

**QuickLab**

**Resonance**

Go to a playground, and swing on one of the swings. Try pumping (or being pushed) at different rates—faster than, slower than, and equal to the natural frequency of the swing. Observe whether the rate at which you pump (or are pushed) affects how easily the amplitude of the vibration increases. Are some rates more effective at building your amplitude than others? You should find that the pushes are most effective when they match the swing’s natural frequency. Explain how your results support the statement that resonance works best when the frequency of the applied force matches the system’s natural frequency.

**Materials**

- swing set

**Differentiated Instruction**

**Inclusion**

To reinforce the concept of symphonic vibration with kinesthetic learners, mimic the pendulum and guitar examples in the classroom with a single rubber band and again with multiple rubber bands. Stretch the bands over a box or cup.
resonance. Because energy is transferred from one pendulum to the other, the amplitude of vibration of the first blue pendulum will decrease as the second blue pendulum’s amplitude increases.

A striking example of structural resonance occurred in 1940, when the Tacoma Narrows bridge in Washington, shown in Figure 2.5, was set in motion by the wind. High winds set up standing waves in the bridge, causing the bridge to oscillate at one of its natural frequencies. The amplitude of the vibrations increased until the bridge collapsed. A more recent example of structural resonance occurred during the Loma Prieta earthquake near Oakland, California, in 1989, when part of the upper deck of a freeway collapsed. The collapse of this particular section of roadway has been traced to the fact that the earthquake waves had a frequency of 1.5 Hz, very close to the natural frequency of that section of the roadway.

**FIGURE 2.5**

**Effects of Resonance** On November 7, 1940, the Tacoma Narrows suspension bridge collapsed, just four months after it opened. Standing waves caused by strong winds set the bridge in motion and led to its collapse.

**Conceptual Challenge**

**Concert** If a 15-person musical ensemble gains 15 new members, so that its size doubles, will a listener perceive the music created by the ensemble to be twice as loud? Why or why not?

**A Noisy Factory** Federal regulations require that no office or factory worker be exposed to noise levels that average above 90 dB over an 8 h day. Thus, a factory that currently averages 100 dB must reduce its noise level by 10 dB. Assuming that each piece of machinery produces the same amount of noise, what percentage of equipment must be removed? Explain your answer.

**Broken Crystal** Opera singers have been known to set crystal goblets in vibration with their powerful voices. In fact, an amplified human voice can shatter the glass, but only at certain fundamental frequencies. Speculate about why only certain fundamental frequencies will break the glass.

**Electric Guitars** Electric guitars, which use electric amplifiers to magnify their sound, can have a variety of shapes, but acoustic guitars all have the same basic shape. Explain why.

**Answers**

**Conceptual Challenge**

1. No; The intensity doubles, but loudness is not directly proportional to intensity.

2. Reducing the decibel level by 10 requires reducing the intensity by a factor of 10. Thus, 90 percent of the equipment must be removed.

3. Only frequencies that match one of the natural frequencies of the glass can establish a resonance condition. Only then can the vibrations become large enough to shatter the goblet.

4. The body of an acoustic guitar is designed so that it can transmit the strings’ vibrations to the air efficiently. (The guitar’s particular shape also determines the characteristic sound that distinguishes the guitar from similar instruments, such as banjos and lutes.) Because the vibrations of an electric guitar’s strings are converted into electrical signals, there are fewer restrictions on the electric guitar’s shape.

**PRE-AP**

Explain to students that structural resonance frequency must be considered in the building of suspension bridges and other structures. Select a few structures (e.g., Golden Gate Bridge, crystal water glass, etc.) Provide the equation for structural resonance frequency and the values needed to solve it, and ask students to determine whether the given structures could withstand various frequencies.
Assess and Reteach

Assess Use the Formative Assessment on this page to evaluate student mastery of the section. Reteach For students who need additional instruction, download the Section Study Guide. Response to Intervention To reassess students’ mastery, use the Section Quiz, available to print or to take directly online at HMDScience.com.

SECTION 2 FORMATIVE ASSESSMENT

Reviewing Main Ideas

1. When the decibel level of traffic in the street goes from 40 to 60 dB, how much greater is the intensity of the noise?

2. If two flutists play their instruments together at the same intensity, is the sound twice as loud as that of either flutist playing alone at that intensity? Why or why not?

3. A tuning fork consists of two metal prongs that vibrate at a single frequency when struck lightly. What will happen if a vibrating tuning fork is placed near another tuning fork of the same frequency? Explain.

4. A certain microphone placed in the ocean is sensitive to sounds emitted by dolphins. To produce a usable signal, sound waves striking the microphone must have a decibel level of 10 dB. If dolphins emit sound waves with a power of 0.050 W, how far can a dolphin be from the microphone and still be heard? (Assume the sound waves propagate spherically, and disregard absorption of the sound waves.)

Critical Thinking

5. Which of the following factors change when a sound gets louder? Which change when a pitch gets higher?
   a. intensity
   b. speed of the sound waves
   c. frequency
   d. decibel level
   e. wavelength
   f. amplitude

Answers to Section Assessment

1. The intensity has increased by a factor of 100 ($10^2$).

2. no; because the sensation of loudness is approximately logarithmic in the human ear

3. The second tuning fork will pick up the vibrations of the first tuning fork, and a faint sound will be heard from the second fork. This occurs because the two forks have the same natural frequency, which is the condition required for resonance.

4. $2.0 \times 10^4$ m

5. a, d, f; c, e

The human ear transmits vibrations that cause nerve impulses. The human ear is divided into three sections—outer, middle, and inner—as shown in Figure 2.6. Sound waves travel down the ear canal of the outer ear. The ear canal terminates at a thin, flat piece of tissue called the eardrum.

The eardrum vibrates with the sound waves and transfers these vibrations to the three small bones of the middle ear, known as the hammer, the anvil, and the stirrup. These bones in turn transmit the vibrations to the inner ear, which contains a snail-shaped tube about 2 cm long called the cochlea.

The basilar membrane runs through the coiled cochlea, dividing it roughly in half. The basilar membrane has different natural frequencies at different positions along its length, according to the width and thickness of the membrane at that point. Sound waves of varying frequencies resonate at different spots along the basilar membrane, creating impulses in hair cells—specialized nerve cells—embedded in the membrane. These impulses are then sent to the brain, which interprets them as sounds of varying frequencies.