17 PHYSICS OF HEARING

This tree fell some time ago. When it fell, atoms in the air were disturbed. Physicists would call this disturbance sound whether someone was around to hear it or not. (credit: B.A. Bowen Photography)

Chapter Outline

17.1. Sound
- Define sound and hearing.
- Describe sound as a longitudinal wave.

17.2. Speed of Sound, Frequency, and Wavelength
- Define pitch.
- Describe the relationship between the speed of sound, its frequency, and its wavelength.
- Describe the effects on the speed of sound as it travels through various media.
- Describe the effects of temperature on the speed of sound.

17.3. Sound Intensity and Sound Level
- Define intensity, sound intensity, and sound pressure level.
- Calculate sound intensity levels in decibels (dB).

17.4. Doppler Effect and Sonic Booms
- Define Doppler effect, Doppler shift, and sonic boom.
- Calculate the frequency of a sound heard by someone observing Doppler shift.
- Describe the sounds produced by objects moving faster than the speed of sound.

17.5. Sound Interference and Resonance: Standing Waves in Air Columns
- Define antinode, node, fundamental, overtones, and harmonics.
- Identify instances of sound interference in everyday situations.
- Describe how sound interference occurring inside open and closed tubes changes the characteristics of the sound, and how this applies to sounds produced by musical instruments.
- Calculate the length of a tube using sound wave measurements.

17.6. Hearing
- Define hearing, pitch, loudness, timbre, note, tone, phon, ultrasound, and infrasound.
- Compare loudness to frequency and intensity of a sound.
- Identify structures of the inner ear and explain how they relate to sound perception.

17.7. Ultrasound
- Define acoustic impedance and intensity reflection coefficient.
- Describe medical and other uses of ultrasound technology.
- Calculate acoustic impedance using density values and the speed of ultrasound.
- Calculate the velocity of a moving object using Doppler-shifted ultrasound.
Introduction to the Physics of Hearing

If a tree falls in the forest and no one is there to hear it, does it make a sound? The answer to this old philosophical question depends on how you define sound. If sound only exists when someone is around to perceive it, then there was no sound. However, if we define sound in terms of physics; that is, a disturbance of the atoms in matter transmitted from its origin outward (in other words, a wave), then there was a sound, even if nobody was around to hear it.

Such a wave is the physical phenomenon we call sound. Its perception is hearing. Both the physical phenomenon and its perception are interesting and will be considered in this text. We shall explore both sound and hearing; they are related, but are not the same thing. We will also explore the many practical uses of sound waves, such as in medical imaging.

17.1 Sound

Sound can be used as a familiar illustration of waves. Because hearing is one of our most important senses, it is interesting to see how the physical properties of sound correspond to our perceptions of it. Hearing is the perception of sound, just as vision is the perception of visible light. But sound has important applications beyond hearing. Ultrasound, for example, is not heard but can be employed to form medical images and is also used in treatment.

The physical phenomenon of sound is defined to be a disturbance of matter that is transmitted from its source outward. Sound is a wave. On the atomic scale, it is a disturbance of atoms that is far more ordered than their thermal motions. In many instances, sound is a periodic wave, and the atoms undergo simple harmonic motion. In this text, we shall explore such periodic sound waves.

A vibrating string produces a sound wave as illustrated in Figure 17.3, Figure 17.4, and Figure 17.5. As the string oscillates back and forth, it transfers energy to the air, mostly as thermal energy created by turbulence. But a small part of the string’s energy goes into compressing and expanding the surrounding air, creating slightly higher and lower local pressures. These compressions (high pressure regions) and rarefactions (low pressure regions) move out as longitudinal pressure waves having the same frequency as the string—they are the disturbance that is a sound wave. (Sound waves in air and most fluids are longitudinal, because fluids have almost no shear strength. In solids, sound waves can be both transverse and longitudinal.) Figure 17.5 shows a graph of gauge pressure versus distance from the vibrating string.
After many vibrations, there are a series of compressions and rarefactions moving out from the string as a sound wave. The graph shows gauge pressure versus distance from the source. Pressures vary only slightly from atmospheric for ordinary sounds.

The amplitude of a sound wave decreases with distance from its source, because the energy of the wave is spread over a larger and larger area. But it is also absorbed by objects, such as the eardrum in Figure 17.6, and converted to thermal energy by the viscosity of air. In addition, during each compression a little heat transfers to the air and during each rarefaction even less heat transfers from the air, so that the heat transfer reduces the organized disturbance into random thermal motions. (These processes can be viewed as a manifestation of the second law of thermodynamics presented in Introduction to the Second Law of Thermodynamics: Heat Engines and Their Efficiency.) Whether the heat transfer from compression to rarefaction is significant depends on how far apart they are—that is, it depends on wavelength. Wavelength, frequency, amplitude, and speed of propagation are important for sound, as they are for all waves.

Sound wave compressions and rarefactions travel up the ear canal and force the eardrum to vibrate. There is a net force on the eardrum, since the sound wave pressures differ from the atmospheric pressure found behind the eardrum. A complicated mechanism converts the vibrations to nerve impulses, which are perceived by the person.

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**PhET Explorations: Wave Interference**

Make waves with a dripping faucet, audio speaker, or laser! Add a second source or a pair of slits to create an interference pattern.

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**PhET Interactive Simulation**

Figure 17.7 Wave Interference (http://cnx.org/content/m42255/1.3/wave-interference_en.jar)
17.2 Speed of Sound, Frequency, and Wavelength

Figure 17.8 When a firework explodes, the light energy is perceived before the sound energy. Sound travels more slowly than light does. (credit: Dominic Alves, Flickr)

Sound, like all waves, travels at a certain speed and has the properties of frequency and wavelength. You can observe direct evidence of the speed of sound while watching a fireworks display. The flash of an explosion is seen well before its sound is heard, implying both that sound travels at a finite speed and that it is much slower than light. You can also directly sense the frequency of a sound. Perception of frequency is called pitch. The wavelength of sound is not directly sensed, but indirect evidence is found in the correlation of the size of musical instruments with their pitch. Small instruments, such as a piccolo, typically make high-pitch sounds, while large instruments, such as a tuba, typically make low-pitch sounds. High pitch means small wavelength, and the size of a musical instrument is directly related to the wavelengths of sound it produces. So a small instrument creates short-wavelength sounds. Similar arguments hold that a large instrument creates long-wavelength sounds.

The relationship of the speed of sound, its frequency, and wavelength is the same as for all waves:

\[ v_w = f\lambda, \quad (17.1) \]

where \( v_w \) is the speed of sound, \( f \) is its frequency, and \( \lambda \) is its wavelength. The wavelength of a sound is the distance between adjacent identical parts of a wave—for example, between adjacent compressions as illustrated in Figure 17.9. The frequency is the same as that of the source and is the number of waves that pass a point per unit time.

Figure 17.9 A sound wave emanates from a source vibrating at a frequency \( f \), propagates at \( v_w \), and has a wavelength \( \lambda \).

Table 17.1 makes it apparent that the speed of sound varies greatly in different media. The speed of sound in a medium is determined by a combination of the medium's rigidity (or compressibility in gases) and its density. The more rigid (or less compressible) the medium, the faster the speed of sound. This observation is analogous to the fact that the frequency of a simple harmonic motion is directly proportional to the stiffness of the oscillating object. The greater the density of a medium, the slower the speed of sound. This observation is analogous to the fact that the frequency of a simple harmonic motion is inversely proportional to the mass of the oscillating object. The speed of sound in air is low, because air is compressible. Because liquids and solids are relatively rigid and very difficult to compress, the speed of sound in such media is generally greater than in gases.
Table 17.1 Speed of Sound in Various Media

<table>
<thead>
<tr>
<th>Medium</th>
<th>$v_w$(m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gases at 0°C</strong></td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>331</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>259</td>
</tr>
<tr>
<td>Oxygen</td>
<td>316</td>
</tr>
<tr>
<td>Helium</td>
<td>965</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>1290</td>
</tr>
<tr>
<td><strong>Liquids at 20°C</strong></td>
<td></td>
</tr>
<tr>
<td>Ethanol</td>
<td>1160</td>
</tr>
<tr>
<td>Mercury</td>
<td>1450</td>
</tr>
<tr>
<td>Water, fresh</td>
<td>1480</td>
</tr>
<tr>
<td>Sea water</td>
<td>1540</td>
</tr>
<tr>
<td>Human tissue</td>
<td>1540</td>
</tr>
<tr>
<td><strong>Solids (longitudinal or bulk)</strong></td>
<td></td>
</tr>
<tr>
<td>Vulcanized rubber</td>
<td>54</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>920</td>
</tr>
<tr>
<td>Marble</td>
<td>3810</td>
</tr>
<tr>
<td>Glass, Pyrex</td>
<td>5640</td>
</tr>
<tr>
<td>Lead</td>
<td>1960</td>
</tr>
<tr>
<td>Aluminum</td>
<td>5120</td>
</tr>
<tr>
<td>Steel</td>
<td>5960</td>
</tr>
</tbody>
</table>

Earthquakes, essentially sound waves in Earth’s crust, are an interesting example of how the speed of sound depends on the rigidity of the medium. Earthquakes have both longitudinal and transverse components, and these travel at different speeds. The bulk modulus of granite is greater than its shear modulus. For that reason, the speed of longitudinal or pressure waves ($P$-waves) in earthquakes in granite is significantly higher than the speed of transverse or shear waves ($S$-waves). Both components of earthquakes travel slower in less rigid material, such as sediments. $P$-waves have speeds of 4 to 7 km/s, and $S$-waves correspondingly range in speed from 2 to 5 km/s, both being faster in more rigid material. The $P$-wave gets progressively farther ahead of the $S$-wave as they travel through Earth’s crust. The time between the $P$- and $S$-waves is routinely used to determine the distance to their source, the epicenter of the earthquake.

The speed of sound is affected by temperature in a given medium. For air at sea level, the speed of sound is given by

$$v_w = \left(331 \text{ m/s}\right)\sqrt{\frac{T}{273 \text{ K}}},$$

where the temperature (denoted as $T$) is in units of kelvin. The speed of sound in gases is related to the average speed of particles in the gas, $v_{rms}$, and that

$$v_{rms} = \sqrt{\frac{kT}{m}},$$

where $k$ is the Boltzmann constant ($1.38 \times 10^{-23}$ J/K) and $m$ is the mass of each (identical) particle in the gas. So, it is reasonable that the speed of sound in air and other gases should depend on the square root of temperature. While not negligible, this is not a strong dependence. At 0°C, the speed of sound is 331 m/s, whereas at 20.0°C it is 343 m/s, less than a 4% increase. Figure 17.10 shows a use of the speed of sound by a bat to sense distances. Echoes are also used in medical imaging.
One of the more important properties of sound is that its speed is nearly independent of frequency. This independence is certainly true in open air for sounds in the audible range of 20 to 20,000 Hz. If this independence were not true, you would certainly notice it for music played by a marching band in a football stadium, for example. Suppose that high-frequency sounds traveled faster—then the farther you were from the band, the more the sound from the low-pitch instruments would lag that from the high-pitch ones. But the music from all instruments arrives in cadence independent of distance, and so all frequencies must travel at nearly the same speed. Recall that

$$v_w = f\lambda.$$  \hspace{1cm} (17.4)

In a given medium under fixed conditions, $v_w$ is constant, so that there is a relationship between $f$ and $\lambda$; the higher the frequency, the smaller the wavelength. See Figure 17.11 and consider the following example.

**Example 17.1 Calculating Wavelengths: What Are the Wavelengths of Audible Sounds?**

Calculate the wavelengths of sounds at the extremes of the audible range, 20 and 20,000 Hz, in 30.0°C air. (Assume that the frequency values are accurate to two significant figures.)

**Strategy**
To find wavelength from frequency, we can use $v_w = f\lambda$.

**Solution**
1. Identify knowns. The value for $v_w$ is given by

$$v_w = (331 \text{ m/s})\left(\frac{T}{273 \text{ K}}\right).$$  \hspace{1cm} (17.5)

2. Convert the temperature into kelvin and then enter the temperature into the equation

$$v_w = (331 \text{ m/s})\left(\frac{303 \text{ K}}{273 \text{ K}}\right) = 348.7 \text{ m/s}.$$  \hspace{1cm} (17.6)

3. Solve the relationship between speed and wavelength for $\lambda$:

$$\lambda = \frac{v_w}{f}.$$  \hspace{1cm} (17.7)

4. Enter the speed and the minimum frequency to give the maximum wavelength:

$$\lambda_{\text{max}} = \frac{348.7 \text{ m/s}}{20 \text{ Hz}} = 17 \text{ m}.$$  \hspace{1cm} (17.8)
5. Enter the speed and the maximum frequency to give the minimum wavelength:

\[ \lambda_{\text{min}} = \frac{348.7 \text{ m/s}}{20,000 \text{ Hz}} = 0.017 \text{ m} = 1.7 \text{ cm.} \]  

**Discussion**

Because the product of \( f \) multiplied by \( \lambda \) equals a constant, the smaller \( f \) is, the larger \( \lambda \) must be, and vice versa.

The speed of sound can change when sound travels from one medium to another. However, the frequency usually remains the same because it is like a driven oscillation and has the frequency of the original source. If \( v_w \) changes and \( f \) remains the same, then the wavelength \( \lambda \) must change. That is, because \( v_w = f \lambda \), the higher the speed of a sound, the greater its wavelength for a given frequency.

**Making Connections: Take-Home Investigation—Voice as a Sound Wave**

Suspend a sheet of paper so that the top edge of the paper is fixed and the bottom edge is free to move. You could tape the top edge of the paper to the edge of a table. Gently blow near the edge of the bottom of the sheet and note how the sheet moves. Speak softly and then louder such that the sounds hit the edge of the bottom of the paper, and note how the sheet moves. Explain the effects.

**Check Your Understanding**

Imagine you observe two fireworks explode. You hear the explosion of one as soon as you see it. However, you see the other firework for several milliseconds before you hear the explosion. Explain why this is so.

**Solution**

Sound and light both travel at definite speeds. The speed of sound is slower than the speed of light. The first firework is probably very close by, so the speed difference is not noticeable. The second firework is farther away, so the light arrives at your eyes noticeably sooner than the sound wave arrives at your ears.

**Check Your Understanding**

You observe two musical instruments that you cannot identify. One plays high-pitch sounds and the other plays low-pitch sounds. How could you determine which is which without hearing either of them play?

**Solution**

Compare their sizes. High-pitch instruments are generally smaller than low-pitch instruments because they generate a smaller wavelength.

### 17.3 Sound Intensity and Sound Level

In a quiet forest, you can sometimes hear a single leaf fall to the ground. After settling into bed, you may hear your blood pulsing through your ears. But when a passing motorist has his stereo turned up, you cannot even hear what the person next to you in your car is saying. We are all very familiar with the loudness of sounds and aware that they are related to how energetically the source is vibrating. In cartoons depicting a screaming person (or an animal making a loud noise), the cartoonist often shows an open mouth with a vibrating uvula, the hanging tissue at the back of the mouth, to suggest a loud sound coming from the throat. High noise exposure is hazardous to hearing, and it is common for musicians to have hearing losses that are
sufficiently severe that they interfere with the musicians’ abilities to perform. The relevant physical quantity is sound intensity, a concept that is valid for all sounds whether or not they are in the audible range.

Intensity is defined to be the power per unit area carried by a wave. Power is the rate at which energy is transferred by the wave. In equation form, intensity $I$ is

$$ I = \frac{P}{A}. $$

(17.10)

where $P$ is the power through an area $A$. The SI unit for $I$ is $\text{W/m}^2$. The intensity of a sound wave is related to its amplitude squared by the following relationship:

$$ I = \frac{(\Delta p)^2}{2\rho v_w}. $$

(17.11)

Here $\Delta p$ is the pressure variation or pressure amplitude (half the difference between the maximum and minimum pressure in the sound wave) in units of pascals (Pa) or $\text{N/m}^2$. (We are using a lower case $p$ for pressure to distinguish it from power, denoted by $P$ above.) The energy (as kinetic energy $\frac{mv^2}{2}$) of an oscillating element of air due to a traveling sound wave is proportional to its amplitude squared. In this equation, $\rho$ is the density of the material in which the sound wave travels, in units of $\text{kg/m}^3$, and $v_w$ is the speed of sound in the medium, in units of $\text{m/s}$. The pressure variation is proportional to the amplitude of the oscillation, and so $I$ varies as $(\Delta p)^2$ (Figure 17.13). This relationship is consistent with the fact that the sound wave is produced by some vibration; the greater its pressure amplitude, the more the air is compressed in the sound it creates.

![Figure 17.13](image)

Figure 17.13 Graphs of the gauge pressures in two sound waves of different intensities. The more intense sound is produced by a source that has larger-amplitude oscillations and has greater pressure maxima and minima. Because pressures are higher in the greater-intensity sound, it can exert larger forces on the objects it encounters.

Sound intensity levels are quoted in decibels (dB) much more often than sound intensities in watts per meter squared. Decibels are the unit of choice in the scientific literature as well as in the popular media. The reasons for this choice of units are related to how we perceive sounds. How our ears perceive sound can be more accurately described by the logarithm of the intensity rather than directly to the intensity. The sound intensity level $\beta$ in decibels of a sound having an intensity $I$ in watts per meter squared is defined to be

$$ \beta (\text{dB}) = 10 \log_{10} \left( \frac{I}{I_0} \right). $$

(17.12)

where $I_0 = 10^{-12} \text{ W/m}^2$ is a reference intensity. In particular, $I_0$ is the lowest or threshold intensity of sound a person with normal hearing can perceive at a frequency of 1000 Hz. Sound intensity level is not the same as intensity. Because $\beta$ is defined in terms of a ratio, it is a unitless quantity telling you the level of the sound relative to a fixed standard (10$^{-12}$ $\text{ W/m}^2$, in this case). The units of decibels (dB) are used to indicate this ratio is multiplied by 10 in its definition. The bel, upon which the decibel is based, is named for Alexander Graham Bell, the inventor of the telephone.
Table 17.2 Sound Intensity Levels and Intensities

<table>
<thead>
<tr>
<th>Sound intensity level $\beta$ (dB)</th>
<th>Intensity $I$ (W/m$^2$)</th>
<th>Example/effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$1 \times 10^{-12}$</td>
<td>Threshold of hearing at 1000 Hz</td>
</tr>
<tr>
<td>10</td>
<td>$1 \times 10^{-11}$</td>
<td>Rustle of leaves</td>
</tr>
<tr>
<td>20</td>
<td>$1 \times 10^{-10}$</td>
<td>Whisper at 1 m distance</td>
</tr>
<tr>
<td>30</td>
<td>$1 \times 10^{-9}$</td>
<td>Quiet home</td>
</tr>
<tr>
<td>40</td>
<td>$1 \times 10^{-8}$</td>
<td>Average home</td>
</tr>
<tr>
<td>50</td>
<td>$1 \times 10^{-7}$</td>
<td>Average office, soft music</td>
</tr>
<tr>
<td>60</td>
<td>$1 \times 10^{-6}$</td>
<td>Normal conversation</td>
</tr>
<tr>
<td>70</td>
<td>$1 \times 10^{-5}$</td>
<td>Noisy office, busy traffic</td>
</tr>
<tr>
<td>80</td>
<td>$1 \times 10^{-4}$</td>
<td>Loud radio, classroom lecture</td>
</tr>
<tr>
<td>90</td>
<td>$1 \times 10^{-3}$</td>
<td>Inside a heavy truck; damage from prolonged exposure$^1$</td>
</tr>
<tr>
<td>100</td>
<td>$1 \times 10^{-2}$</td>
<td>Noisy factory, siren at 30 m; damage from 8 h per day exposure</td>
</tr>
<tr>
<td>110</td>
<td>$1 \times 10^{-1}$</td>
<td>Damage from 30 min per day exposure</td>
</tr>
<tr>
<td>120</td>
<td>1</td>
<td>Loud rock concert, pneumatic chipper at 2 m; threshold of pain</td>
</tr>
<tr>
<td>140</td>
<td>$1 \times 10^{2}$</td>
<td>Jet airplane at 30 m; severe pain, damage in seconds</td>
</tr>
<tr>
<td>160</td>
<td>$1 \times 10^{4}$</td>
<td>Bursting of eardrums</td>
</tr>
</tbody>
</table>

The decibel level of a sound having the threshold intensity of $10^{-12}$ W/m$^2$ is $\beta = 0$ dB, because $\log_{10} 1 = 0$. That is, the threshold of hearing is 0 decibels. Table 17.2 gives levels in decibels and intensities in watts per meter squared for some familiar sounds.

One of the more striking things about the intensities in Table 17.2 is that the intensity in watts per meter squared is quite small for most sounds. The ear is sensitive to as little as a trillionth of a watt per meter squared—even more impressive when you realize that the area of the eardrum is only about $1 \text{ cm}^2$, so that only $10^{-16}$ W falls on it at the threshold of hearing! Air molecules in a sound wave of this intensity vibrate over a distance of less than one molecular diameter, and the gauge pressures involved are less than $10^{-9}$ atm.

Another impressive feature of the sounds in Table 17.2 is their numerical range. Sound intensity varies by a factor of $10^{12}$ from threshold to a sound that causes damage in seconds. You are unaware of this tremendous range in sound intensity because how your ears respond can be described approximately as the logarithm of intensity. Thus, sound intensity levels in decibels fit your experience better than intensities in watts per meter squared. The decibel scale is also easier to relate to because most people are more accustomed to dealing with numbers such as 0, 53, or 120 than numbers such as $1.00 \times 10^{-11}$.

One more observation readily verified by examining Table 17.2 or using $I = \frac{(\Delta p)^2}{2 \rho v_w}$ is that each factor of 10 in intensity corresponds to 10 dB. For example, a 90 dB sound compared with a 60 dB sound is 30 dB greater, or three factors of 10 (that is, $10^3$ times) as intense. Another example is that if one sound is $10^7$ as intense as another, it is 70 dB higher. See Table 17.3.

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1. Several government agencies and health-related professional associations recommend that 85 dB not be exceeded for 8-hour daily exposures in the absence of hearing protection.
Table 17.3 Ratios of Intensities and Corresponding Differences in Sound Intensity Levels

<table>
<thead>
<tr>
<th>$I_2/I_1$</th>
<th>$\beta_2 - \beta_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>3.0 dB</td>
</tr>
<tr>
<td>5.0</td>
<td>7.0 dB</td>
</tr>
<tr>
<td>10.0</td>
<td>10.0 dB</td>
</tr>
</tbody>
</table>

Example 17.2 Calculating Sound Intensity Levels: Sound Waves

Calculate the sound intensity level in decibels for a sound wave traveling in air at 0ºC and having a pressure amplitude of 0.656 Pa.

**Strategy**

We are given $\Delta p$, so we can calculate $I$ using the equation $I = (\Delta p)^2/(2\rho v_w)^2$. Using $I$, we can calculate $\beta$ straight from its definition in $\beta$ (dB) = $10 \log_{10}(I/I_0)$.

**Solution**

(1) Identify knowns:

- Sound travels at 331 m/s in air at 0ºC.
- Air has a density of 1.29 kg/m³ at atmospheric pressure and 0ºC.

(2) Enter these values and the pressure amplitude into $I = (\Delta p)^2/(2\rho v_w)$:

$$I = \frac{(0.656\text{ Pa})^2}{2(1.29\text{ kg/m}^3)(331\text{ m/s})} = 5.04 \times 10^{-4}\text{ W/m}^2.$$  

(17.13)

(3) Enter the value for $I$ and the known value for $I_0$ into $\beta$ (dB) = $10 \log_{10}(I/I_0)$.

$$10 \log_{10}(5.04 \times 10^{-8}) = 10 \left(8.70\right)\text{ dB} = 87\text{ dB}.$$  

(17.14)

**Discussion**

This 87 dB sound has an intensity five times as great as an 80 dB sound. So a factor of five in intensity corresponds to a difference of 7 dB in sound intensity level. This value is true for any intensities differing by a factor of five.

Example 17.3 Change Intensity Levels of a Sound: What Happens to the Decibel Level?

Show that if one sound is twice as intense as another, it has a sound level about 3 dB higher.

**Strategy**

You are given that the ratio of two intensities is 2 to 1, and are then asked to find the difference in their sound levels in decibels. You can solve this problem using of the properties of logarithms.

**Solution**

(1) Identify knowns:

- The ratio of the two intensities is 2 to 1, or:

$$\frac{I_2}{I_1} = 2.00.$$  

(17.15)

We wish to show that the difference in sound levels is about 3 dB. That is, we want to show:

$$\beta_2 - \beta_1 = 3\text{ dB}.$$  

(17.16)

Note that:

$$\log_{10}b - \log_{10}a = \log_{10}\left(\frac{b}{a}\right)$$  

(17.17)
(2) Use the definition of $\beta$ to get:

$$\beta_2 - \beta_1 = 10 \log_{10} \left( \frac{I_2}{I_1} \right) = 10 \log_{10} 2.00 = 10 (0.301) \text{ dB.} \quad (17.18)$$

Thus,

$$\beta_2 - \beta_1 = 3.01 \text{ dB.} \quad (17.19)$$

**Discussion**

This means that the two sound intensity levels differ by $3.01 \text{ dB}$, or about $3 \text{ dB}$, as advertised. Note that because only the ratio $I_2 / I_1$ is given (and not the actual intensities), this result is true for any intensities that differ by a factor of two. For example, a $56.0 \text{ dB}$ sound is twice as intense as a $53.0 \text{ dB}$ sound, a $97.0 \text{ dB}$ sound is half as intense as a $100 \text{ dB}$ sound, and so on.

It should be noted at this point that there is another decibel scale in use, called the **sound pressure level**, based on the ratio of the pressure amplitude to a reference pressure. This scale is used particularly in applications where sound travels in water. It is beyond the scope of most introductory texts to treat this scale because it is not commonly used for sounds in air, but it is important to note that very different decibel levels may be encountered when sound pressure levels are quoted. For example, ocean noise pollution produced by ships may be as great as $200 \text{ dB}$ expressed in the sound pressure level, where the more familiar sound intensity level we use here would be something under $140 \text{ dB}$ for the same sound.

**Take-Home Investigation: Feeling Sound**

Find a CD player and a CD that has rock music. Place the player on a light table, insert the CD into the player, and start playing the CD. Place your hand gently on the table next to the speakers. Increase the volume and note the level when the table just begins to vibrate as the rock music plays. Increase the reading on the volume control until it doubles. What has happened to the vibrations?

**Check Your Understanding**

Describe how amplitude is related to the loudness of a sound.

**Solution**

Amplitude is directly proportional to the experience of loudness. As amplitude increases, loudness increases.

**Check Your Understanding**

Identify common sounds at the levels of $10 \text{ dB}$, $50 \text{ dB}$, and $100 \text{ dB}$.

**Solution**

$10 \text{ dB}$: Running fingers through your hair.
$50 \text{ dB}$: Inside a quiet home with no television or radio.
$100 \text{ dB}$: Take-off of a jet plane.

### 17.4 Doppler Effect and Sonic Booms

The characteristic sound of a motorcycle buzzing by is an example of the **Doppler effect**. The high-pitch scream shifts dramatically to a lower-pitch roar as the motorcycle passes by a stationary observer. The closer the motorcycle brushes by, the more abrupt the shift. The faster the motorcycle moves, the greater the shift. We also hear this characteristic shift in frequency for passing race cars, airplanes, and trains. It is so familiar that it is used to imply motion and children often mimic it in play.

The Doppler effect is an alteration in the observed frequency of a sound due to motion of either the source or the observer. Although less familiar, this effect is easily noticed for a stationary source and moving observer. For example, if you ride a train past a stationary warning bell, you will hear the bell's frequency shift from high to low as you pass by. The actual change in frequency due to relative motion of source and observer is called a **Doppler shift**. The Doppler effect and Doppler shift are named for the Austrian physicist and mathematician Christian Johann Doppler (1803–1853), who did experiments with both moving sources and moving observers. Doppler, for example, had musicians play on a moving open train car and also play standing next to the train tracks as a train passed by. Their music was observed both on and off the train, and changes in frequency were measured.

What causes the Doppler shift? **Figure 17.14**, **Figure 17.15**, and **Figure 17.16** compare sound waves emitted by stationary and moving sources in a stationary air mass. Each disturbance spreads out spherically from the point where the sound was emitted. If the source is stationary, then all of the spheres representing the air compressions in the sound wave centered on the same
point, and the stationary observers on either side see the same wavelength and frequency as emitted by the source, as in Figure 17.14. If the source is moving, as in Figure 17.15, then the situation is different. Each compression of the air moves out in a sphere from the point where it was emitted, but the point of emission moves. This moving emission point causes the air compressions to be closer together on one side and farther apart on the other. Thus, the wavelength is shorter in the direction the source is moving (on the right in Figure 17.15), and longer in the opposite direction (on the left in Figure 17.15). Finally, if the observers move, as in Figure 17.16, the frequency at which they receive the compressions changes. The observer moving toward the source receives them at a higher frequency, and the person moving away from the source receives them at a lower frequency.

![Figure 17.14](image1.png) Sounds emitted by a source spread out in spherical waves. Because the source, observers, and air are stationary, the wavelength and frequency are the same in all directions and to all observers.

![Figure 17.15](image2.png) Sounds emitted by a source moving to the right spread out from the points at which they were emitted. The wavelength is reduced and, consequently, the frequency is increased in the direction of motion, so that the observer on the right hears a higher-pitch sound. The opposite is true for the observer on the left, where the wavelength is increased and the frequency is reduced.

![Figure 17.16](image3.png) The same effect is produced when the observers move relative to the source. Motion toward the source increases frequency as the observer on the right passes through more wave crests than she would if stationary. Motion away from the source decreases frequency as the observer on the left passes through fewer wave crests than he would if stationary.

We know that wavelength and frequency are related by \( v_w = f \lambda \), where \( v_w \) is the fixed speed of sound. The sound moves in a medium and has the same speed \( v_w \) in that medium whether the source is moving or not. Thus \( f \) multiplied by \( \lambda \) is a constant. Because the observer on the right in Figure 17.15 receives a shorter wavelength, the frequency she receives must be higher. Similarly, the observer on the left receives a longer wavelength, and hence he hears a lower frequency. The same thing happens in Figure 17.16. A higher frequency is received by the observer moving toward the source, and a lower frequency is received by an observer moving away from the source. In general, then, relative motion of source and observer toward one another increases the received frequency. Relative motion apart decreases frequency. The greater the relative speed is, the greater the effect.

### The Doppler Effect

The Doppler effect occurs not only for sound but for any wave when there is relative motion between the observer and the source. There are Doppler shifts in the frequency of sound, light, and water waves, for example. Doppler shifts can be used...
to determine velocity, such as when ultrasound is reflected from blood in a medical diagnostic. The recession of galaxies is
determined by the shift in the frequencies of light received from them and has implied much about the origins of the
universe. Modern physics has been profoundly affected by observations of Doppler shifts.

For a stationary observer and a moving source, the frequency $f_{\text{obs}}$ received by the observer can be shown to be

$$f_{\text{obs}} = f_s \left( \frac{v_w}{v_w \pm v_s} \right) \quad (17.20)$$

where $f_s$ is the frequency of the source, $v_s$ is the speed of the source along a line joining the source and observer, and
$v_w$ is the speed of sound. The minus sign is used for motion toward the observer and the plus sign for motion away from
the observer, producing the appropriate shifts up and down in frequency. Note that the greater the speed of the
source, the greater the effect. Similarly, for a stationary source and moving observer, the frequency received by
the observer $f_{\text{obs}}$ is given by

$$f_{\text{obs}} = f_s \left( \frac{v_w \pm v_{\text{obs}}}{v_w} \right) \quad (17.21)$$

where $v_{\text{obs}}$ is the speed of the observer along a line joining the source and observer. Here the plus sign is for motion
toward the source, and the minus is for motion away from the source.

**Example 17.4 Calculate Doppler Shift: A Train Horn**

Suppose a train that has a 150-Hz horn is moving at 35.0 m/s in still air on a day when the speed of sound is 340 m/s.

(a) What frequencies are observed by a stationary person at the side of the tracks as the train approaches and after it
passes?

(b) What frequency is observed by the train’s engineer traveling on the train?

**Strategy**

To find the observed frequency in (a), $f_{\text{obs}} = f_s \left( \frac{v_w}{v_w \pm v_s} \right)$, must be used because
the source is moving. The minus sign is used for the approaching train, and the plus sign for the receding train. In (b),
there are two Doppler shifts—one for a moving source and the other for a moving observer.

**Solution for (a)**

(1) Enter known values into $f_{\text{obs}} = f_s \left( \frac{v_w}{v_w \pm v_s} \right)$.

$$f_{\text{obs}} = f_s \left( \frac{v_w}{v_w - v_s} \right) = (150 \text{ Hz}) \left( \frac{340 \text{ m/s}}{340 \text{ m/s} - 35.0 \text{ m/s}} \right)$$

(2) Calculate the frequency observed by a stationary person as the train approaches.

$$f_{\text{obs}} = (150 \text{ Hz})(1.11) = 167 \text{ Hz} \quad (17.23)$$

(3) Use the same equation with the plus sign to find the frequency heard by a stationary person as the train recedes.

$$f_{\text{obs}} = f_s \left( \frac{v_w + v_{\text{obs}}}{v_w} \right) = (150 \text{ Hz}) \left( \frac{340 \text{ m/s}}{340 \text{ m/s} + 35.0 \text{ m/s}} \right)$$

(4) Calculate the second frequency.

$$f_{\text{obs}} = (150 \text{ Hz})(0.907) = 136 \text{ Hz} \quad (17.25)$$

**Discussion on (a)**

The numbers calculated are valid when the train is far enough away that the motion is nearly along the line joining
train and observer. In both cases, the shift is significant and easily noticed. Note that the shift is 17.0 Hz for motion
toward and 14.0 Hz for motion away. The shifts are not symmetric.

**Solution for (b)**

(1) Identify knowns:

- It seems reasonable that the engineer would receive the same frequency as emitted by the horn, because the relative
  velocity between them is zero.
- Relative to the medium (air), the speeds are $v_s = v_{\text{obs}} = 35.0 \text{ m/s}$.
- The first Doppler shift is for the moving observer; the second is for the moving source.

(2) Use the following equation:
\[ f_{\text{obs}} = \left[ f_s \left( \frac{v_w \pm v_{\text{obs}}}{v_w} \right) \right] \left( \frac{v_w}{v_w \pm v_s} \right) \quad (17.26) \]

The quantity in the square brackets is the Doppler-shifted frequency due to a moving observer. The factor on the right is the effect of the moving source.

(3) Because the train engineer is moving in the direction toward the horn, we must use the plus sign for \( v_{\text{obs}} \); however, because the horn is also moving in the direction away from the engineer, we also use the plus sign for \( v_s \). But the train is carrying both the engineer and the horn at the same velocity, so \( v_s = v_{\text{obs}} \). As a result, everything but \( f_s \) cancels, yielding

\[ f_{\text{obs}} = f_s. \quad (17.27) \]

**Discussion for (b)**

We may expect that there is no change in frequency when source and observer move together because it fits your experience. For example, there is no Doppler shift in the frequency of conversations between driver and passenger on a motorcycle. People talking when a wind moves the air between them also observe no Doppler shift in their conversation. The crucial point is that source and observer are not moving relative to each other.

### Sonic Booms to Bow Wakes

What happens to the sound produced by a moving source, such as a jet airplane, that approaches or even exceeds the speed of sound? The answer to this question applies not only to sound but to all other waves as well.

Suppose a jet airplane is coming nearly straight at you, emitting a sound of frequency \( f_s \). The greater the plane’s speed \( v_s \), the greater the Doppler shift and the greater the value observed for \( f_{\text{obs}} \). Now, as \( v_s \) approaches the speed of sound, \( f_{\text{obs}} \) approaches infinity, because the denominator in \( f_{\text{obs}} = f_s \left( \frac{v_w}{v_w \pm v_s} \right) \) approaches zero. At the speed of sound, this result means that in front of the source, each successive wave is superimposed on the previous one because the source moves forward at the speed of sound. The observer gets them all at the same instant, and so the frequency is infinite. (Before airplanes exceeded the speed of sound, some people argued it would be impossible because such constructive superposition would produce pressures great enough to destroy the airplane.) If the source exceeds the speed of sound, no sound is received by the observer until the source has passed, so that the sounds from the approaching source are mixed with those from it when receding. This mixing appears messy, but something interesting happens—a sonic boom is created. (See Figure 17.17.)

![Figure 17.17](https://example.com/fig17_17.png)

*Figure 17.17* Sound waves from a source that moves faster than the speed of sound spread spherically from the point where they are emitted, but the source moves ahead of each. Constructive interference along the lines shown (actually a cone in three dimensions) creates a shock wave called a sonic boom. The faster the speed of the source, the smaller the angle \( \theta \).

There is constructive interference along the lines shown (a cone in three dimensions) from similar sound waves arriving there simultaneously. This superposition forms a disturbance called a sonic boom, a constructive interference of sound created by an object moving faster than sound. Inside the cone, the interference is mostly destructive, and so the sound intensity there is much less than on the shock wave. An aircraft creates two sonic booms, one from its nose and one from its tail. (See Figure 17.18.) During television coverage of space shuttle landings, two distinct booms could often be heard. These were separated by exactly the time it would take the shuttle to pass by a point. Observers on the ground often do not see the aircraft creating the sonic boom, because it has passed by before the shock wave reaches them, as seen in Figure 17.18. If the aircraft flies close by at low altitude, pressures in the sonic boom can be destructive and break windows as well as rattle nerves. Because of how destructive sonic booms can be, supersonic flights are banned over populated areas of the United States.
Sonic booms are one example of a broader phenomenon called bow wakes. A **bow wake**, such as the one in Figure 17.19, is created when the wave source moves faster than the wave propagation speed. Water waves spread out in circles from the point where created, and the bow wake is the familiar V-shaped wake trailing the source. A more exotic bow wake is created when a subatomic particle travels through a medium faster than the speed of light travels in that medium. (In a vacuum, the maximum speed of light will be $c = 3.00 \times 10^8$ m/s; in the medium of water, the speed of light is closer to $0.75c$.) If the particle creates light in its passage, that light spreads on a cone with an angle indicative of the speed of the particle, as illustrated in Figure 17.20. Such a bow wake is called Cerenkov radiation and is commonly observed in particle physics.

Doppler shifts and sonic booms are interesting sound phenomena that occur in all types of waves. They can be of considerable use. For example, the Doppler shift in ultrasound can be used to measure blood velocity, while police use the Doppler shift in radar (a microwave) to measure car velocities. In meteorology, the Doppler shift is used to track the motion of storm clouds; such “Doppler Radar” can give velocity and direction and rain or snow potential of imposing weather fronts. In astronomy, we can examine the light emitted from distant galaxies and determine their speed relative to ours. As galaxies move away from us, their light is shifted to a lower frequency, and so to a longer wavelength—the so-called red shift. Such information from galaxies far, far away has allowed us to estimate the age of the universe (from the Big Bang) as about 14 billion years.
Check Your Understanding

Why did scientist Christian Doppler observe musicians both on a moving train and also from a stationary point not on the train?

Solution
Doppler needed to compare the perception of sound when the observer is stationary and the sound source moves, as well as when the sound source and the observer are both in motion.

Check Your Understanding

Describe a situation in your life when you might rely on the Doppler shift to help you either while driving a car or walking near traffic.

Solution
If I am driving and I hear Doppler shift in an ambulance siren, I would be able to tell when it was getting closer and also if it has passed by. This would help me to know whether I needed to pull over and let the ambulance through.

17.5 Sound Interference and Resonance: Standing Waves in Air Columns

Interference is the hallmark of waves, all of which exhibit constructive and destructive interference exactly analogous to that seen for water waves. In fact, one way to prove something “is a wave” is to observe interference effects. So, sound being a wave, we expect it to exhibit interference; we have already mentioned a few such effects, such as the beats from two similar notes played simultaneously.

Figure 17.22 shows a clever use of sound interference to cancel noise. Larger-scale applications of active noise reduction by destructive interference are contemplated for entire passenger compartments in commercial aircraft. To obtain destructive interference, a fast electronic analysis is performed, and a second sound is introduced with its maxima and minima exactly reversed from the incoming noise. Sound waves in fluids are pressure waves and consistent with Pascal’s principle; pressures from two different sources add and subtract like simple numbers; that is, positive and negative gauge pressures add to a much smaller pressure, producing a lower-intensity sound. Although completely destructive interference is possible only under the simplest conditions, it is possible to reduce noise levels by 30 dB or more using this technique.

Figure 17.22 Headphones designed to cancel noise with destructive interference create a sound wave exactly opposite to the incoming sound. These headphones can be more effective than the simple passive attenuation used in most ear protection. Such headphones were used on the record-setting, around the world nonstop flight of the Voyager aircraft to protect the pilots' hearing from engine noise.
Where else can we observe sound interference? All sound resonances, such as in musical instruments, are due to constructive and destructive interference. Only the resonant frequencies interfere constructively to form standing waves, while others interfere destructively and are absent. From the toot made by blowing over a bottle, to the characteristic flavor of a violin's sounding box, to the recognizability of a great singer's voice, resonance and standing waves play a vital role.

**Interference**

Interference is such a fundamental aspect of waves that observing interference is proof that something is a wave. The wave nature of light was established by experiments showing interference. Similarly, when electrons scattered from crystals exhibited interference, their wave nature was confirmed to be exactly as predicted by symmetry with certain wave characteristics of light.

Suppose we hold a tuning fork near the end of a tube that is closed at the other end, as shown in Figure 17.23, Figure 17.24, Figure 17.25, and Figure 17.26. If the tuning fork has just the right frequency, the air column in the tube resonates loudly, but at most frequencies it vibrates very little. This observation just means that the air column has only certain natural frequencies. The figures show how a resonance at the lowest of these natural frequencies is formed. A disturbance travels down the tube at the speed of sound and bounces off the closed end. If the tube is just the right length, the reflected sound arrives back at the tuning fork exactly half a cycle later, and it interferes constructively with the continuing sound produced by the tuning fork. The incoming and reflected sounds form a standing wave in the tube as shown.

![Figure 17.23 Resonance of air in a tube closed at one end, caused by a tuning fork. A disturbance moves down the tube.](image)

![Figure 17.24 Resonance of air in a tube closed at one end, caused by a tuning fork. The disturbance reflects from the closed end of the tube.](image)

![Figure 17.25 Resonance of air in a tube closed at one end, caused by a tuning fork. If the length of the tube $L$ is just right, the disturbance gets back to the tuning fork half a cycle later and interferes constructively with the continuing sound from the tuning fork. This interference forms a standing wave, and the air column resonates.](image)
The standing wave formed in the tube has its maximum air displacement (an antinode) at the open end, where motion is unconstrained, and no displacement (a node) at the closed end, where air movement is halted. The distance from a node to an antinode is one-fourth of a wavelength, and this equals the length of the tube; thus, \( \lambda = 4L \). This same resonance can be produced by a vibration introduced at or near the closed end of the tube, as shown in Figure 17.27. It is best to consider this a natural vibration of the air column independently of how it is induced.

Given that maximum air displacements are possible at the open end and none at the closed end, there are other, shorter wavelengths that can resonate in the tube, such as the one shown in Figure 17.28. Here the standing wave has three-fourths of its wavelength in the tube, or \( L = (3/4)\lambda' \), so that \( \lambda' = 4L/3 \). Continuing this process reveals a whole series of shorter-wavelength and higher-frequency sounds that resonate in the tube. We use specific terms for the resonances in any system. The lowest resonant frequency is called the fundamental, while all higher resonant frequencies are called overtones. All resonant frequencies are integral multiples of the fundamental, and they are collectively called harmonics. The fundamental is the first harmonic, the first overtone is the second harmonic, and so on. Figure 17.29 shows the fundamental and the first three overtones (the first four harmonics) in a tube closed at one end.
The fundamental and overtones can be present simultaneously in a variety of combinations. For example, middle C on a trumpet has a sound distinctively different from middle C on a clarinet, both instruments being modified versions of a tube closed at one end. The fundamental frequency is the same (and usually the most intense), but the overtones and their mix of intensities are different and subject to shading by the musician. This mix is what gives various musical instruments (and human voices) their distinctive characteristics, whether they have air columns, strings, sounding boxes, or drumheads. In fact, much of our speech is determined by shaping the cavity formed by the throat and mouth and positioning the tongue to adjust the fundamental and combination of overtones. Simple resonant cavities can be made to resonate with the sound of the vowels, for example. (See Figure 17.30.) In boys, at puberty, the larynx grows and the shape of the resonant cavity changes giving rise to the difference in predominant frequencies in speech between men and women.

Now let us look for a pattern in the resonant frequencies for a simple tube that is closed at one end. The fundamental has \( \lambda = 4L \), and frequency is related to wavelength and the speed of sound as given by:

\[
v_w = f \lambda.
\]  

(17.28)

Solving for \( f \) in this equation gives

\[
f = \frac{v_w}{\lambda} = \frac{v_w}{4L}.
\]  

(17.29)

where \( v_w \) is the speed of sound in air. Similarly, the first overtone has \( \lambda' = 4L/3 \) (see Figure 17.29), so that

\[
f' = \frac{3v_w}{4L} = 3f.
\]  

(17.30)

Because \( f' = 3f \), we call the first overtone the third harmonic. Continuing this process, we see a pattern that can be generalized in a single expression. The resonant frequencies of a tube closed at one end are

\[
f_n = n \frac{v_w}{4L}, \quad n = 1, 3, 5,
\]  

(17.31)

where \( f_1 \) is the fundamental, \( f_3 \) is the first overtone, and so on. It is interesting that the resonant frequencies depend on the speed of sound and, hence, on temperature. This dependence poses a noticeable problem for organs in old unheated cathedrals, and it is also the reason why musicians commonly bring their wind instruments to room temperature before playing them.
Example 17.5 Find the Length of a Tube with a 128 Hz Fundamental

(a) What length should a tube closed at one end have on a day when the air temperature, is 22.0°C, if its fundamental frequency is to be 128 Hz (C below middle C)?

(b) What is the frequency of its fourth overtone?

Strategy

The length $L$ can be found from the relationship in $f_n = \frac{n v_w}{4L}$, but we will first need to find the speed of sound $v_w$.

Solution for (a)

(1) Identify knowns:
- the fundamental frequency is 128 Hz
- the air temperature is 22.0°C

(2) Use $f_n = \frac{n v_w}{4L}$ to find the fundamental frequency ($n = 1$).

$$f_1 = \frac{v_w}{4L}$$

(17.32)

(3) Solve this equation for length.

$$L = \frac{v_w}{4f_1}$$

(17.33)

(4) Find the speed of sound using

$$v_w = \sqrt{\frac{T}{273 \text{ K}}} \cdot (331 \text{ m/s})$$

$$v_w = \frac{298 \text{ K}}{273 \text{ K}} \cdot 331 \text{ m/s} = 344 \text{ m/s}$$

(17.34)

(5) Enter the values of the speed of sound and frequency into the expression for $L$.

$$L = \frac{v_w}{4f_1} = \frac{344 \text{ m/s}}{4(128 \text{ Hz})} = 0.672 \text{ m}$$

(17.35)

Discussion on (a)

Many wind instruments are modified tubes that have finger holes, valves, and other devices for changing the length of the resonating air column and hence, the frequency of the note played. Horns producing very low frequencies, such as tubas, require tubes so long that they are coiled into loops.

Solution for (b)

(1) Identify knowns:
- the first overtone has $n = 3$
- the second overtone has $n = 5$
- the third overtone has $n = 7$
- the fourth overtone has $n = 9$

(2) Enter the value for the fourth overtone into $f_n = \frac{n v_w}{4L}$

$$f_0 = 9 \frac{v_w}{4L} = 9 f_1 = 1.15 \text{ kHz}$$

(17.36)

Discussion on (b)

Whether this overtone occurs in a simple tube or a musical instrument depends on how it is stimulated to vibrate and the details of its shape. The trombone, for example, does not produce its fundamental frequency and only makes overtones.

Another type of tube is one that is open at both ends. Examples are some organ pipes, flutes, and oboes. The resonances of tubes open at both ends can be analyzed in a very similar fashion to those for tubes closed at one end. The air columns in tubes open at both ends have maximum air displacements at both ends, as illustrated in Figure 17.31. Standing waves form as shown.
The resonant frequencies of a tube open at both ends are shown, including the fundamental and the first three overtones. In all cases the maximum air displacements occur at both ends of the tube, giving it different natural frequencies than a tube closed at one end.

Based on the fact that a tube open at both ends has maximum air displacements at both ends, and using Figure 17.31 as a guide, we can see that the resonant frequencies of a tube open at both ends are:

\[ f_n = \frac{n \nu w}{2L}, \quad n = 1, 2, 3, \ldots \]

where \( f_1 \) is the fundamental, \( f_2 \) is the first overtone, \( f_3 \) is the second overtone, and so on. Note that a tube open at both ends has a fundamental frequency twice what it would have if closed at one end. It also has a different spectrum of overtones than a tube closed at one end. So if you had two tubes with the same fundamental frequency but one was open at both ends and the other was closed at one end, they would sound different when played because they have different overtones. Middle C, for example, would sound richer played on an open tube, because it has even multiples of the fundamental as well as odd. A closed tube has only odd multiples.

Real-World Applications: Resonance in Everyday Systems

Resonance occurs in many different systems, including strings, air columns, and atoms. Resonance is the driven or forced oscillation of a system at its natural frequency. At resonance, energy is transferred rapidly to the oscillating system, and the amplitude of its oscillations grows until the system can no longer be described by Hooke’s law. An example of this is the distorted sound intentionally produced in certain types of rock music.

Wind instruments use resonance in air columns to amplify tones made by lips or vibrating reeds. Other instruments also use air resonance in clever ways to amplify sound. Figure 17.32 shows a violin and a guitar, both of which have sounding boxes but with different shapes, resulting in different overtone structures. The vibrating string creates a sound that resonates in the sounding box, greatly amplifying the sound and creating overtones that give the instrument its characteristic flavor. The more complex the shape of the sounding box, the greater its ability to resonate over a wide range of frequencies. The marimba, like the one shown in Figure 17.33 uses pots or gourds below the wooden slats to amplify their tones. The resonance of the pot can be adjusted by adding water.
String instruments such as violins and guitars use resonance in their sounding boxes to amplify and enrich the sound created by their vibrating strings. The bridge and supports couple the string vibrations to the sounding boxes and air within. (credits: guitar, Feliciano Guimares, Fotopedia; violin, Steve Snodgrass, Flickr)

Resonance has been used in musical instruments since prehistoric times. This marimba uses gourds as resonance chambers to amplify its sound. (credit: APC Events, Flickr)

We have emphasized sound applications in our discussions of resonance and standing waves, but these ideas apply to any system that has wave characteristics. Vibrating strings, for example, are actually resonating and have fundamentals and overtones similar to those for air columns. More subtle are the resonances in atoms due to the wave character of their electrons. Their orbitals can be viewed as standing waves, which have a fundamental (ground state) and overtones (excited states). It is fascinating that wave characteristics apply to such a wide range of physical systems.

Check Your Understanding

Describe how noise-canceling headphones differ from standard headphones used to block outside sounds.

Solution

Regular headphones only block sound waves with a physical barrier. Noise-canceling headphones use destructive interference to reduce the loudness of outside sounds.
Check Your Understanding

How is it possible to use a standing wave’s node and antinode to determine the length of a closed-end tube?

Solution

When the tube resonates at its natural frequency, the wave’s node is located at the closed end of the tube, and the antinode is located at the open end. The length of the tube is equal to one-fourth of the wavelength of this wave. Thus, if we know the wavelength of the wave, we can determine the length of the tube.

PhET Explorations: Sound

This simulation lets you see sound waves. Adjust the frequency or volume and you can see and hear how the wave changes. Move the listener around and hear what she hears.

PhET Interactive Simulation

Figure 17.34 Sound (http://cnx.org/content/m42296/1.4/sound_en.jar)

17.6 Hearing

The human ear has a tremendous range and sensitivity. It can give us a wealth of simple information—such as pitch, loudness, and direction. And from its input we can detect musical quality and nuances of voiced emotion. How is our hearing related to the physical qualities of sound, and how does the hearing mechanism work?

**Hearing** is the perception of sound. (Perception is commonly defined to be awareness through the senses, a typically circular definition of higher-level processes in living organisms.) Normal human hearing encompasses frequencies from 20 to 20,000 Hz, an impressive range. Sounds below 20 Hz are called infrasound, whereas those above 20,000 Hz are ultrasound. Neither is perceived by the ear, although infrasound can sometimes be felt as vibrations. When we do hear low-frequency vibrations, such as the sounds of a diving board, we hear the individual vibrations only because there are higher-frequency sounds in each. Other animals have hearing ranges different from that of humans. Dogs can hear sounds as high as 30,000 Hz, whereas bats and dolphins can hear up to 100,000-Hz sounds. You may have noticed that dogs respond to the sound of a dog whistle which produces sound out of the range of human hearing. Elephants are known to respond to frequencies below 20 Hz.

The perception of frequency is called **pitch**. Most of us have excellent relative pitch, which means that we can tell whether one sound has a different frequency from another. Typically, we can discriminate between two sounds if their frequencies differ by 0.3% or more. For example, 500.0 and 501.5 Hz are noticeably different. Pitch perception is directly related to frequency and is not greatly affected by other physical quantities such as intensity. Musical notes are particular sounds that can be produced by most instruments and in Western music have particular names. Combinations of notes constitute music. Some people can identify musical notes, such as A-sharp, C, or E-flat, just by listening to them. This uncommon ability is called perfect pitch.

The ear is remarkably sensitive to low-intensity sounds. The lowest audible intensity or threshold is about $10^{-12}$ W/m$^2$ or 0 dB. Sounds as much as $10^{12}$ more intense can be briefly tolerated. Very few measuring devices are capable of observations over a range of a trillion. The perception of intensity is called **loudness**. At a given frequency, it is possible to discern differences of about 1 dB, and a change of 3 dB is easily noticed. But loudness is not related to intensity alone. Frequency has a major effect on how loud a sound seems. The ear has its maximum sensitivity to frequencies in the range of 2000 to 5000 Hz, so that sounds in this range are perceived as being louder than, say, those at 500 or 10,000 Hz, even when they all have the same intensity. Sounds near the high- and low-frequency extremes of the hearing range seem even less loud, because the ear is even less sensitive at those frequencies. Table 17.4 gives the dependence of certain human hearing perceptions on physical quantities.