

## Learning Objectives

By the end of this section, you will be able to:

- Define the term intensity
- Explain the concept of sound intensity level
- Describe how the human ear translates sound

In a quiet forest, you can sometimes hear a single leaf fall to the ground. 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 ([Figure 17.12](#)). We are all very familiar with the loudness of sounds and are aware that loudness is related to how energetically the source is vibrating. High noise exposure is hazardous to hearing, which is why it is important for people working in industrial settings to wear ear protection. The relevant physical quantity is sound intensity, a concept that is valid for all sounds whether or not they are in the audible range.



**Figure 17.12** Noise on crowded roadways, like this one in Delhi, makes it hard to hear others unless they shout. (credit: "Lingaraj G J"/Flickr)

In [Waves](#), we defined intensity as 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

$$I = \frac{P}{A}, \quad (17.8)$$

where  $P$  is the power through an area  $A$ . The SI unit for  $I$  is  $\text{W}/\text{m}^2$ . If we assume that the sound wave is spherical, and that no energy is lost to thermal processes, the energy of the sound wave is spread over a larger area as distance increases, so the intensity decreases. The area of a sphere is  $A = 4\pi r^2$ . As the wave spreads out from  $r_1$  to  $r_2$ , the energy also spreads out over a larger area:

$$\begin{aligned} P_1 &= P_2 \\ I_1 4\pi r_1^2 &= I_2 4\pi r_2^2; \end{aligned}$$

$$I_2 = I_1 \left( \frac{r_1}{r_2} \right)^2. \quad (17.9)$$

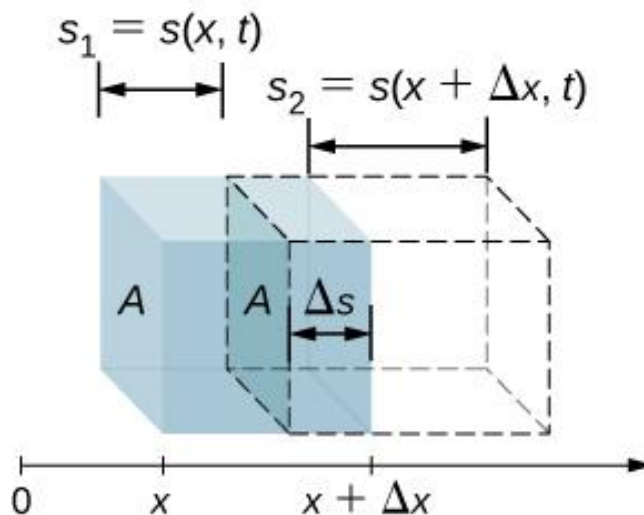
The intensity decreases as the wave moves out from the source. In an inverse square relationship, such as the intensity, when you double the distance, the intensity decreases to one quarter,

$$I_2 = I_1 \left( \frac{r_1}{r_2} \right)^2 = I_1 \left( \frac{r_1}{2r_1} \right)^2 = \frac{1}{4} I_1.$$

Generally, when considering the intensity of a sound wave, we take the intensity to be the time-averaged value of the power, denoted by  $\langle P \rangle$ , divided by the area,

$$I = \frac{\langle P \rangle}{A}. \quad (17.10)$$

The intensity of a sound wave is proportional to the change in the pressure squared and inversely proportional to the density and the speed. Consider a parcel of a medium initially undisturbed and then influenced by a sound wave at time  $t$ , as shown in [Figure 17.13](#).



**Figure 17.13** An undisturbed parcel of a medium with a volume  $V = A\Delta x$  shown in blue. A sound wave moves through the medium at time  $t$ , and the parcel is displaced and expands, as shown by dotted lines.

The change in volume is

$\Delta V = A\Delta s = A(s_2 - s_1)$ , where  $s_1$  is the displacement of the leading edge of the parcel and  $s_2$  is the displacement of the trailing edge of the parcel. In the figure,  $s_2 > s_1$  and the parcel expands, but the parcel can either expand or compress ( $s_2 < s_1$ ), depending on which part of the sound wave (compression or rarefaction) is moving through the parcel.

As the sound wave moves through the parcel, the parcel is displaced and may expand or contract. If  $s_2 > s_1$ , the volume has increased and the pressure decreases. If  $s_2 < s_1$ , the volume has decreased and the pressure increases. The change in the volume is

$$\Delta V = A\Delta s = A(s_2 - s_1) = A(s(x + \Delta x, t) - s(x, t)).$$

The fractional change in the volume is the change in volume divided by the original volume:

$$\frac{dV}{V} = \lim_{\Delta x \rightarrow 0} \frac{A[s(x + \Delta x, t) - s(x, t)]}{A\Delta x} = \frac{\partial s(x, t)}{\partial x}.$$

The fractional change in volume is related to the pressure fluctuation by the bulk modulus  $\beta = -\frac{\Delta p(x, t)}{dV/V}$ . Recall that the minus sign is required because the volume is *inversely* related to the pressure. (We use lowercase  $p$  for pressure to distinguish it from power, denoted by  $P$ .) The change in pressure is therefore  $\Delta p(x, t) = -\beta \frac{dV}{V} = -\beta \frac{\partial s(x, t)}{\partial x}$ . If the sound wave is sinusoidal, then the displacement as shown in [Equation 17.2](#) is  $s(x, t) = s_{\max} \cos(kx \mp \omega t + \phi)$  and the pressure is found to be

$$\Delta p(x, t) = -\beta \frac{dV}{V} = -\beta \frac{\partial s(x, t)}{\partial x} = \beta k s_{\max} \sin(kx - \omega t + \phi) = \Delta p_{\max} \sin(kx - \omega t).$$

The intensity of the sound wave is the power per unit area, and the power is the force times the velocity,  $I = \frac{P}{A} = \frac{Fv}{A} = pv$ . Here, the velocity is the velocity of the oscillations of the medium, and not the velocity of the sound wave. The velocity of the medium is the time rate of change in the displacement:

$$v(x, t) = \frac{\partial}{\partial t} s(x, t) = \frac{\partial}{\partial t} (s_{\max} \cos(kx - \omega t + \phi)) = s_{\max} \omega \sin(kx - \omega t + \phi).$$

Thus, the intensity becomes

$$\begin{aligned} I &= \Delta p(x, t) v(x, t) \\ &= \beta k s_{\max} \sin(kx - \omega t + \phi) [s_{\max} \omega \sin(kx - \omega t + \phi)] \\ &= \beta k \omega s_{\max}^2 \sin^2(kx - \omega t + \phi). \end{aligned}$$

To find the time-averaged intensity over one period  $T = \frac{2\pi}{\omega}$  for a position  $x$ , we integrate over the period,  $I = \frac{\beta k \omega s_{\max}^2}{2}$ . Using  $\Delta p_{\max} = \beta k s_{\max}$ ,  $v = \sqrt{\frac{\beta}{\rho}}$ , and  $v = \frac{\omega}{k}$ , we obtain

$$I = \frac{\beta k \omega s_{\max}^2}{2} = \frac{\beta^2 k^2 \omega s_{\max}^2}{2\beta k} = \frac{\omega (\Delta p_{\max})^2}{2(\rho v^2) k} = \frac{v (\Delta p_{\max})^2}{2(\rho v^2)} = \frac{(\Delta p_{\max})^2}{2\rho v}.$$

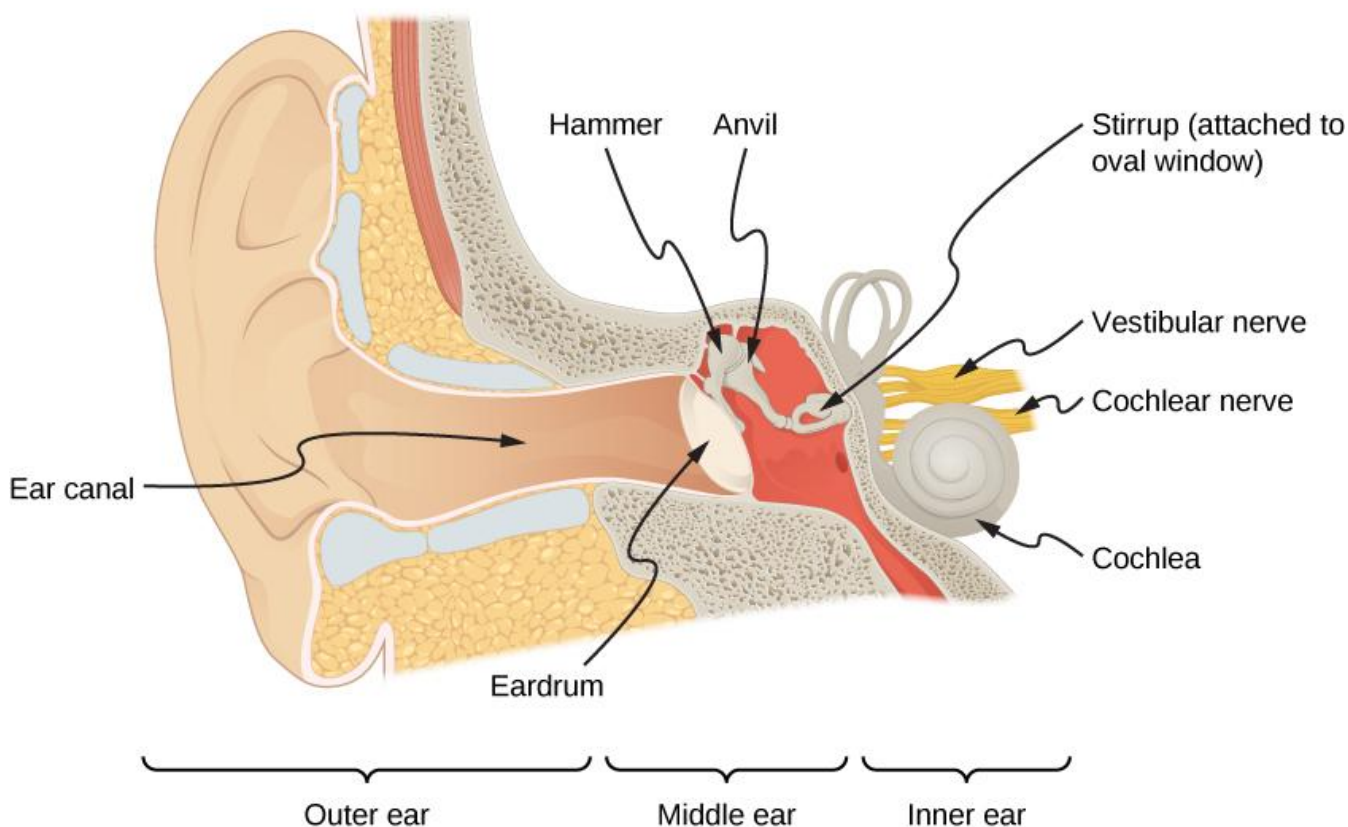
That is, the intensity of a sound wave is related to its amplitude squared by

$$I = \frac{(\Delta p_{\max})^2}{2\rho v}. \quad (17.11)$$

Here,  $\Delta p_{\max}$  is the pressure variation or pressure amplitude in units of pascals (Pa) or  $\text{N/m}^2$ . The energy (as kinetic energy  $\frac{1}{2}mv^2$ ) 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  $v$  is the speed of sound in the medium, in units of m/s. The pressure variation is proportional to the amplitude of the oscillation, so  $I$  varies as  $(\Delta p)^2$ . 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.

## Human Hearing and Sound Intensity Levels

As stated earlier in this chapter, hearing is the perception of sound. The hearing mechanism involves some interesting physics. The sound wave that impinges upon our ear is a pressure wave. The ear is a **transducer** that converts sound waves into electrical nerve impulses in a manner much more sophisticated than, but analogous to, a microphone. [Figure 17.14](#) shows the anatomy of the ear.



**Figure 17.14** The anatomy of the human ear.

The outer ear, or ear canal, carries sound to the recessed, protected eardrum. The air column in the ear canal resonates and is partially responsible for the sensitivity of the ear to sounds in the 2000–5000-Hz range. The middle ear converts sound into mechanical vibrations and applies these vibrations to the cochlea.

### INTERACTIVE

Watch this [video](#) for a more detailed discussion of the workings of the human ear.

The range of intensities that the human ear can hear depends on the frequency of the sound, but, in general, the range is quite large. The minimum threshold intensity that can be heard is



$I_0 = 10^{-12} \text{ W/m}^2$ . Pain is experienced at intensities of  $I_{\text{pain}} = 1 \text{ W/m}^2$ . Measurements of sound intensity (in units of  $\text{W/m}^2$ ) are very cumbersome due to this large range in values. For this reason, as well as for other reasons, the concept of sound intensity level was proposed.

The **sound intensity level**  $\beta$  of a sound, measured in decibels, having an intensity  $I$  in watts per meter squared, is defined as

$$\beta(\text{dB}) = 10 \log_{10} \left( \frac{I}{I_0} \right), \quad (17.12)$$

where  $I_0 = 10^{-12} \text{ W/m}^2$  is a reference intensity, corresponding to the threshold intensity of sound that a person with normal hearing can perceive at a frequency of 1.00 kHz. It is more common to consider sound intensity levels in dB than in  $\text{W/m}^2$ . How human ears perceive sound can be more accurately described by the logarithm of the intensity rather than directly by the 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 ( $10^{-12} \text{ W/m}^2$ ). 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.

The decibel level of a sound having the threshold intensity of  $10^{-12} \text{ W/m}^2$  is  $\beta = 0 \text{ dB}$ , because  $\log_{10} 1 = 0$ . [Table 17.2](#) gives levels in decibels and intensities in watts per meter squared for some familiar 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  $10^{-16} \text{ W}$  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  $10^{-9} \text{ atm}$ .

Sound intensity level $\beta$ (dB)	Intensity $I$ ( $\text{W/m}^2$ )	Example/effect
0	$1 \times 10^{-12}$	Threshold of hearing at 1000 Hz
10	$1 \times 10^{-11}$	Rustle of leaves
20	$1 \times 10^{-10}$	Whisper at 1-m distance
30	$1 \times 10^{-9}$	Quiet home
40	$1 \times 10^{-8}$	Average home

Sound intensity level $\beta$ (dB)	Intensity $I$ ( $\text{W}/\text{m}^2$ )	Example/effect
50	$1 \times 10^{-7}$	Average office, soft music
60	$1 \times 10^{-6}$	Normal conversation
70	$1 \times 10^{-5}$	Noisy office, busy traffic
80	$1 \times 10^{-4}$	Loud radio, classroom lecture
90	$1 \times 10^{-3}$	Inside a heavy truck; damage from prolonged exposure <sup>1</sup>
100	$1 \times 10^{-2}$	Noisy factory, siren at 30 m; damage from 8 h per day exposure
110	$1 \times 10^{-1}$	Damage from 30 min per day exposure
120	1	Loud rock concert; pneumatic chipper at 2 m; threshold of pain
140	$1 \times 10^2$	Jet airplane at 30 m; severe pain, damage in seconds
160	$1 \times 10^4$	Bursting of eardrums

**Table 17.2** Sound Intensity Levels and Intensities <sup>[1]</sup> 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.

An observation readily verified by examining [Table 17.2](#) or by using [Equation 17.12](#) 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 ([Table 17.3](#)).

$I_2/I_1$	$\beta_2 - \beta_1$
2.0	3.0 dB
5.0	7.0 dB
10.0	10.0 dB

$I_2/I_1$	$\beta_2 - \beta_1$
100.0	20.0 dB
1000.0	30.0 dB

**Table 17.3** Ratios of Intensities and Corresponding Differences in Sound Intensity Levels**EXAMPLE 17.2****Calculating Sound Intensity Levels**

Calculate the sound intensity level in decibels for a sound wave traveling in air at  $0^\circ\text{C}$  and having a pressure amplitude of 0.656 Pa.

**Strategy**

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

**Solution**

1. Identify knowns:

Sound travels at 331 m/s in air at  $0^\circ\text{C}$ .

Air has a density of  $1.29 \text{ kg/m}^3$  at atmospheric pressure and  $0^\circ\text{C}$ .

2. Enter these values and the pressure amplitude into  $I = \frac{(\Delta p)^2}{2\rho v}$ .

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

3. Enter the value for  $I$  and the known value for  $I_0$  into  $\beta(\text{dB}) = 10 \log_{10} (I/I_0)$ . Calculate to find the sound intensity level in decibels:

$$10 \log_{10} (5.04 \times 10^{-4}) = 10(8.70) \text{ dB} = 87 \text{ dB}.$$

**Significance**

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**



## Changing Intensity Levels of a Sound

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

### Strategy

We 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. We can solve this problem by using of the properties of logarithms.

### Solution

1. Identify knowns:

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

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

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

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

Note that

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

2. Use the definition of  $\beta$  to obtain

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

Thus,

$$\beta_2 - \beta_1 = 3.01 \text{ dB}.$$

### Significance

This means that the two sound intensity levels differ by 3.01 dB, or about 3 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-dB sound is twice as intense as a 53.0-dB sound, a 97.0-dB sound is half as intense as a 100-dB sound, and so on.

## CHECK YOUR UNDERSTANDING 17.2

Identify common sounds at the levels of 10 dB, 50 dB, and 100 dB.

Another decibel scale is also 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 this text 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.

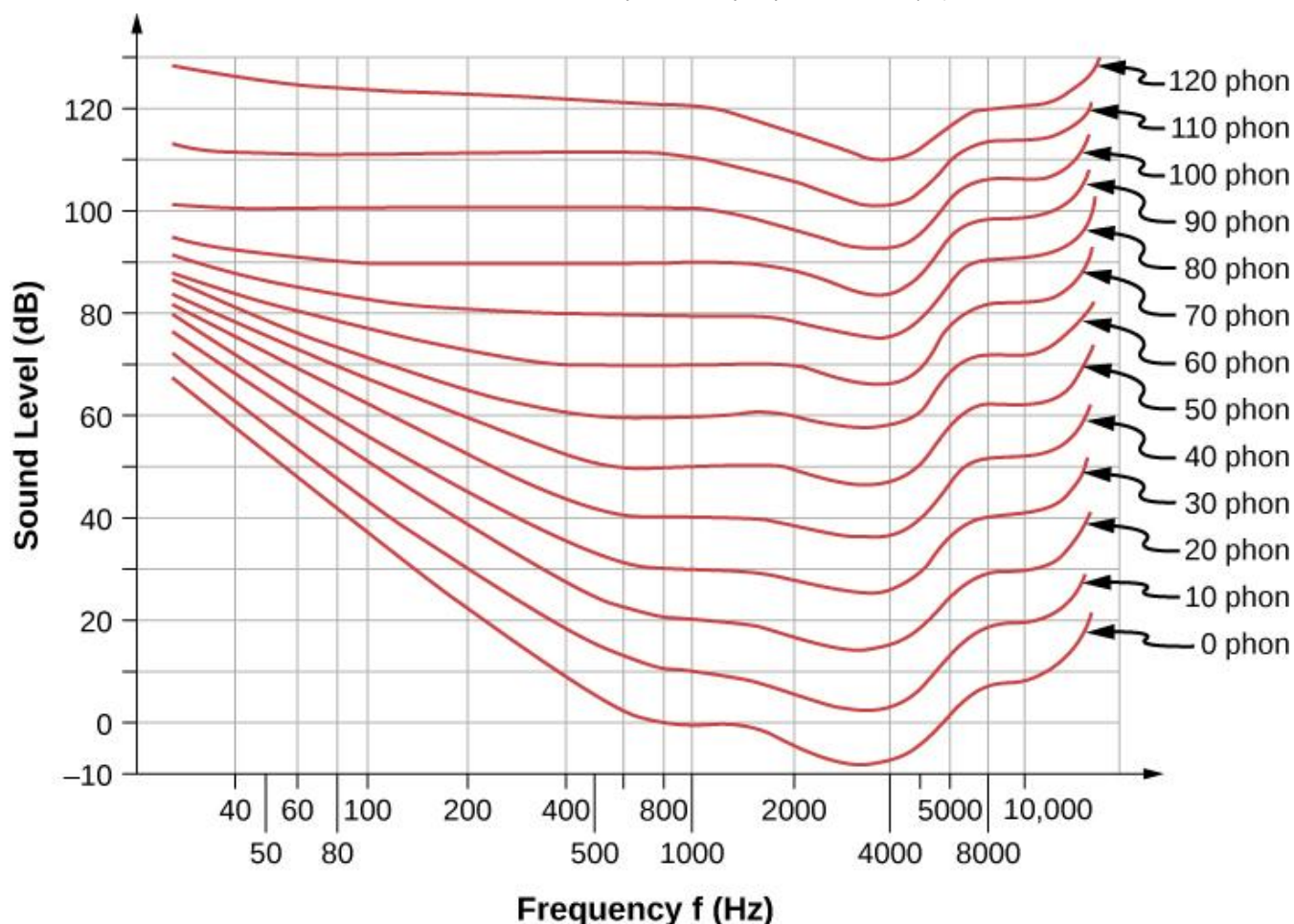
## Hearing and Pitch

The human ear has a tremendous range and sensitivity. It can give us a wealth of simple information—such as pitch, loudness, and direction.

The perception of frequency is called **pitch**. Typically, humans have excellent relative pitch and 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. Musical **notes** are sounds of a particular frequency that can be produced by most instruments and in Western music have particular names, such as A-sharp, C, or E-flat.

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. Sounds near the high- and low-frequency extremes of the hearing range seem even less loud, because the ear is less sensitive at those frequencies. When a violin plays middle C, there is no mistaking it for a piano playing the same note. The reason is that each instrument produces a distinctive set of frequencies and intensities. We call our perception of these combinations of frequencies and intensities tone quality or, more commonly, the **timbre** of the sound. Timbre is the shape of the wave that arises from the many reflections, resonances, and superposition in an instrument.

A unit called a **phon** is used to express loudness numerically. Phons differ from decibels because the phon is a unit of loudness perception, whereas the decibel is a unit of physical intensity. [Figure 17.15](#) shows the relationship of loudness to intensity (or intensity level) and frequency for persons with normal hearing. The curved lines are equal-loudness curves. Each curve is labeled with its loudness in phons. Any sound along a given curve is perceived as equally loud by the average person. The curves were determined by having large numbers of people compare the loudness of sounds at different frequencies and sound intensity levels. At a frequency of 1000 Hz, phons are taken to be numerically equal to decibels.



**Figure 17.15** The relationship of loudness in phons to intensity level (in decibels) and intensity (in watts per meter squared) for persons with normal hearing. The curved lines are equal-loudness curves—all sounds on a given curve are perceived as equally loud. Phons and decibels are defined to be the same at 1000 Hz.

### EXAMPLE 17.4

#### Measuring Loudness

(a) What is the loudness in phons of a 100-Hz sound that has an intensity level of 80 dB? (b) What is the intensity level in decibels of a 4000-Hz sound having a loudness of 70 phons? (c) At what intensity level will an 8000-Hz sound have the same loudness as a 200-Hz sound at 60 dB?

#### Strategy

The graph in [Figure 17.15](#) should be referenced to solve this example. To find the loudness of a given sound, you must know its frequency and intensity level, locate that point on the square grid, and then interpolate between loudness curves to get the loudness in phons. Once that point is located, the intensity level can be determined from the vertical axis.

#### Solution

1. Identify knowns: The square grid of the graph relating phons and decibels is a plot of intensity level versus frequency—both physical quantities: 100 Hz at 80 dB lies halfway between the curves marked 70 and 80 phons.  
Find the loudness: 75 phons.
2. Identify knowns: Values are given to be 4000 Hz at 70 phons.  
Follow the 70-phon curve until it reaches 4000 Hz. At that point, it is below the 70 dB line at about 67 dB.  
Find the intensity level: 67 dB.
3. Locate the point for a 200 Hz and 60 dB sound.  
Find the loudness: This point lies just slightly above the 50-phon curve, and so its loudness is 51 phons.  
Look for the 51-phon level is at 8000 Hz: 63 dB.

**Significance**

These answers, like all information extracted from [Figure 17.15](#), have uncertainties of several phons or several decibels, partly due to difficulties in interpolation, but mostly related to uncertainties in the equal-loudness curves.

**CHECK YOUR UNDERSTANDING 17.3**

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

In this section, we discussed the characteristics of sound and how we hear, but how are the sounds we hear produced? Interesting sources of sound are musical instruments and the human voice, and we will discuss these sources. But before we can understand how musical instruments produce sound, we need to look at the basic mechanisms behind these instruments. The theories behind the mechanisms used by musical instruments involve interference, superposition, and standing waves, which we discuss in the next section.

**Footnotes**

- 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.