Answer to Essential Question 21.3: Doubling the angular frequency, ω, causes the frequency to double in part (a). This, in turn, means that that wave speed must double, in part (b). In part (c), the tension is proportional to the square of the speed, so the tension is increased by a factor of 4. In part (e), the maximum transverse speed is proportional to ω, so the maximum transverse speed doubles. Finally, in part (f) we get a completely different value, $y = -0.39$ cm.

21-4 Sound and Sound Intensity

One way to produce a sound wave in air is to use a speaker. The surface of the speaker vibrates back and forth, creating areas of high and low density (corresponding to pressure a little higher than, and a little lower than, standard atmospheric pressure, respectively) in the region of air next to the speaker. These regions of high and low pressure (the sound wave) travel away from the speaker at the speed of sound. The air molecules, on average, just vibrate back and forth as the pressure wave travels through them. In fact, it is through the collisions of air molecules that the sound wave is propagated. Because air molecules are not coupled together, the sound wave travels through gas at a relatively low speed (for sound!) of around 340 m/s. As Table 21.1 shows, the speed of sound in air increases with temperature.

Medium	**Speed of sound**
Air (0°C)	331 m/s
Air (20°C)	343 m/s
Helium	965 m/s
Water	1400 m/s
Steel	5940 m/s
Aluminum	6420 m/s

Table 21.1: Values of the speed of sound through various media.

For other material, such as liquids or solids, in which there is more coupling between neighboring molecules, vibrations of the atoms and molecules (that is, sound waves) generally travel more quickly than they do in gases. This also is shown in Table 21.1.

Our ears can typically hear sounds with frequencies that lie between 20 Hz and 20 kHz, although the maximum frequency we are sensitive to tends to decrease with age (not to mention with prolonged exposure to high-intensity sound, such as loud music). We are typically most sensitive to sound waves that have frequencies near 2000 Hz, and considerably less sensitive to sounds at the extremes of our frequency range.

Other animals are sensitive to sounds outside of the human range. Elephants, for instance, communicate using sounds below 20 Hz. Because these sounds are not audible to humans, it took scientists quite a while to realize that elephants communicate with one another more than was first thought. Beyond the upper end of the human range, above 20 kHz, we classify sound as **ultrasound**. Dogs, bats, dolphins, and other animals can hear sounds in this range. Ultrasound also has important medical applications, such as in the imaging of a developing fetus in the womb. High-frequency sound waves traveling through the mother's body reflect differently from bone versus tissue, with the pattern of the reflected waves allowing an image to be formed.

Sound intensity

The intensity of a wave is defined to be its power per unit area: $I = P/A$.

For a source broadcasting uniformly in all directions, the wave spreads out like an inflating sphere, so the area in question is the surface area of a sphere.

$$I = \frac{P}{4\pi r^2}.$$ (Eq. 21.6: **Intensity for a source broadcasting uniformly in all directions**)

The sound intensity is proportional to the inverse square of the distance from the source. If the distance is doubled, for instance, the sound intensity decreases by a factor of four. Interestingly, a decrease in sound intensity by a factor of 4 is not perceived as such by the ear-brain system. The ear, in fact, responds logarithmically to sound intensity, and so we use a logarithmic scale for sound that is much like the Richter scale for earthquakes. Just as an earthquake measuring 7.0 on the Richter scale is 10 times more powerful than a quake measuring 6.0, and 100 times more powerful than an earthquake measuring 5.0, a 70 decibel (dB) sound has 10 times the power of a 60 dB sound, and 100 times the power of a 50 dB sound. Every 10 dB represents a change of one order of magnitude in intensity, no matter what the initial intensity is.

For the human ear, the smallest sound intensity that is audible has been determined to correspond to a sound intensity of about $I_0 = 1 \times 10^{-12}$ W/m^2. This value is known as the **threshold of hearing**. On the decibel scale, sounds are viewed in terms of how their intensity compares to the threshold of hearing.

$$\beta = (10\text{ dB})\log\left(\frac{I}{I_0}\right),$$ (Equation 21.7: **Absolute sound intensity level, in decibels**)

where the equation involves the log in base 10. An interesting reference point on the decibel scale is the **threshold of pain**, the most intense sound an average person can tolerate, which is 120 dB. Substituting 120 dB into equation 21.6, we find that, for the threshold of pain,

$$120\text{ dB} = (10\text{ dB})\log\left(\frac{I}{I_0}\right), \text{ so } 12 = \log\left(\frac{I}{I_0}\right).$$

To solve the equation for I, the sound intensity corresponding to the threshold of pain, we do 10 to the power of each side of the equation. 10^x is the inverse function of $\log(x)$, so:

$$10^{12} = 10^{\log\left(\frac{I}{I_0}\right)} = \frac{I}{I_0} = \frac{I}{1\times10^{-12}\text{ W/m}^2}.$$

Thus, the intensity of the threshold of pain is 12 orders of magnitude larger than the threshold of hearing, or 1 W/m^2. The most amazing thing about this, however, is what this result tells us about the human ear. The human ear is an incredible instrument, allowing us to hear sounds covering 12 orders of magnitude – that's a factor of 1 trillion.

One convenient feature of the logarithmic scale is that an increase of X decibels corresponds to an increase by a particular factor in intensity, no matter where you start from. This is reflected in the following equation:

$$\Delta\beta = (10\text{ dB})\log\left(\frac{I_f}{I_i}\right).$$ (Equation 21.8: **Relative sound intensity level, in decibels**)

Related End-of-Chapter Exercises: 18 – 22, 39.

Essential Question 21.4: If a sound intensity level increases by 5 dB, by what factor does the intensity increase?