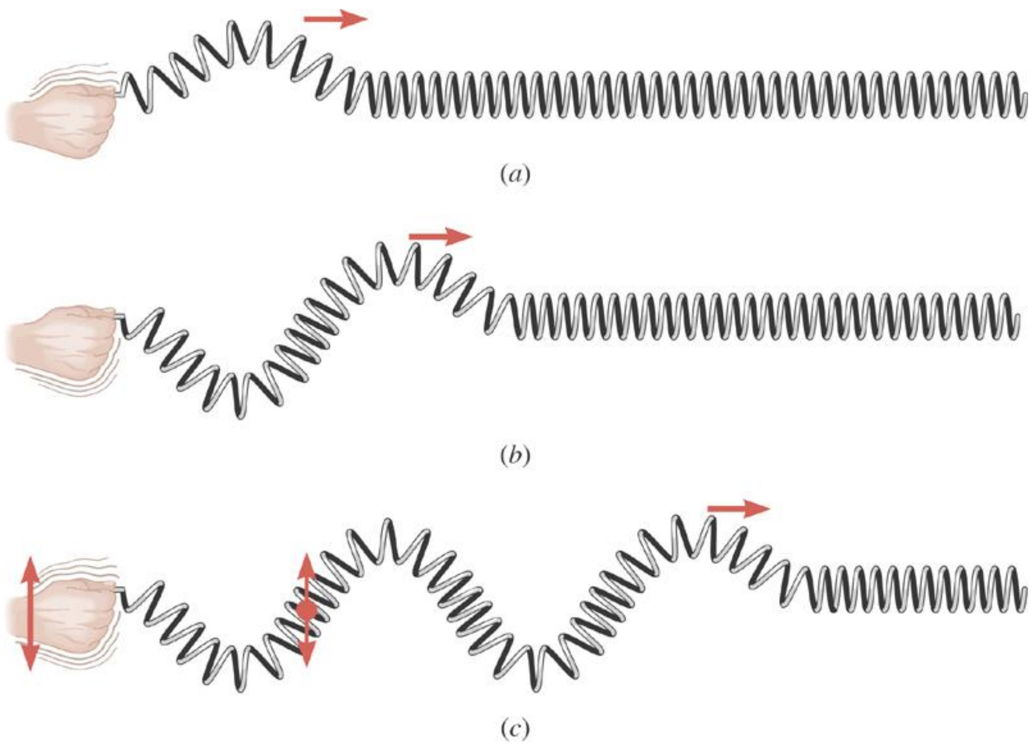
Chapter 16

Waves and Sound

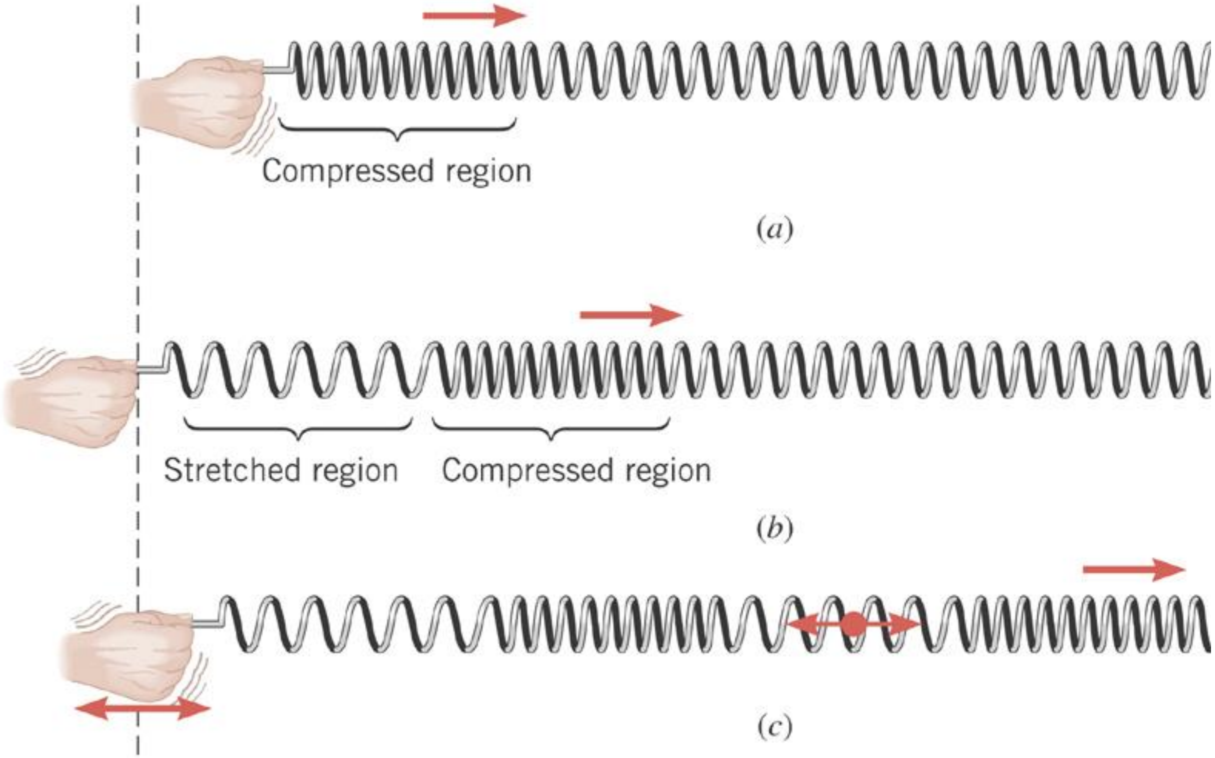
16.1 The Nature of Waves

1. A wave is a traveling disturbance.

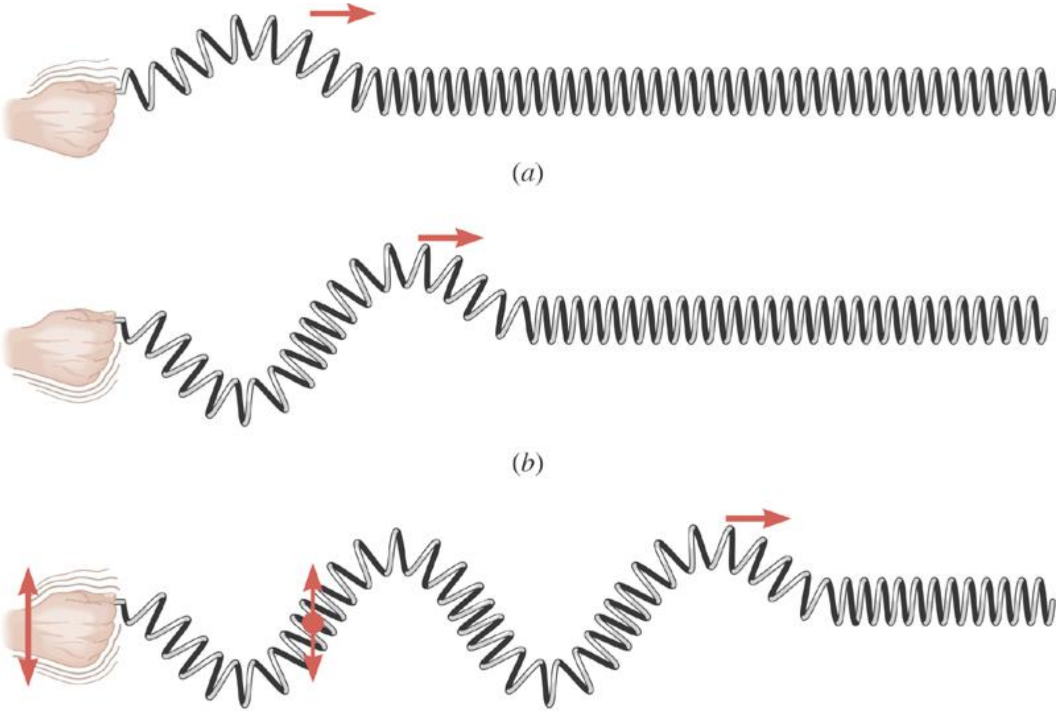
2. A wave carries energy from place to place.



Longitudinal Wave



Transverse Wave

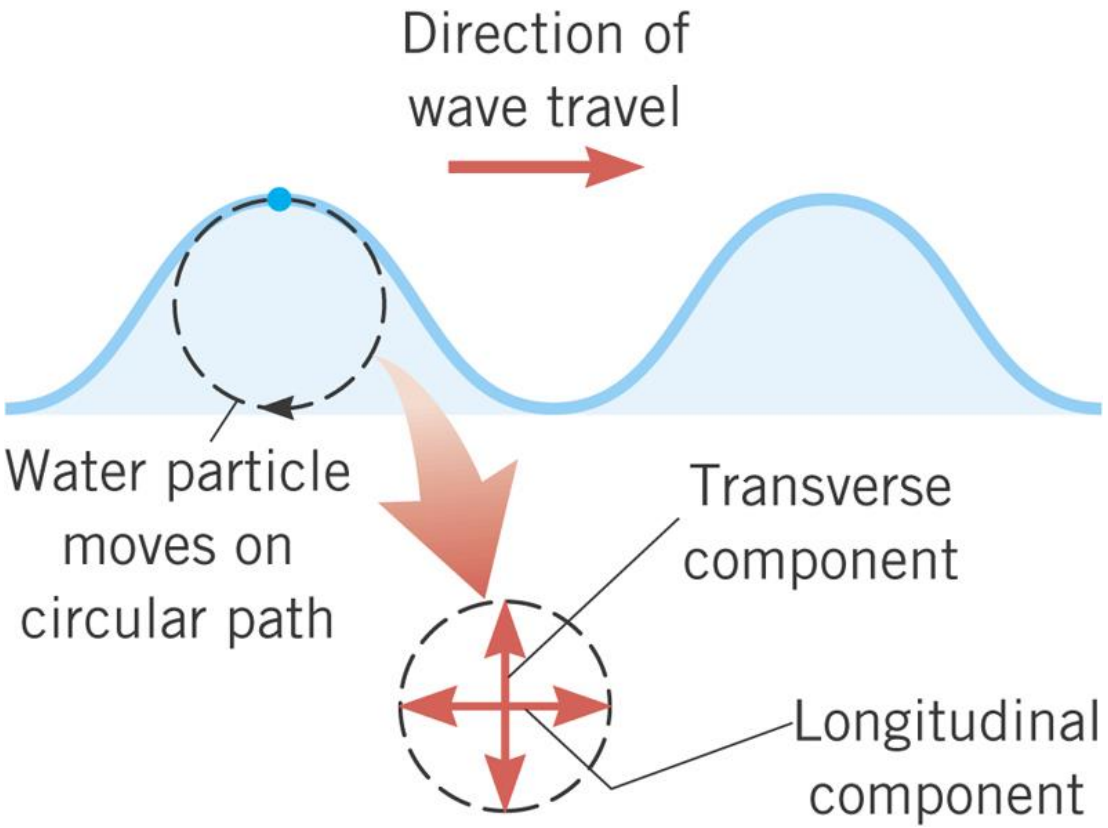


(a)

(b)

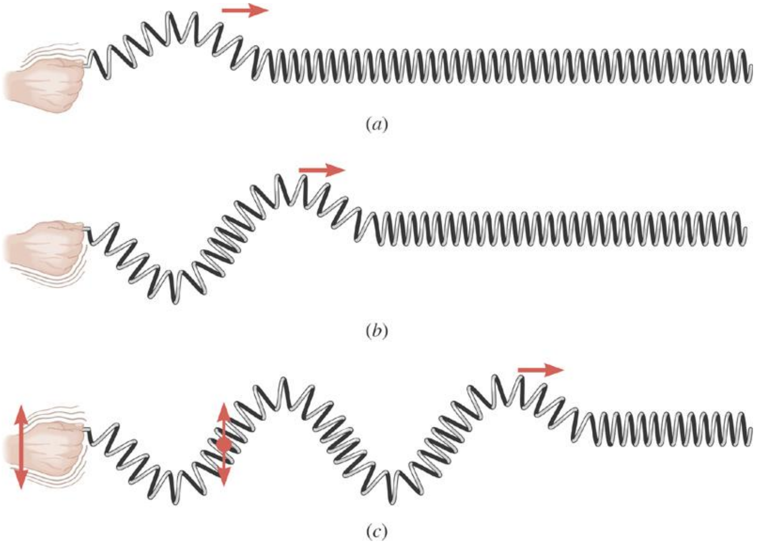
(c)

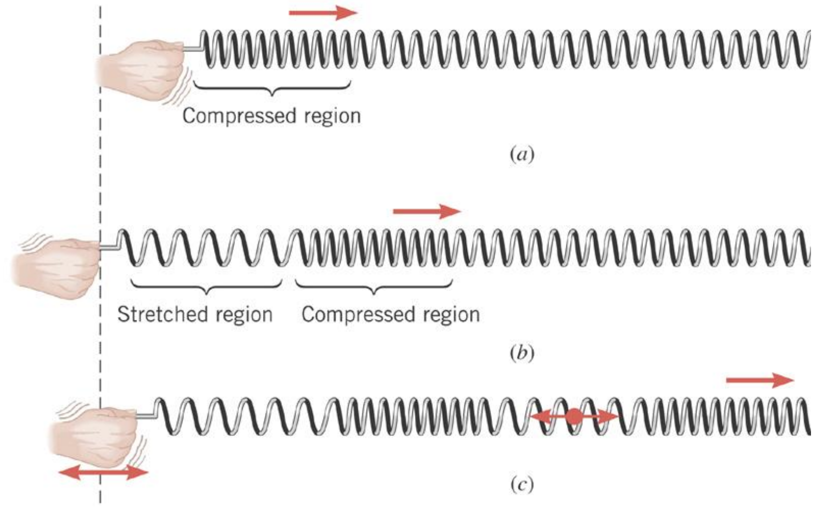
Water waves are partially transverse and partially longitudinal.



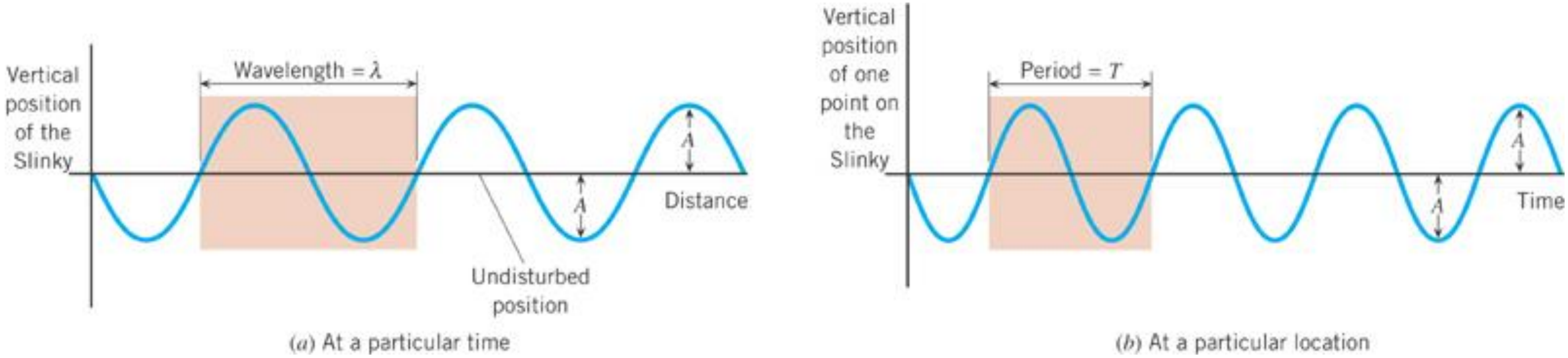
Periodic waves consist of cycles or patterns that are produced over and over again by the source.

In the figures, every segment of the slinky vibrates in simple harmonic motion, provided the end of the slinky is moved in simple harmonic motion.





16.2 *Periodic Waves*



In the drawing, one ***cycle*** is shaded in color.

The ***amplitude*** A is the maximum excursion of a particle of the medium from the particles undisturbed position.

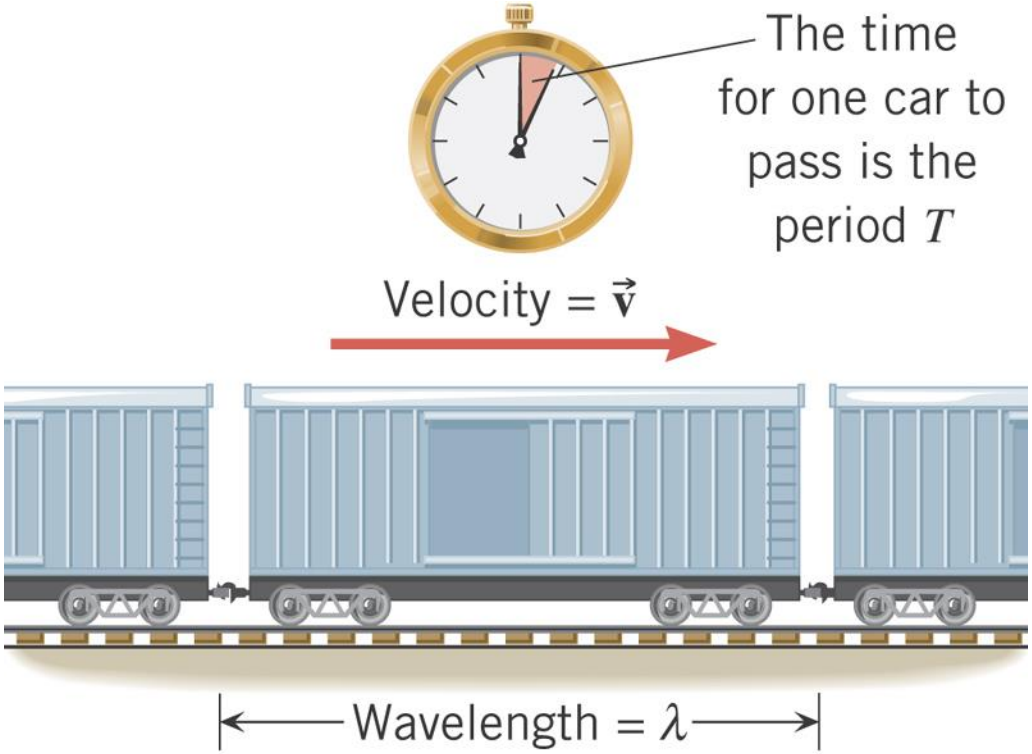
The ***wavelength*** is the horizontal length of one cycle of the wave.

The ***period*** is the time required for one complete cycle.

The ***frequency*** is related to the period and has units of Hz, or s^{-1}.

$$f = \frac{1}{T}$$

16.2 Periodic Waves



$$v = \frac{\lambda}{T} = f\lambda$$

Example 1 The Wavelengths of Radio Waves

AM and FM radio waves are transverse waves consisting of electric and magnetic field disturbances traveling at a speed of 3.00×10^8 m/s. A station broadcasts AM radio waves whose frequency is 1230×10^3 Hz and an FM radio wave whose frequency is 91.9×10^6 Hz. Find the distance between adjacent crests in each wave.

$$v = \frac{\lambda}{T} = f\lambda$$

$$\Downarrow$$

$$\lambda = \frac{v}{f}$$

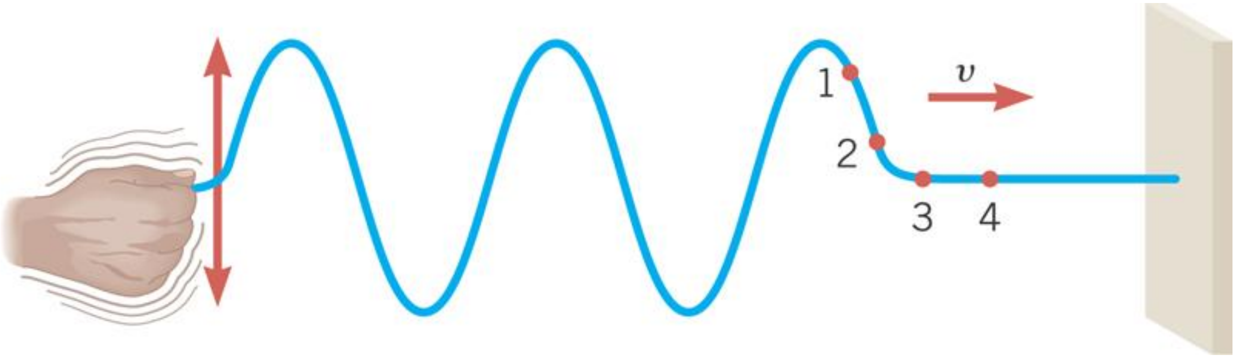
AM

$$\lambda = \frac{v}{f} = \frac{3.00\times10^{8}\ \text{m/s}}{1230\times10^{3}\,\text{Hz}} = 244\,\text{m}$$

FM

$$\lambda = \frac{v}{f} = \frac{3.00\times10^{8}\ \text{m/s}}{91.9\times10^{6}\,\text{Hz}} = 3.26\,\text{m}$$

The speed at which the wave moves to the right depends on how quickly one particle of the string is accelerated upward in response to the net pulling force.



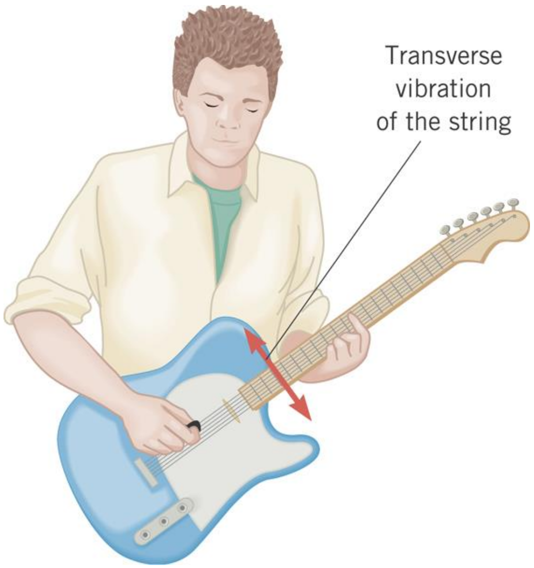
$$v = \sqrt{\frac{F}{m/L}}$$

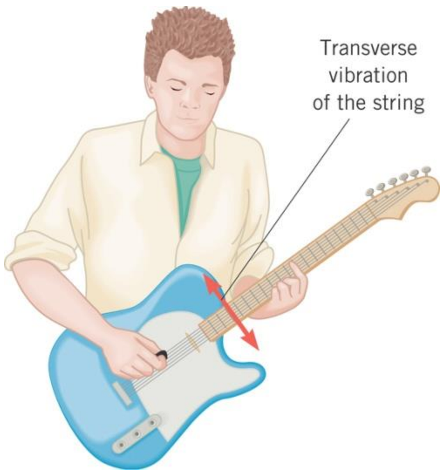
tension

linear density

Example 2 Waves Traveling on Guitar Strings

Transverse waves travel on each string of an electric guitar after the string is plucked. The length of each string between its two fixed ends is 0.628 m, and the mass is 0.208 g for the highest pitched E string and 3.32 g for the lowest pitched E string. Each string is under a tension of 226 N. Find the speeds of the waves on the two strings.





High E

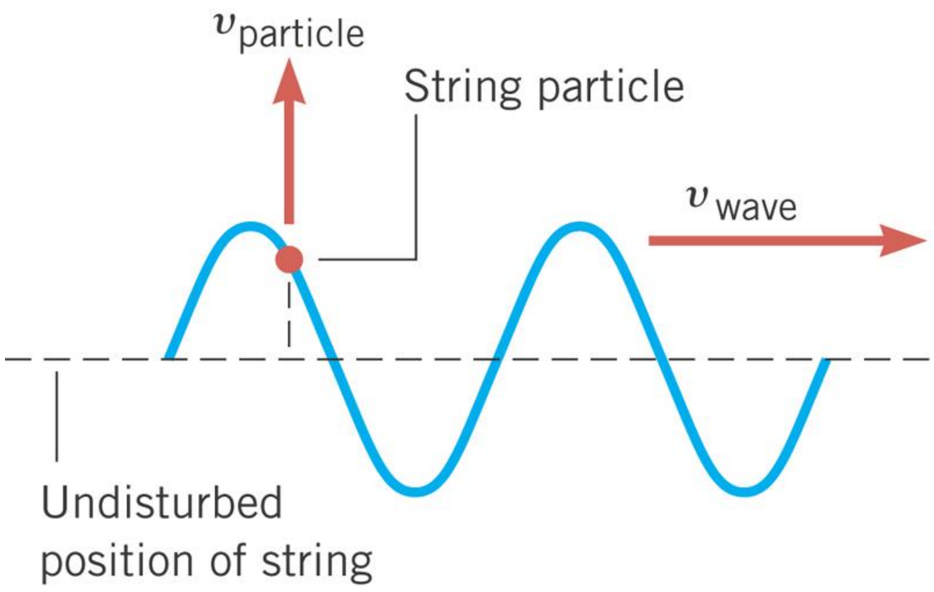
$$v = \sqrt{\frac{F}{m/L}} = \sqrt{\frac{226\ \text{N}}{\left(0.208\times 10^{-3}\ \text{kg}\right)/\left(0.628\ \text{m}\right)}} = 826\ \text{m/s}$$

Low E

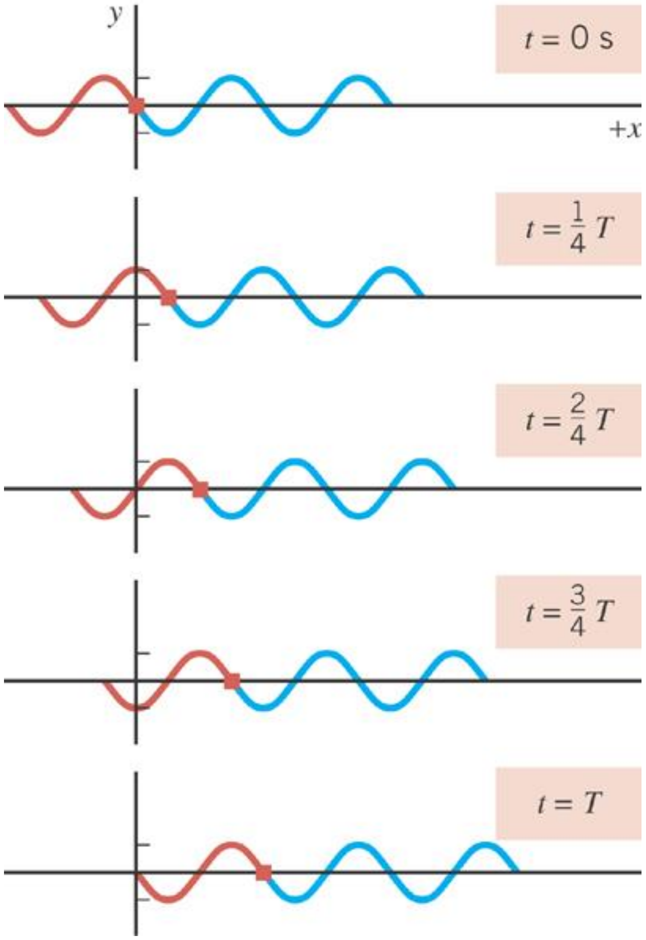
$$v = \sqrt{\frac{F}{m/L}} = \sqrt{\frac{226\ \text{N}}{\left(3.32\times 10^{-3}\ \text{kg}\right)/\left(0.628\ \text{m}\right)}} = 207\ \text{m/s}$$

Conceptual Example 3 **Wave Speed Versus Particle Speed**

Is the speed of a transverse wave on a string the same as the speed at which a particle on the string moves?



What is the displacement *y* at time *t* of a particle located at *x*?



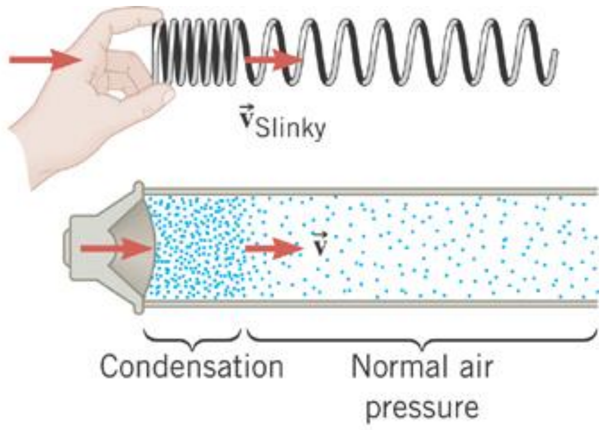
Wave motion toward +x

$$y = A \sin\left(2\pi f t - \frac{2\pi x}{\lambda}\right) \qquad (16.3)$$

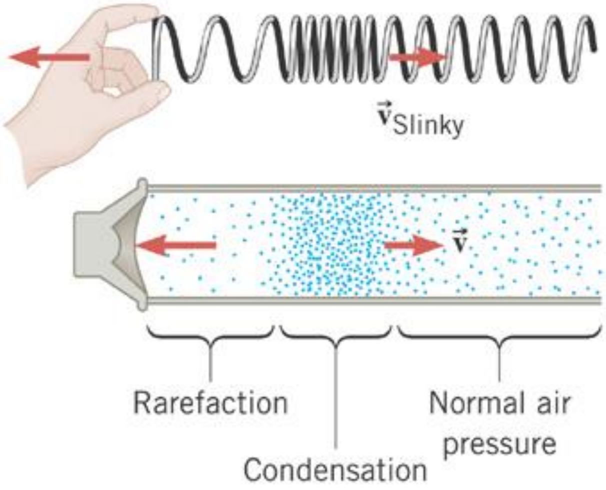
Wave motion toward −x

$$y = A \sin\left(2\pi f t + \frac{2\pi x}{\lambda}\right) \qquad (16.4)$$

LONGITUDINAL SOUND WAVES

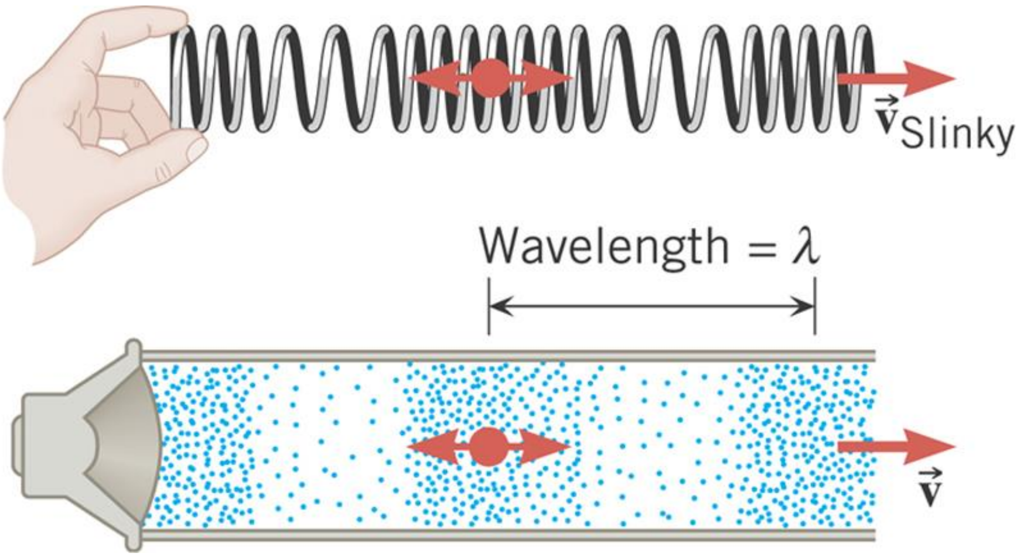


(a)

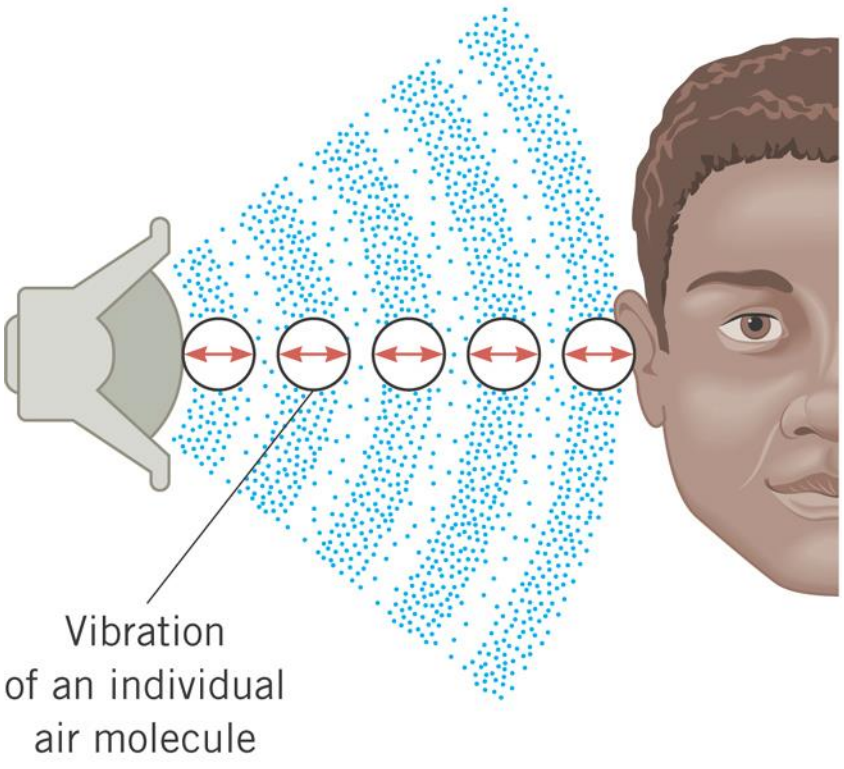


(b)

The distance between adjacent condensations is equal to the wavelength of the sound wave.



Individual air molecules are not carried along with the wave.



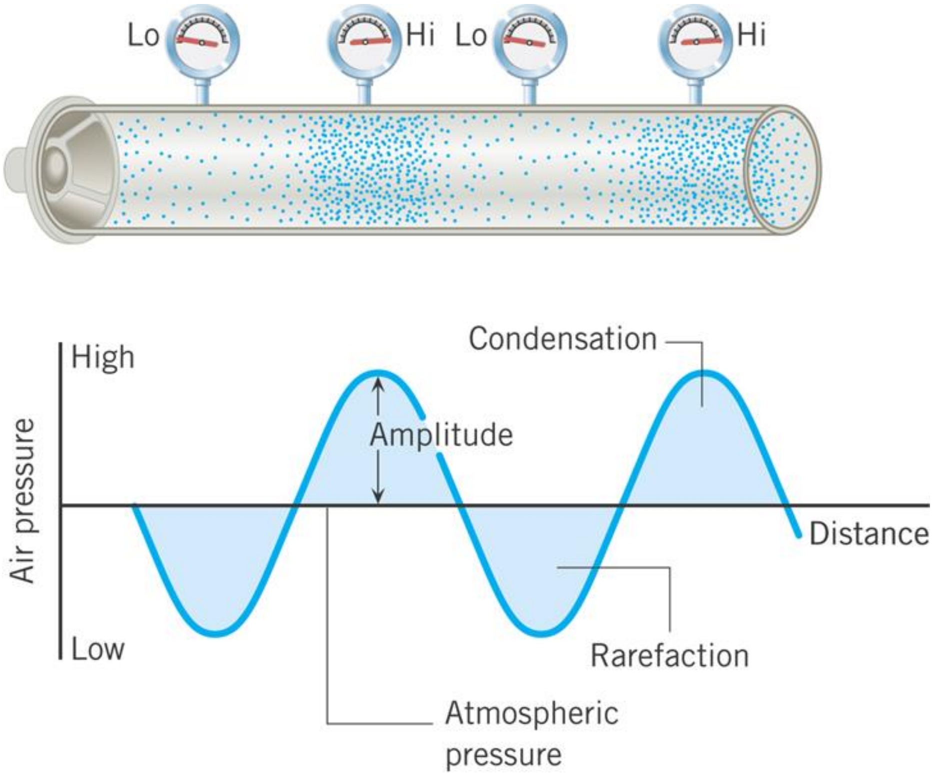
THE FREQUENCY OF A SOUND WAVE

The ***frequency*** is the number of cycles per second.

A sound with a single frequency is called a ***pure tone***.

The brain interprets the frequency in terms of the subjective quality called ***pitch***.

THE PRESSURE AMPLITUDE OF A SOUND WAVE



Loudness is an attribute of a sound that depends primarily on the pressure amplitude of the wave.

16.6 The Speed of Sound

Sound travels through gases, liquids, and solids at considerably different speeds.

Table 16.1 Speed of Sound in Gases, Liquids, and Solids

Substance	Speed (m/s)
Gases	
Air (0 °C)	331
Air (20 °C)	343
Carbon dioxide (0 °C)	259
Oxygen (0 °C)	316
Helium (0 °C)	965
Liquids	
Chloroform (20 °C)	1004
Ethyl alcohol (20 °C)	1162
Mercury (20 °C)	1450
Fresh water (20 °C)	1482
Seawater (20 °C)	1522
Solids	
Copper	5010
Glass (Pyrex)	5640
Lead	1960
Steel	5960

In a gas, it is only when molecules collide that the condensations and rarefactions of a sound wave can move from place to place.

$$v_{rms} = \sqrt{\frac{3kT}{m}}$$

Ideal Gas

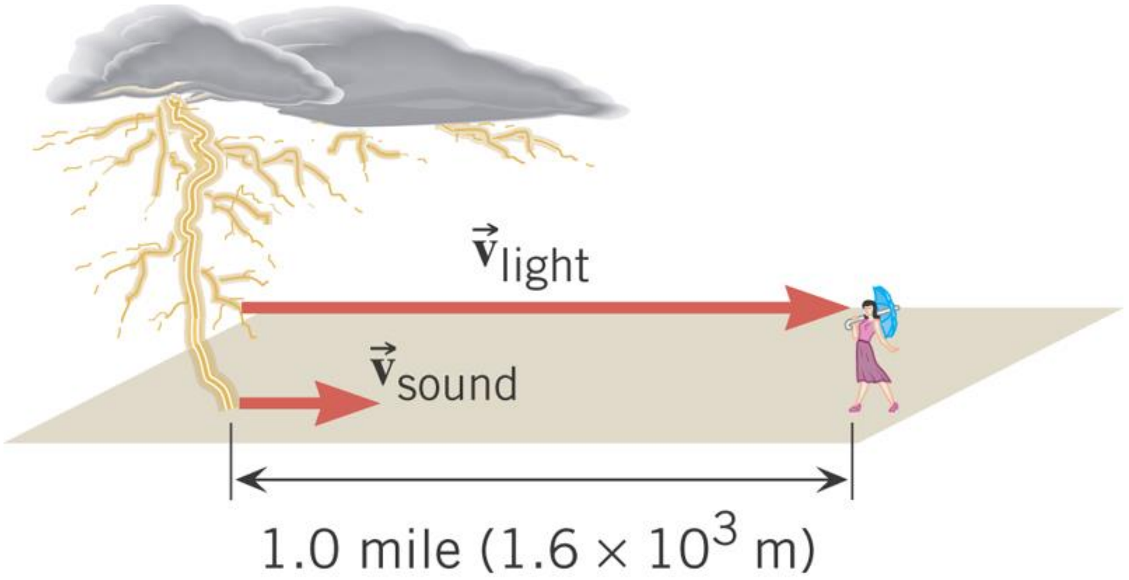
$$v = \sqrt{\frac{\gamma kT}{m}}$$

$$k = 1.38 \times 10^{-23}\ \mathrm{J/K}$$

$$\gamma = \frac{5}{3} \ \text{or} \ \frac{7}{5}$$

Conceptual Example 5 **Lightning, Thunder, and a Rule of Thumb**

There is a rule of thumb for estimating how far away a thunderstorm is. After you see a flash of lighting, count off the seconds until the thunder is heard. Divide the number of seconds by five. The result gives the approximate distance (in miles) to the thunderstorm. Why does this rule work?



16.6 The Speed of Sound

Table 11.1 Mass Densities[a] of Common Substances

Substance	Mass Density ρ (kg/m^3)
Solids	
Aluminum	2700
Brass	8470
Concrete	2200
Copper	8890
Diamond	3520
Gold	19 300
Ice	917
Iron (steel)	7860
Lead	11 300
Quartz	2660
Silver	10 500
Wood (yellow pine)	550
Liquids	
Blood (whole, 37 °C)	1060
Ethyl alcohol	806
Mercury	13 600
Oil (hydraulic)	800
Water (4 °C)	1.000×10^3
Gases	
Air	1.29
Carbon dioxide	1.98
Helium	0.179
Hydrogen	0.0899
Nitrogen	1.25
Oxygen	1.43

[a] Unless otherwise noted, densities are given at 0 °C and 1 atm pressure.

LIQUIDS

$$v = \sqrt{\frac{B_{ad}}{\rho}}$$

Table 10.3 Values for the Bulk Modulus of Solid and Liquid Materials

Material	Bulk Modulus B [N/m^2 (=Pa)]
Solids	
Aluminum	7.1×10^{10}
Brass	6.7×10^{10}
Copper	1.3×10^{11}
Diamond	4.43×10^{11}
Lead	4.2×10^{10}
Nylon	6.1×10^{9}
Osmium	4.62×10^{11}
Pyrex glass	2.6×10^{10}
Steel	1.4×10^{11}
Liquids	
Ethanol	8.9×10^{8}
Oil	1.7×10^{9}
Water	2.2×10^{9}

SOLID BARS

$$v = \sqrt{\frac{Y}{\rho}}$$

Table 10.1 Values for the Young's Modulus of Solid Materials

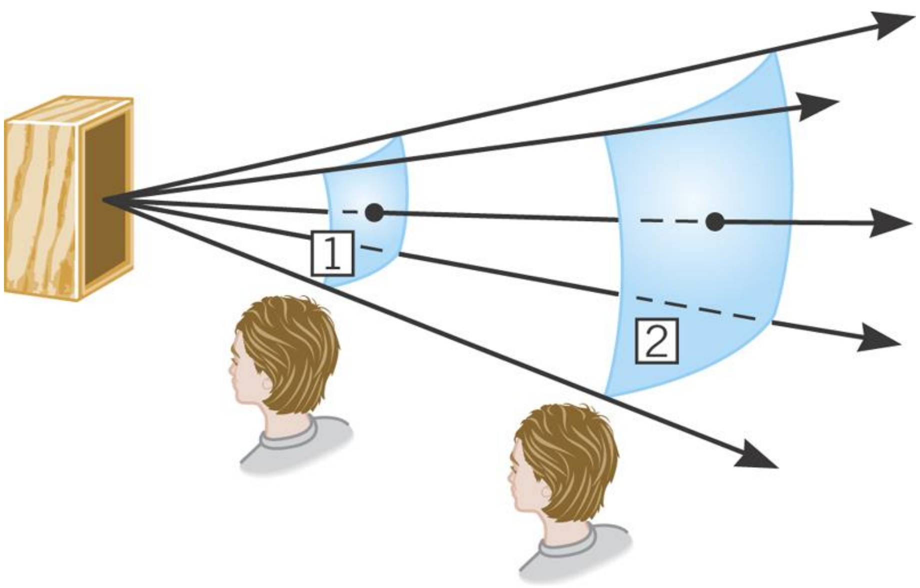
Material	Young's Modulus Y (N/m^2)
Aluminum	6.9×10^{10}
Bone	
Compression	9.4×10^{9}
Tension	1.6×10^{10}
Brass	9.0×10^{10}
Brick	1.4×10^{10}
Copper	1.1×10^{11}
Mohair	2.9×10^{9}
Nylon	3.7×10^{9}
Pyrex glass	6.2×10^{10}
Steel	2.0×10^{11}
Teflon	3.7×10^{8}
Titanium	1.2×10^{11}
Tungsten	3.6×10^{11}

16.7 Sound Intensity

Sound waves carry energy that can be used to do work.

The amount of energy transported per second is called the ***power*** of the wave.

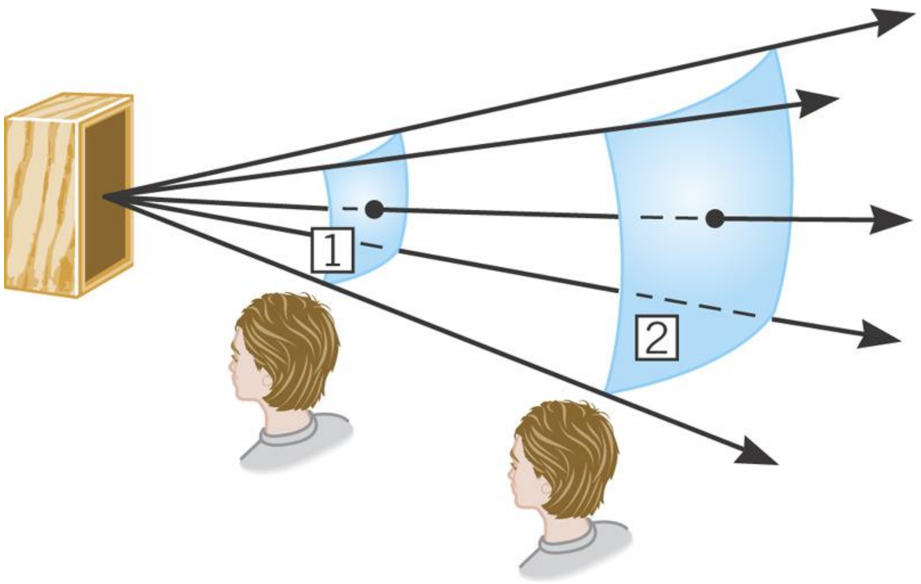
The ***sound intensity*** is defined as the power that passes perpendicularly through a surface divided by the area of that surface.



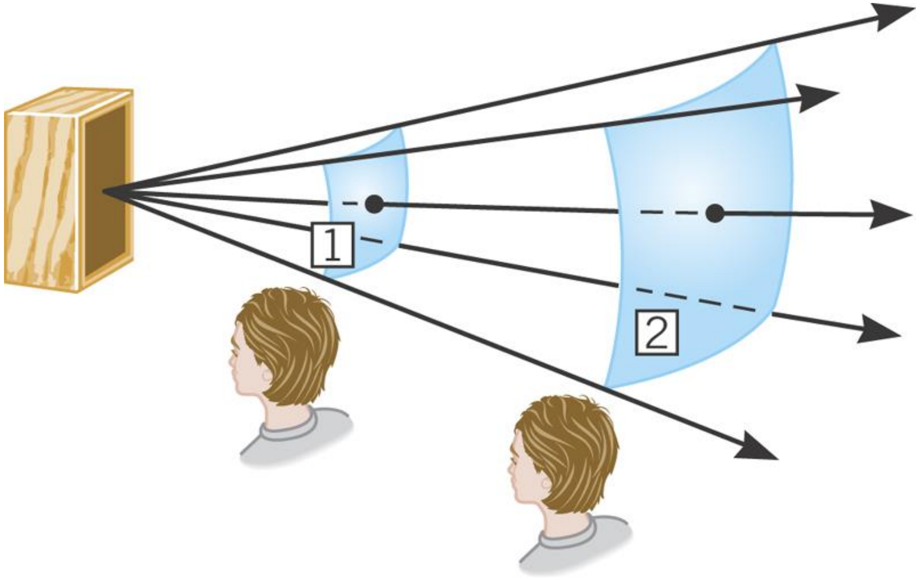
$$I = \frac{P}{A}$$

Example 6 Sound Intensities

12×10^{-5}W of sound power passed through the surfaces labeled 1 and 2. The areas of these surfaces are 4.0m^2 and 12m^2. Determine the sound intensity at each surface.



16.7 Sound Intensity



$$I_1 = \frac{P}{A_1} = \frac{12\times10^{-5}\,\text{W}}{4.0\text{m}^2} = 3.0\times10^{-5}\,\text{W/m}^2$$

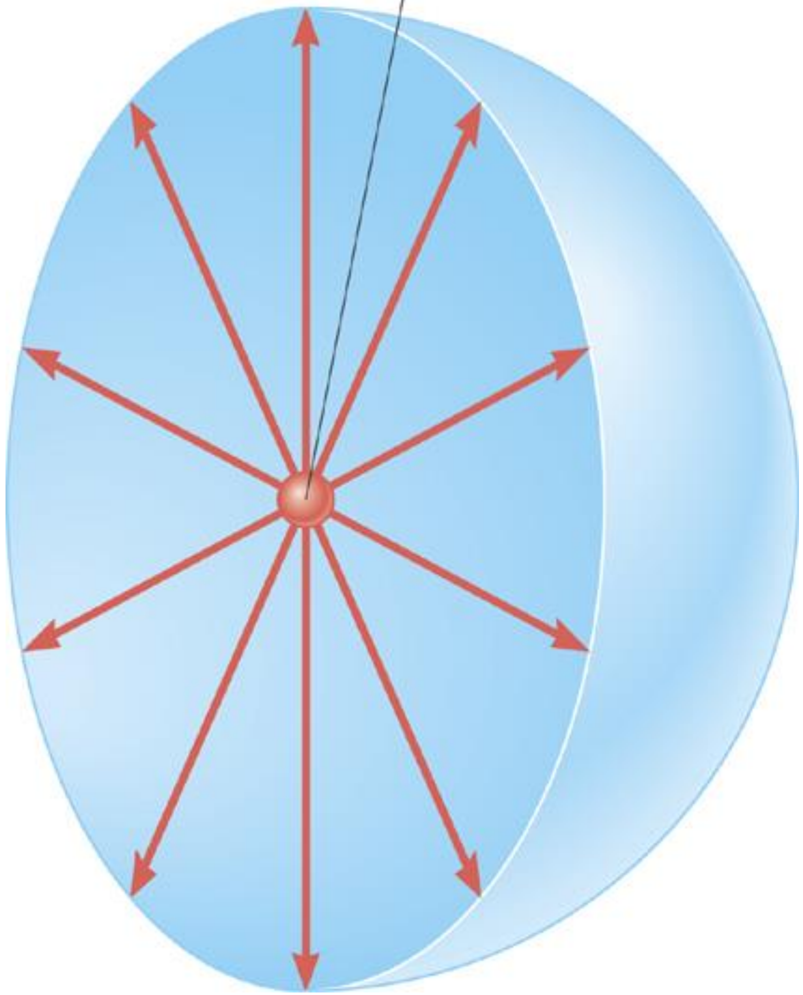
$$I_2 = \frac{P}{A_2} = \frac{12\times10^{-5}\,\text{W}}{12\text{m}^2} = 1.0\times10^{-5}\,\text{W/m}^2$$

For a 1000 Hz tone, the smallest sound intensity that the human ear can detect is about 1×10^{-12} W/m^2. This intensity is called the ***threshold of hearing***.

On the other extreme, continuous exposure to intensities greater than 1W/m^2 can be painful.

If the source emits sound *uniformly in all directions,* the intensity depends on the distance from the source in a simple way.

16.7 Sound Intensity



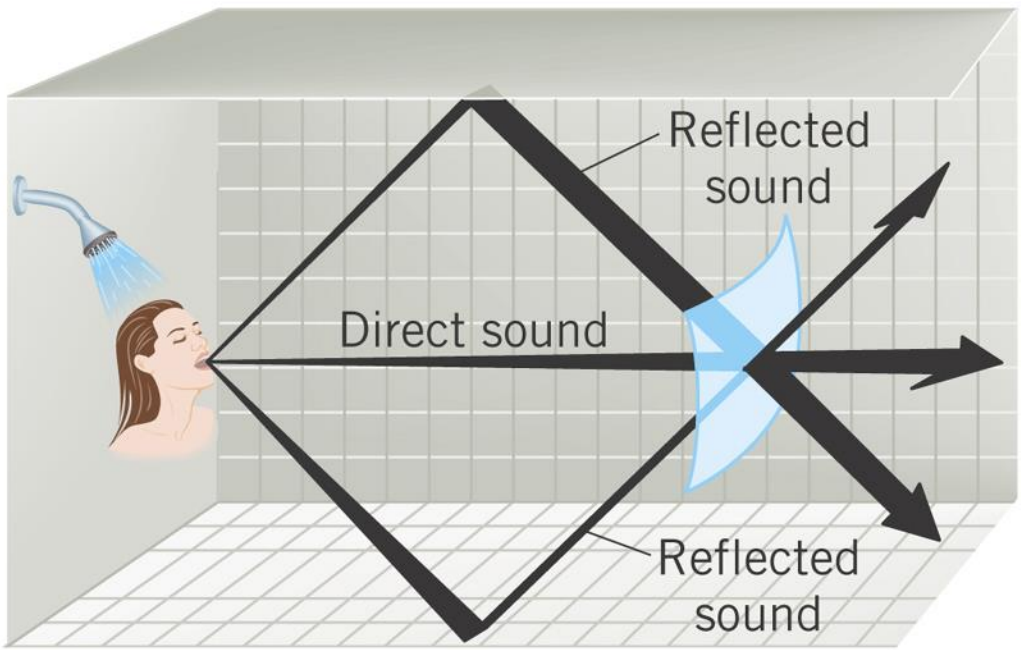
power of sound source

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

area of sphere

Conceptual Example 8 Reflected Sound and Sound Intensity

Suppose the person singing in the shower produces a sound power P. Sound reflects from the surrounding shower stall. At a distance *r* in front of the person, does the equation for the intensity of sound emitted uniformly in all directions underestimate, overestimate, or give the correct sound intensity?



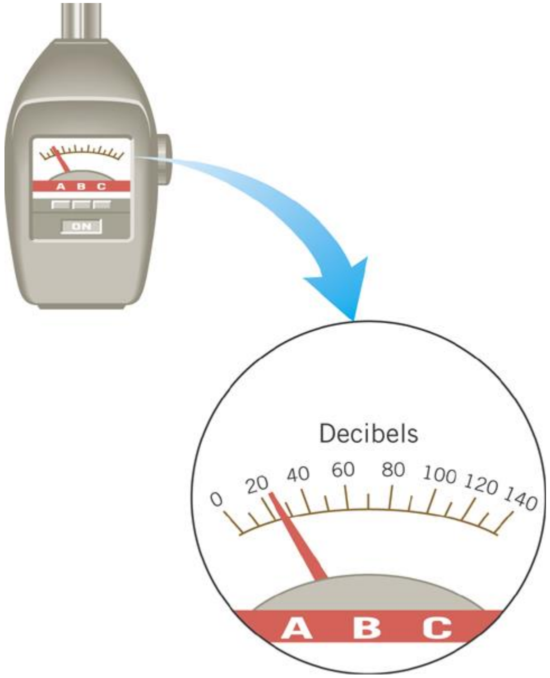
$$I = \frac{P}{4\pi r^2}$$

The ***decibel*** (dB) is a measurement unit used when comparing two sound intensities.

Because of the way in which the human hearing mechanism responds to intensity, it is appropriate to use a logarithmic scale called the ***intensity level:***

$$\beta = (10\,\mathrm{dB})\log\left(\frac{I}{I_o}\right)$$

$$I_o = 1.00\times 10^{-12}\ \mathrm{W/m^2}$$



Note that log(1)=0, so when the intensity of the sound is equal to the threshold of hearing, the intensity level is zero.

16.8 Decibels

$$\beta = (10\ \text{dB})\log\left(\frac{I}{I_o}\right) \qquad I_o = 1.00\times 10^{-12}\ \text{W/m}^2$$

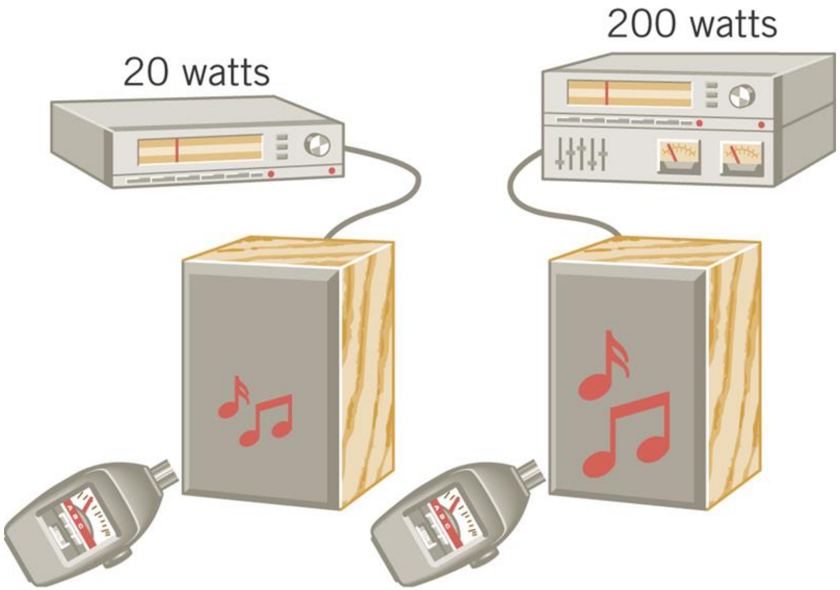
Table 16.2 Typical Sound Intensities and Intensity Levels Relative to the Threshold of Hearing

	Intensity I (W/m^2)	Intensity Level β (dB)
Threshold of hearing	1.0×10^{-12}	0
Rustling leaves	1.0×10^{-11}	10
Whisper	1.0×10^{-10}	20
Normal conversation (1 meter)	3.2×10^{-6}	65
Inside car in city traffic	1.0×10^{-4}	80
Car without muffler	1.0×10^{-2}	100
Live rock concert	1.0	120
Threshold of pain	10	130

Example 9 Comparing Sound Intensities

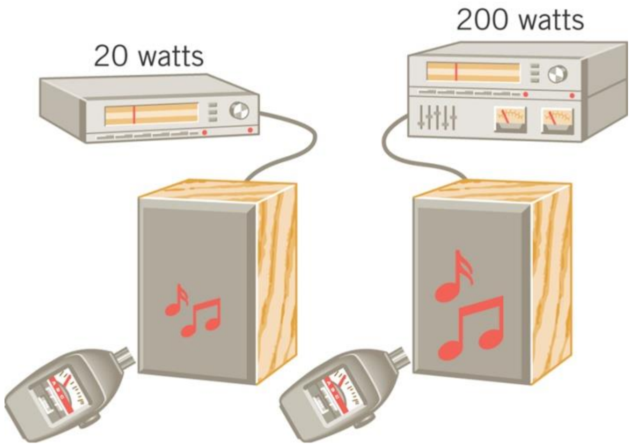
Audio system 1 produces a sound intensity level of 90.0 dB, and system 2 produces an intensity level of 93.0 dB. Determine the ratio of intensities.

$$\beta = (10\,\mathrm{dB})\log\left(\frac{I}{I_o}\right)$$



16.8 Decibels

$$\beta = (10\,\text{dB})\log\left(\frac{I}{I_o}\right)$$



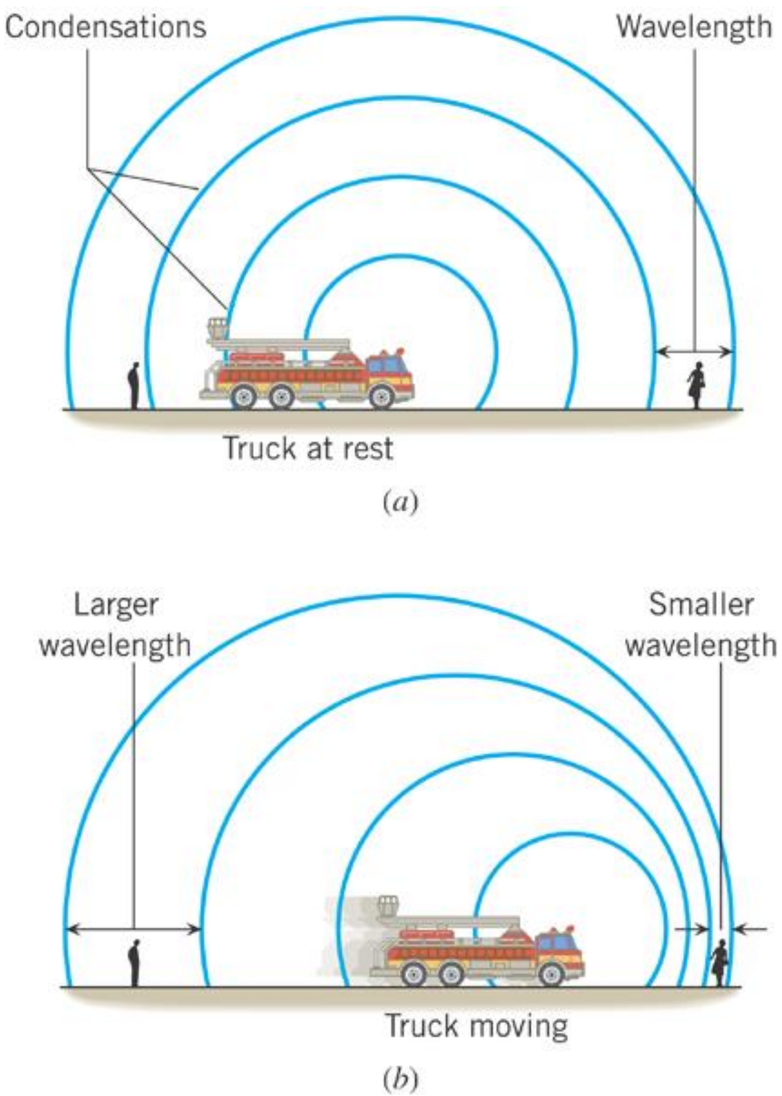
$$\beta_1 = (10\,\text{dB})\log\left(\frac{I_1}{I_o}\right) \qquad \beta_2 = (10\,\text{dB})\log\left(\frac{I_2}{I_o}\right)$$

$$\beta_2 - \beta_1 = (10\,\text{dB})\log\left(\frac{I_2}{I_o}\right) - (10\,\text{dB})\log\left(\frac{I_1}{I_o}\right) = (10\,\text{dB})\log\left(\frac{I_2/I_o}{I_1/I_o}\right) = (10\,\text{dB})\log\left(\frac{I_2}{I_1}\right)$$

$$3.0\,\text{dB} = (10\,\text{dB})\log\left(\frac{I_2}{I_1}\right)$$

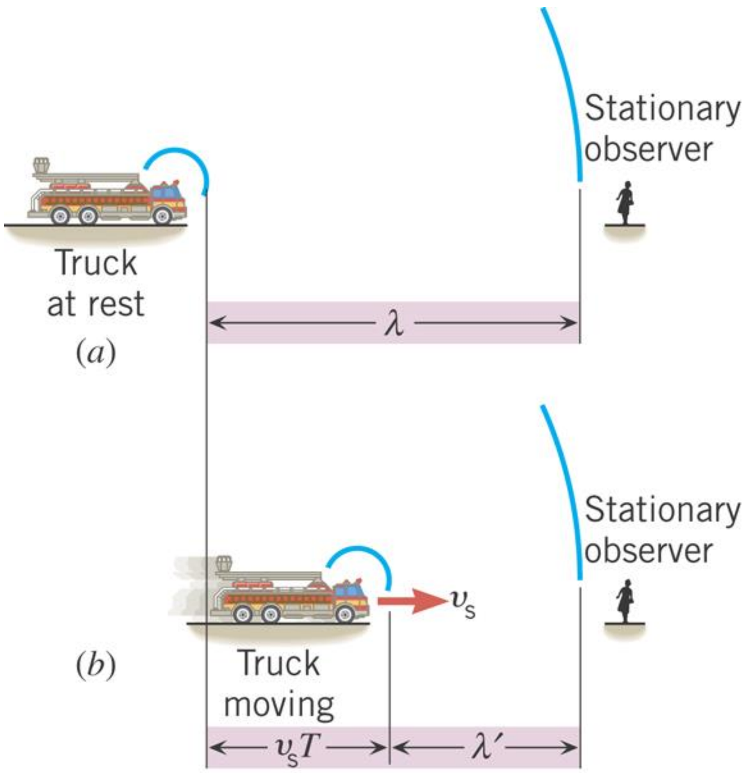
$$0.30 = \log\left(\frac{I_2}{I_1}\right) \qquad \frac{I_2}{I_1} = 10^{0.30} = 2.0$$

16.9 The Doppler Effect



The ***Doppler effect*** is the change in frequency or pitch of the sound detected by an observer because the sound source and the observer have different velocities with respect to the medium of sound propagation.

MOVING SOURCE



$$\lambda' = \lambda - v_s T$$

$$f_o = \frac{v}{\lambda'} = \frac{v}{\lambda - v_s T} = \frac{v}{v/f_s - v_s/f_s}$$

$$f_o = f_s\left(\frac{1}{1 - v_s/v}\right)$$

source moving toward a stationary observer

$$f_o = f_s\left(\frac{1}{1 - v_s/v}\right)$$

source moving away from a stationary observer

$$f_o = f_s\left(\frac{1}{1 + v_s/v}\right)$$

Example 10 The Sound of a Passing Train

A high-speed train is traveling at a speed of 44.7 m/s when the engineer sounds the 415-Hz warning horn. The speed of sound is 343 m/s. What are the frequency and wavelength of the sound, as perceived by a person standing at the crossing, when the train is (a) approaching and (b) leaving the crossing?

$$f_o = f_s\left(\frac{1}{1 - v_s/v}\right)$$

$$f_o = f_s\left(\frac{1}{1 + v_s/v}\right)$$

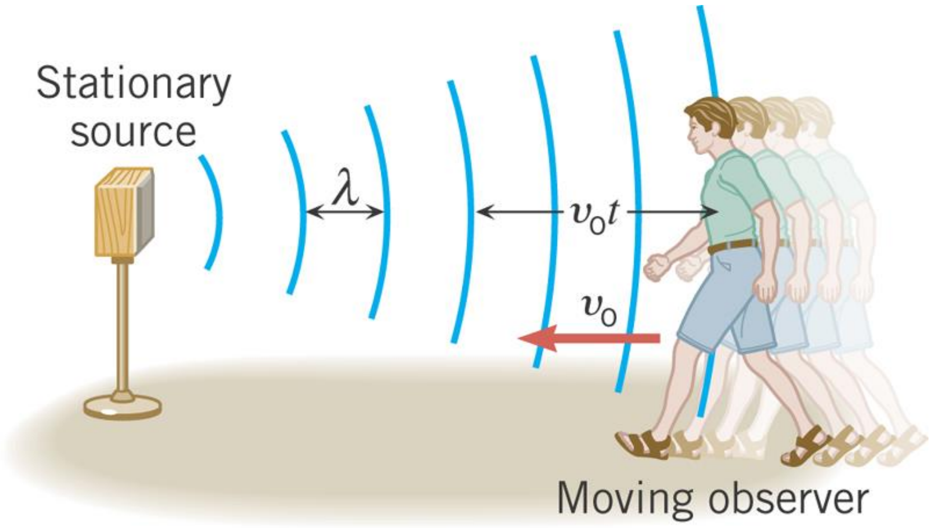
approaching

$$f_o = (415\,\text{Hz})\left(\frac{1}{1-\frac{44.7\,\text{m/s}}{343\,\text{m/s}}}\right) = 477\,\text{Hz}$$

leaving

$$f_o = (415\,\text{Hz})\left(\frac{1}{1+\frac{44.7\,\text{m/s}}{343\,\text{m/s}}}\right) = 367\,\text{Hz}$$

MOVING OBSERVER



$$f_o = f_s + \frac{v_o}{\lambda} = f_s\left(1 + \frac{v_o}{f_s\lambda}\right)$$

$$= f_s\left(1 + \frac{v_o}{v}\right)$$

Observer moving towards stationary source

$$f_o = f_s\left(1+\frac{v_o}{v}\right)$$

Observer moving away from stationary source

$$f_o = f_s\left(1-\frac{v_o}{v}\right)$$

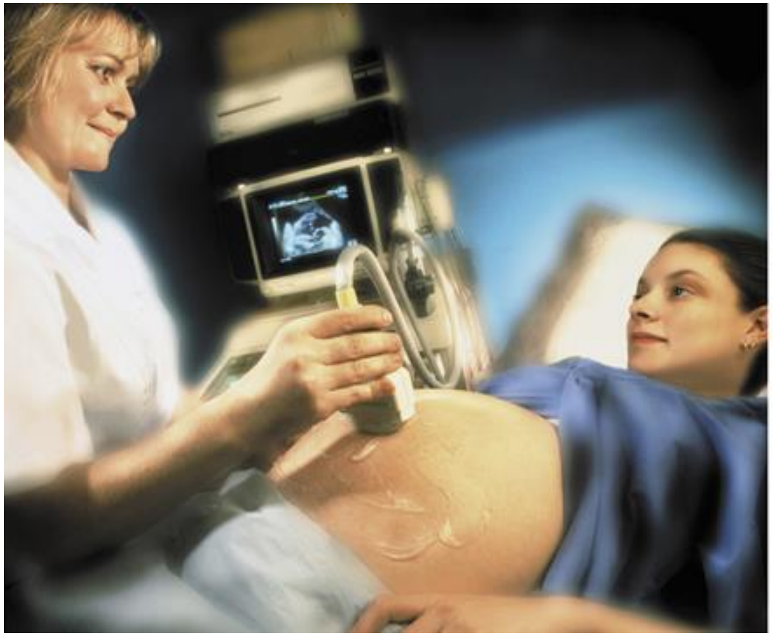
GENERAL CASE

Numerator: plus sign applies when observer moves towards the source

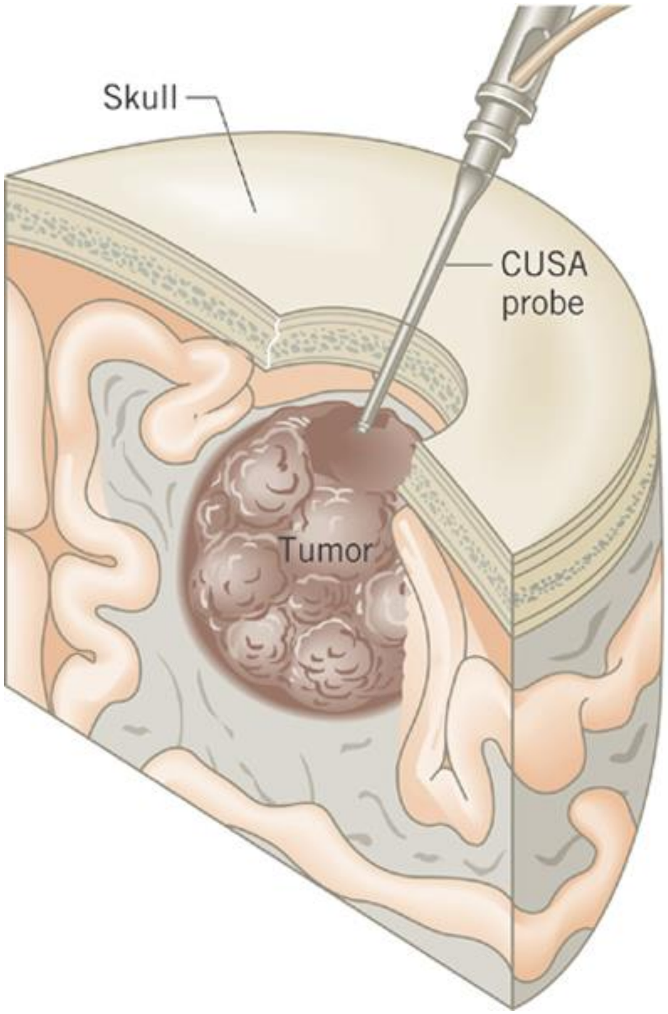
$$f_o = f_s \left(\frac{1 \pm \frac{v_o}{v}}{1 \mp \frac{v_s}{v}} \right)$$

Denominator: minus sign applies when source moves towards the observer

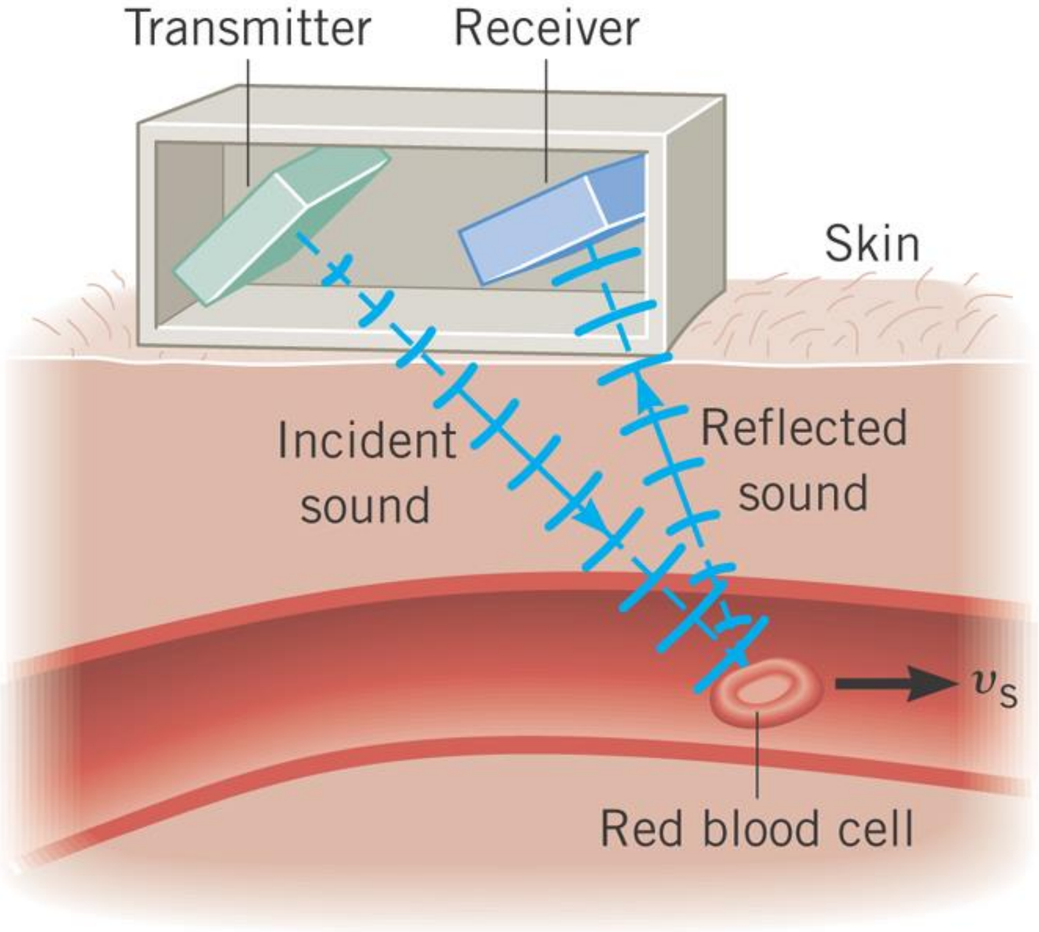
By scanning ultrasonic waves across the body and detecting the echoes from various locations, it is possible to obtain an image.



Ultrasonic sound waves cause the tip of the probe to vibrate at 23 kHz and shatter sections of the tumor that it touches.



When the sound is reflected from the red blood cells, its frequency is changed in a kind of Doppler effect because the cells are moving.



16.11 The Sensitivity of the Human Ear