Chapter 15

Thermodynamics

continued

15.10 Refrigerators, Air Conditioners, and Heat Pumps

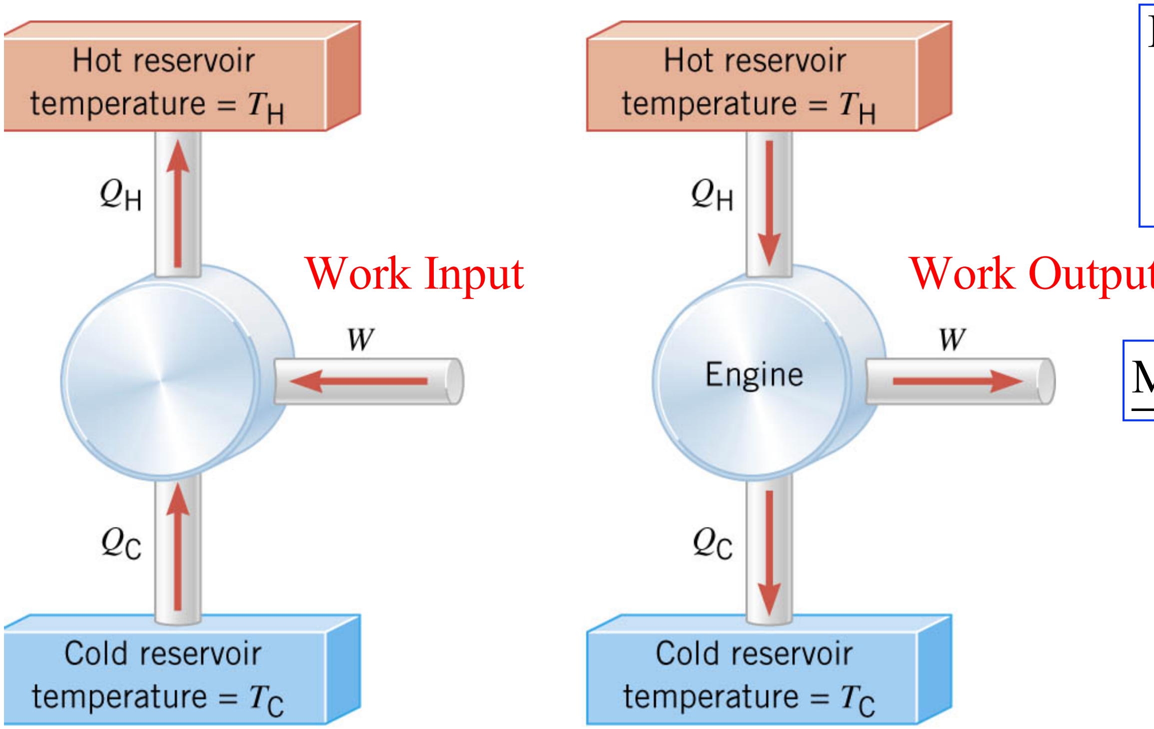
Refrigerators, air conditioners, and heat pumps are devices that make heat flow from cold to hot. This is called the ***refrigeration process***.

Heat-pump coefficient of performance

$$= \frac{|Q_H|}{|W|}$$

Refrigerator coefficient of performance

$$= \frac{|Q_C|}{|W|}$$



Refrigeration Process

Engine Process

Engine Efficiency

$$e = \frac{|W|}{|Q_H|}$$

Maximum efficiency

$$e_{Carnot} = 1 - \frac{T_C}{T_H} = \left[\frac{W}{Q_H}\right]_{Carnot}$$

It is NOT possible to cool your kitchen by leaving the refrigerator door open or to cool your room by putting a window air conditioner on the floor by the bed.

The heat output into the room equals the heat removed PLUS the amount of work necessary to move the heat from a cold reservoir to a hot one.

15.10 Refrigerators, Air Conditioners, and Heat Pumps

Example 10 A Heat Pump

An ideal, or Carnot, heat pump is used to heat a house at 294 K. How much work must the pump do to deliver 3350 J of heat into the house on a day when the outdoor temperature is 273 K?

$$e_{Carnot} = 1 - \frac{T_C}{T_H} = 1 - \frac{Q_C}{Q_H}; \qquad Q_H = Q_C + W$$

$$= 1 - \frac{Q_H - W}{Q_H} = 1 - \left(1 - \frac{W}{Q_H}\right) = \frac{W}{Q_H}$$

If $e_{Heat-Pump}$ is as good as e_{Carnot}

$$\frac{W}{Q_H} = 1 - \frac{T_C}{T_H}$$

$$W = Q_H\left[1 - \frac{T_C}{T_H}\right] = 3350\text{ J}\left[1 - \frac{273}{294}\right]$$

$$= 240\text{ J}$$

Heat-Pump

Coefficient performance

$$\frac{|Q_H|}{|W|} = \frac{3350\text{ J}}{240\text{ J}} = 14$$

15.11 Entropy

In general, irreversible processes cause us to lose some, but not necessarily all, of the ability to do work. This partial loss can be expressed in terms of a concept called ***entropy***.

Carnot Engine (is reversible)

$$\frac{|Q_C|}{|Q_H|} = \frac{T_C}{T_H} \quad \Longrightarrow \quad \frac{|Q_C|}{T_C} = \frac{|Q_H|}{T_H}$$

Entropy change for Reversible (R) Processes

$$\Delta S = \left(\frac{Q}{T}\right)_{\mathrm{R}}$$

Entropy (S) is a state-function of the system (like internal energy)

Consider the entropy change of a Carnot engine + surroundings. The entropy of the hot reservoir decreases and the entropy of the cold reservoir increases.

$$\Delta S_H = (-)\left(\frac{Q_H}{T_H}\right) \quad \text{(heat leaves hot reservoir)}$$

$$\Delta S_C = (+)\left(\frac{Q_C}{T_C}\right) \quad \text{(heat enters cold reservoir)}$$

NO Entropy change of surroundings

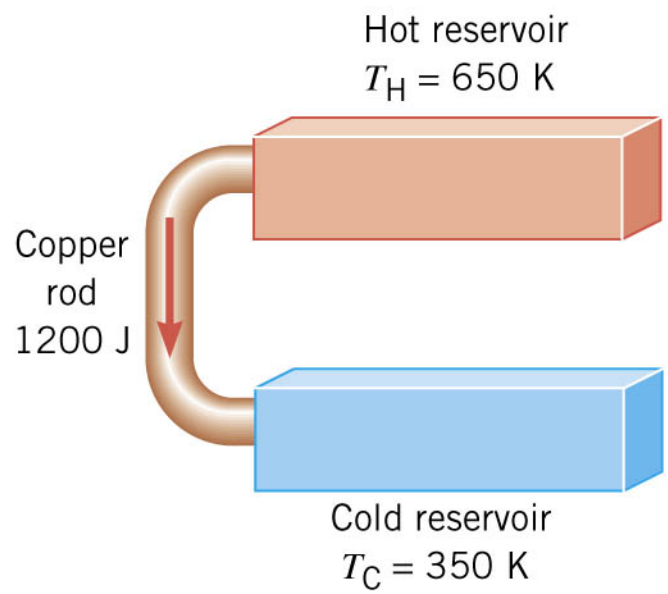
$$\Delta S_{total} = (+)\left(\frac{|Q_C|}{T_C}\right)(-)\left(\frac{|Q_H|}{T_H}\right) = 0$$

Reversible processes do not alter the entropy of the universe.

Irreversible processes (e.g., Kinetic Friction)

Example 11 The Entropy of the Universe Increases

The figure shows 1200 J of heat spontaneously flowing through a copper rod from a hot reservoir at 650 K to a cold reservoir at 350 K. Determine the amount by which this process changes the entropy of the universe.



$$\Delta S_{\text{universe}} = +\frac{|Q_C|}{T_C} - \frac{|Q_H|}{T_H}$$

$$= +\frac{1200\text{ J}}{350\text{ K}} - \frac{1200\text{ J}}{650\text{ K}} = +1.6\,\text{J/K}$$

No work was obtained from this heat transfer (0 efficiency engine)
Irreversible process lowers the amount of work possible between heat reservoirs

15.11 Entropy

Any irreversible process increases the entropy of the universe.

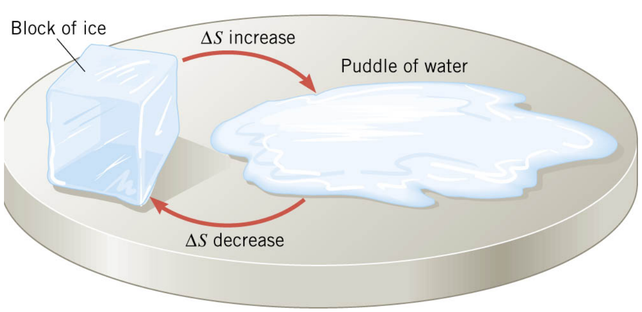
$$\Delta S_{\text{universe}} > 0$$

THE SECOND LAW OF THERMODYNAMICS STATED IN TERMS OF ENTROPY

The total entropy of the universe does not change when a reversible process occurs and increases when an irreversible process occurs.

$$W_{\text{unavailable}} = T_o \Delta S_{\text{universe}}$$

Melting Ice at 0°C (constant temperature) is a reversible process:



$$T_0 = 273\text{K, Melting}$$

$$Q_{ice} = (+)m_{ice}L_f; \quad Q_{surroundings} = (-)m_{ice}L_f$$

$$\Delta S_{universe} = \Delta S_{melt-ice} + \Delta S_{surroundings}$$

$$= \frac{(+)m_{ice}L_f}{T_0} + \frac{(-)m_{ice}L_f}{T_0} = 0$$

15.12 *The Third Law of Thermodynamics*

CORROLARY OF THE SECOND LAW OF THERMODYNAMICS

A perpetual motion machine is IMPOSSIBLE.
There will always be some irreversible process going on.
Most obvious irreversible process is kinetic friction.

Chapter 16

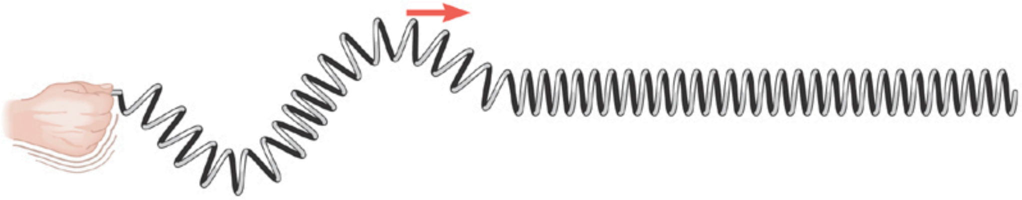
Waves and Sound

16.1 The Nature of Waves

1. A wave is a traveling disturbance.

2. A wave carries energy from place to place.

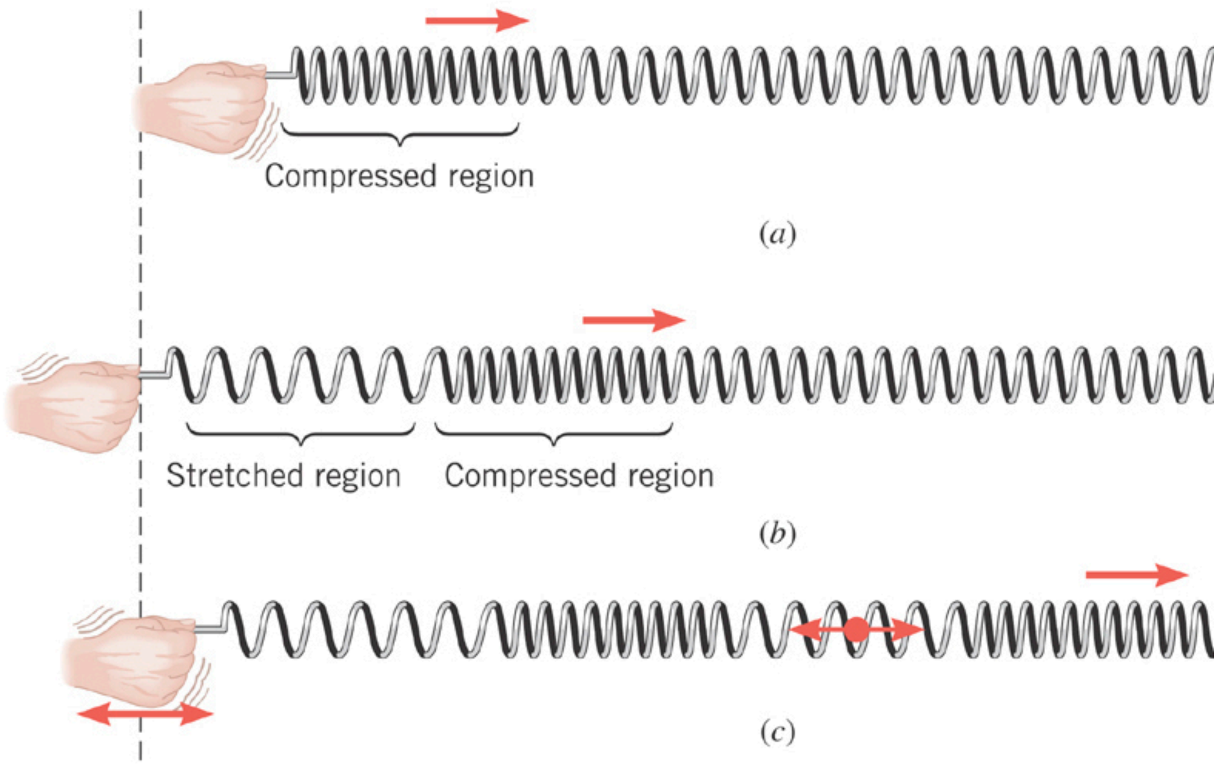
(a)



(b)

(c)

Transverse Wave



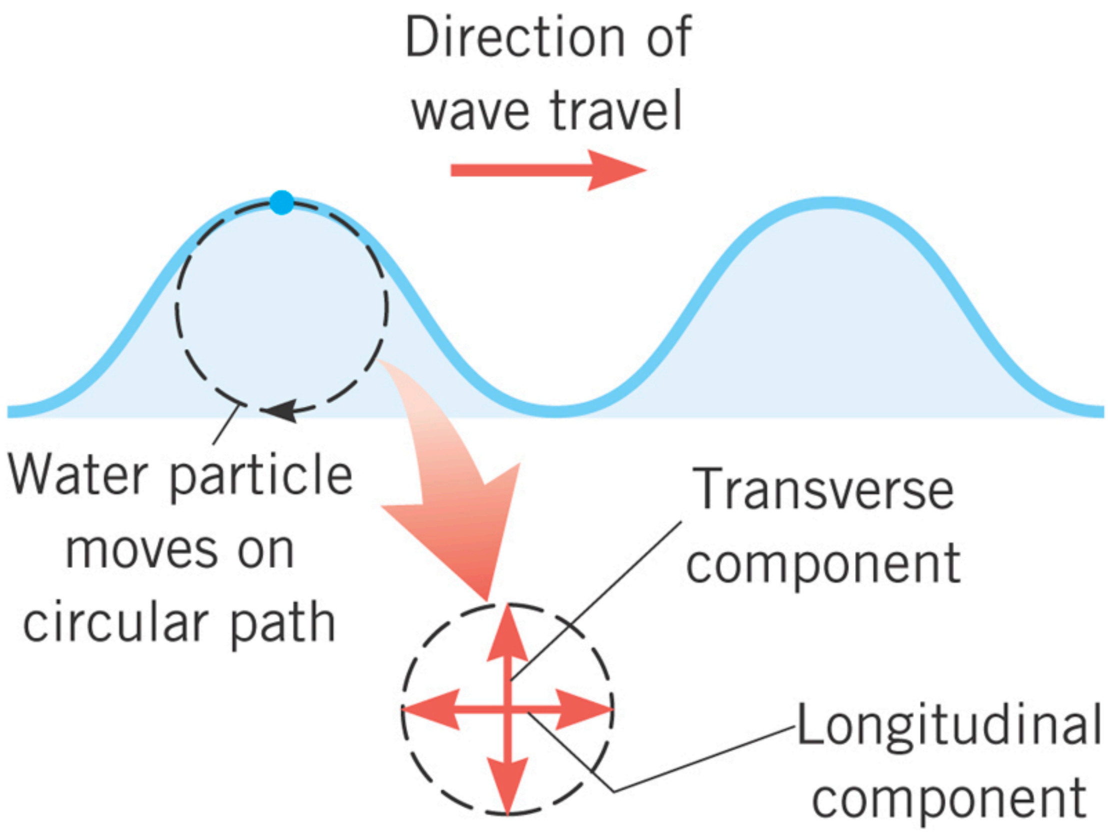
Longitudinal Wave


(a)


(b)


(c)

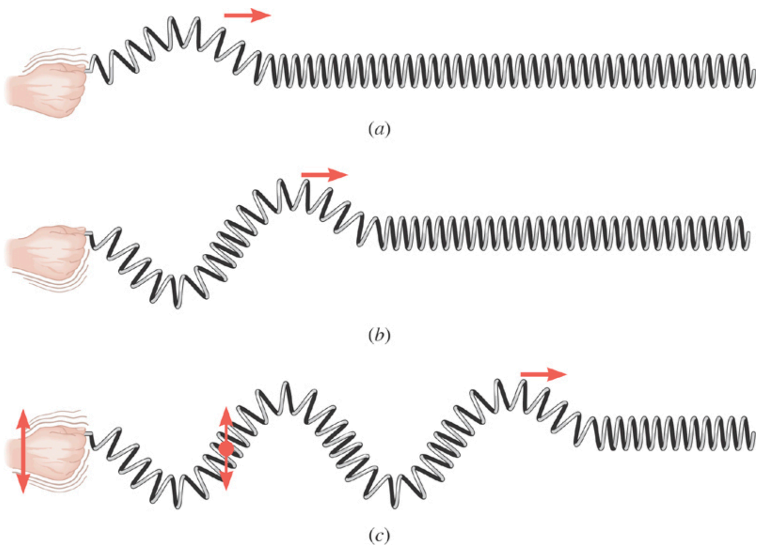
Water waves are partially transverse and partially longitudinal.

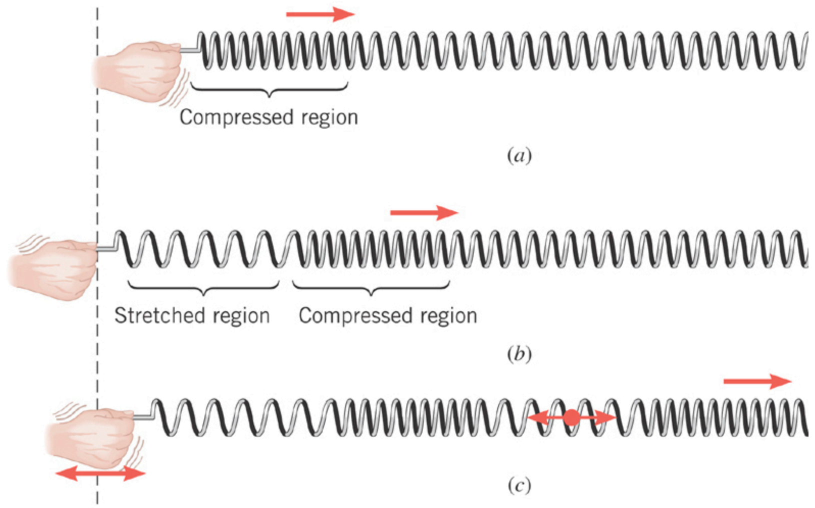


16.2 Periodic Waves

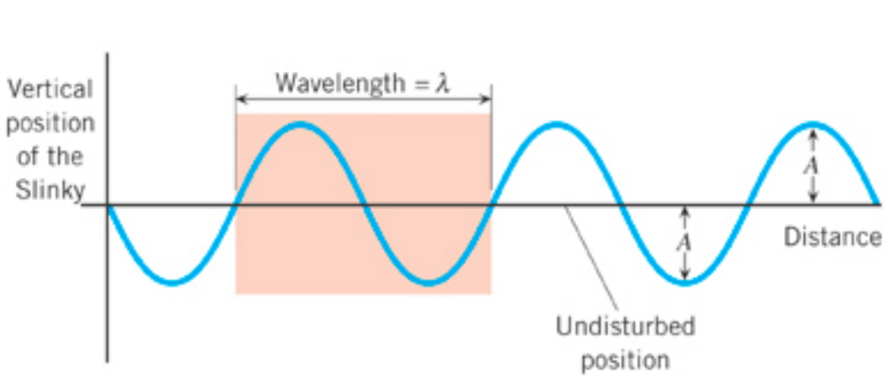
Periodic waves consist of cycles or patterns that are produced over and over again by the source.

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.

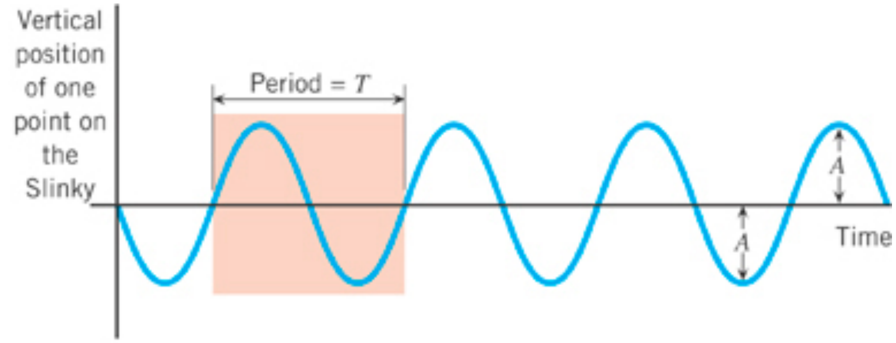




16.2 Periodic Waves



(a) At a particular time



(b) At a particular location

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.

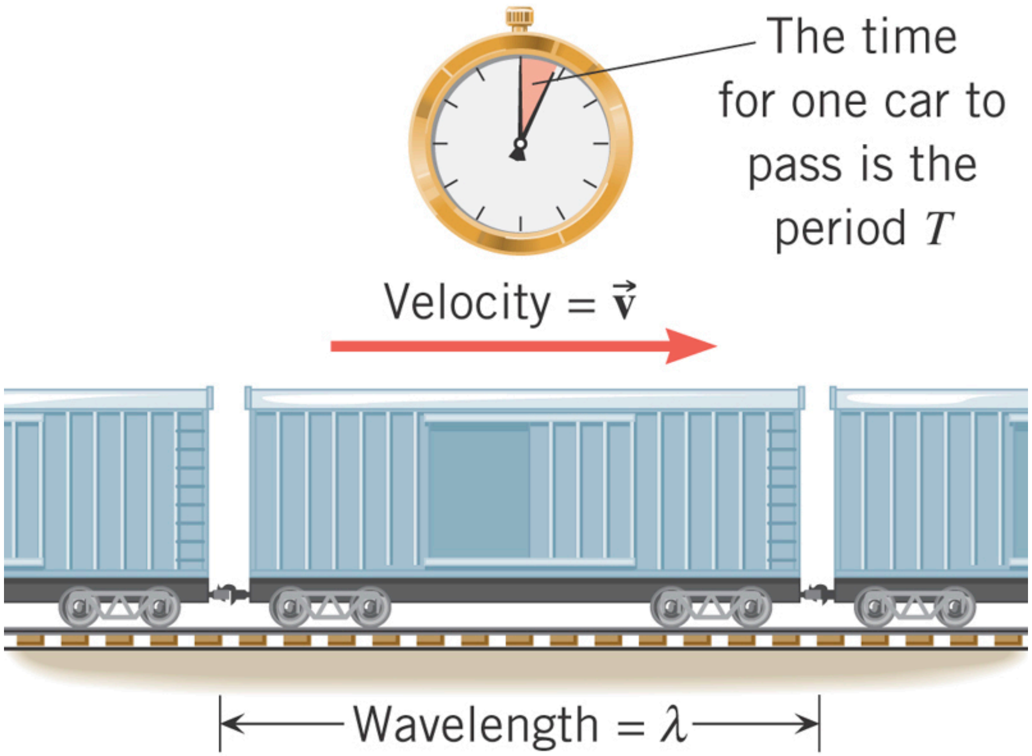
The ***wavelength*** is the horizontal length of one cycle of the wave.

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



$$vT = \lambda; \quad f = \frac{1}{T}$$

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

Example 1 The Wavelengths of Radio Waves

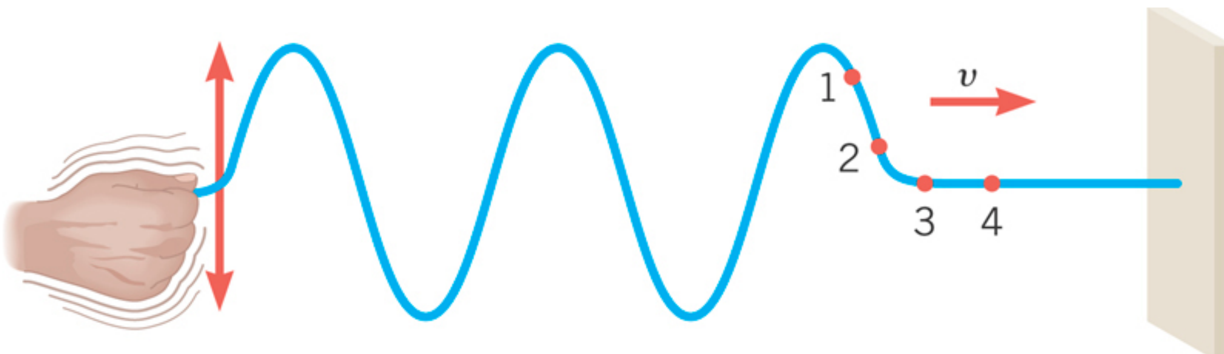
AM and FM radio waves are transverse waves consisting of electric and magnetic field disturbances traveling at a speed of 3.00×10^8 m/s. A station broadcasts AM radio waves whose frequency is 1230×10^3 Hz and an FM radio wave whose frequency is 91.9×10^6 Hz. Find the distance between adjacent crests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

$$\lambda_{\mathrm{AM}} = \frac{v}{f} = \frac{3.00 \times 10^8 \ \mathrm{m/s}}{1230 \times 10^3 \mathrm{Hz}} = 244 \ \mathrm{m}$$

$$\lambda_{\mathrm{FM}} = \frac{v}{f} = \frac{3.00 \times 10^8 \ \mathrm{m/s}}{91.9 \times 10^6 \mathrm{Hz}} = 3.26 \ \mathrm{m}$$

16.3 The Speed of a Wave on a String

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.



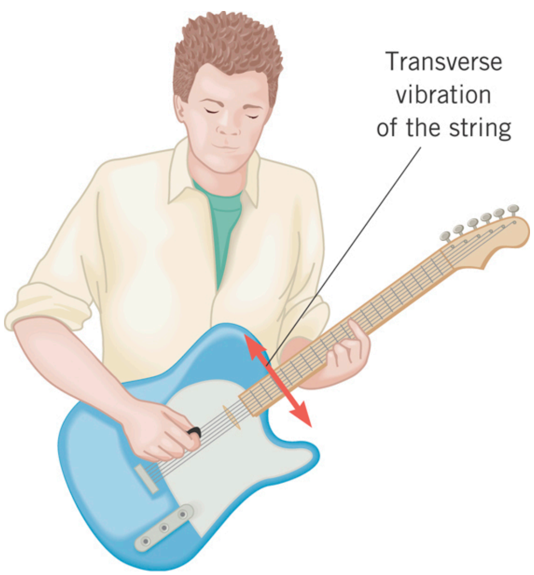
$$v = \sqrt{\frac{F}{m/L}}$$

Tension: F

Linear mass density: m/L

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

$$v = \sqrt{\frac{F}{m/L}} = \sqrt{\frac{226\text{ N}}{\left(0.208\times10^{-3}\text{kg}\right)/\left(0.628\text{ m}\right)}} = 826\,\text{m/s}$$

Low E

$$v = \sqrt{\frac{F}{m/L}} = \sqrt{\frac{226\text{ N}}{\left(3.32\times10^{-3}\text{kg}\right)/\left(0.628\text{ m}\right)}} = 207\,\text{m/s}$$

16.4 The Mathematical Description of a Wave

Traveling wave:

Moving toward +x

$$y = A\sin\left(2\pi ft - 2\pi\frac{x}{\lambda}\right)$$
$$= A\sin(\omega t - kx)$$

$$\omega = 2\pi f,\ k = \frac{2\pi}{\lambda}$$

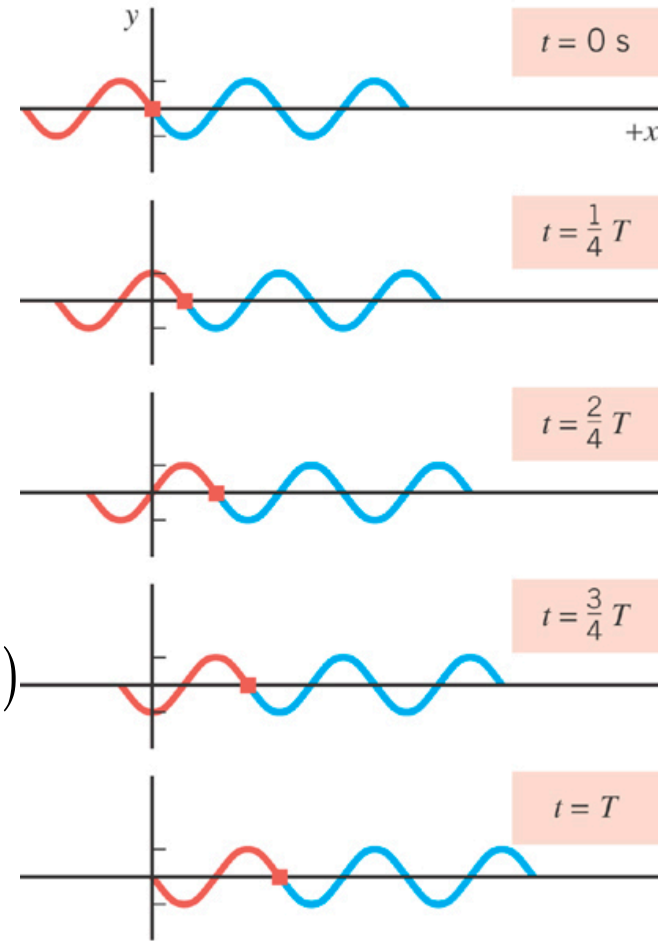
$$y_{t=0} = A\sin(0 - kx)$$

$$y_{t=T/4} = A\sin\left(\tfrac{\pi}{2} - kx\right)$$

$$y_{t=T/2} = A\sin(\pi - kx)$$

$$y_{t=3T/4} = A\sin\left(\tfrac{3\pi}{2} - kx\right)$$

$$y_{t=T} = A\sin(2\pi - kx)$$



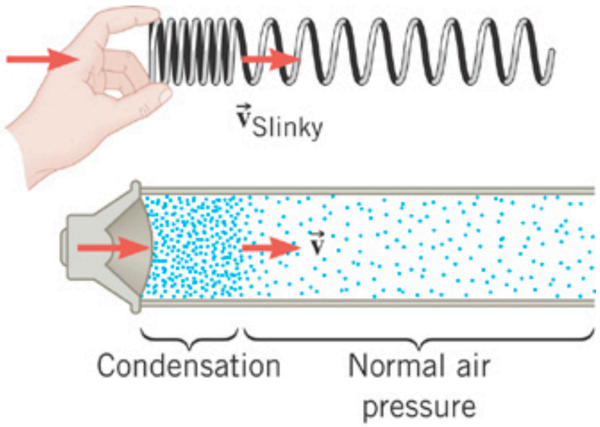
Moving toward –x

$$y = A\sin\left(2\pi ft + 2\pi\frac{x}{\lambda}\right)$$
$$= A\sin(\omega t + kx)$$

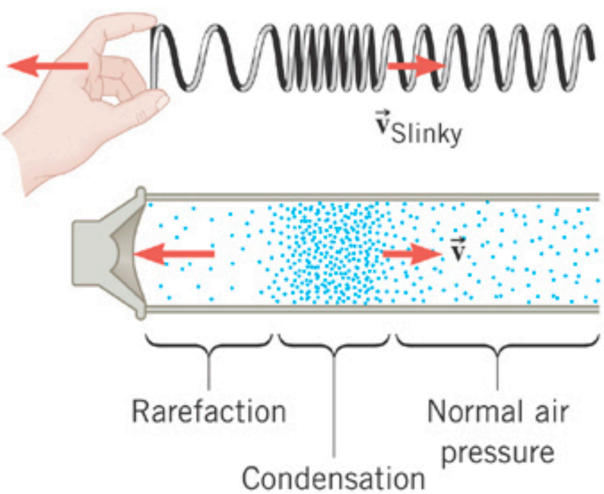
$$\omega = 2\pi f,\ k = \frac{2\pi}{\lambda}$$

16.5 The Nature of Sound Waves

LONGITUDINAL SOUND WAVES

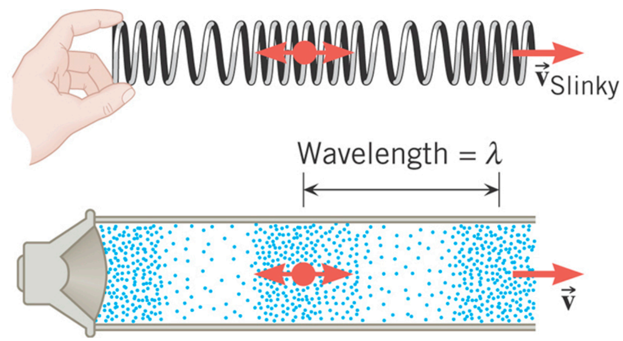


(a)



(b)

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



THE FREQUENCY OF A SOUND WAVE

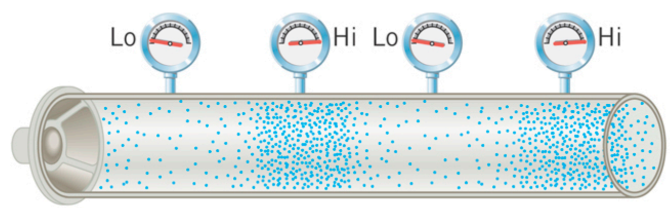
The ***frequency*** is the number of cycles per second.

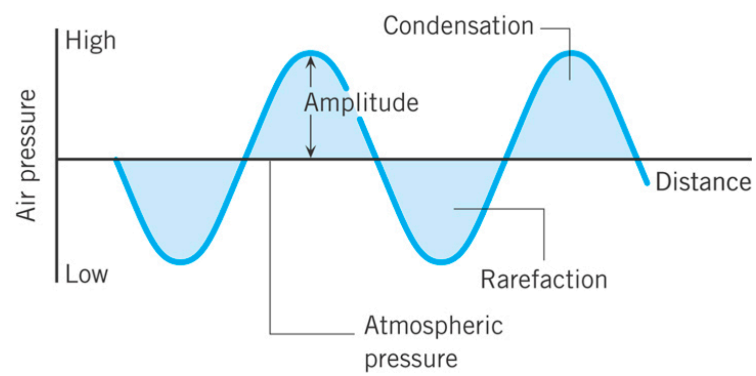
A sound with a single frequency is called a ***pure tone***.

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

THE 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.

Compactions and rerefactions can move from place to place by collisions of gas molecules

Ideal Gas molecular velocities

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

Sound wave speed

$$v_{sound} = \sqrt{\frac{\gamma kT}{m}}$$

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

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

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

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

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

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

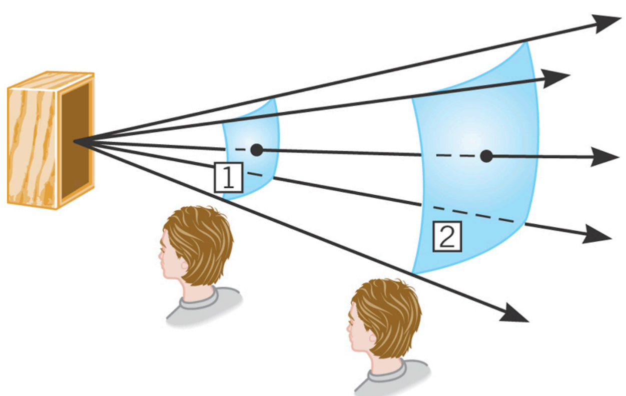
The amount of energy transported per second is called the ***power*** of the wave.

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

$$I = P/A; \quad \text{power: } P \ \ \text{(watts)}$$

Example 6 Sound Intensities

$12\text{x}10^{-5}$ 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.



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

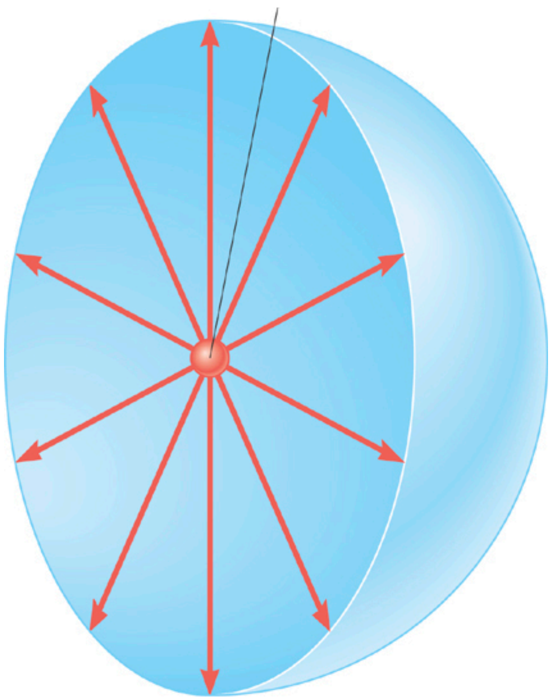
$$I_2 = \frac{P}{A_2} = \frac{12\times10^{-5}\,\text{W}}{12\text{m}^2} = 1.0\times10^{-5}\,\text{W/m}^2$$

16.7 Sound Intensity

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.



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

Intensity depends inversely on the square of the distance from the source.

16.8 Decibels

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

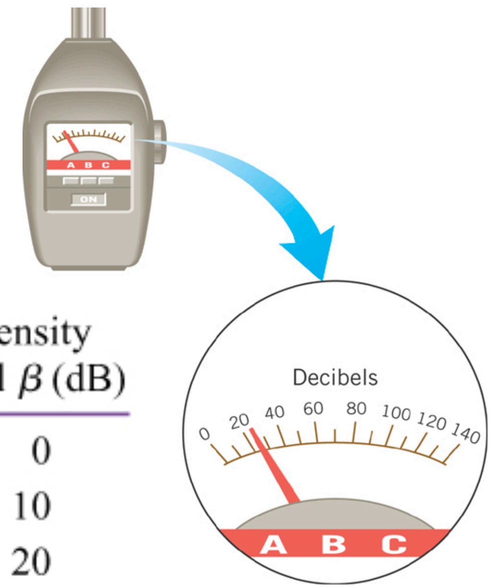
Human hearing mechanism responds to sound ***intensity level*** , logarithmically.

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

dB (decibel)

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

Note that log(1) = 0

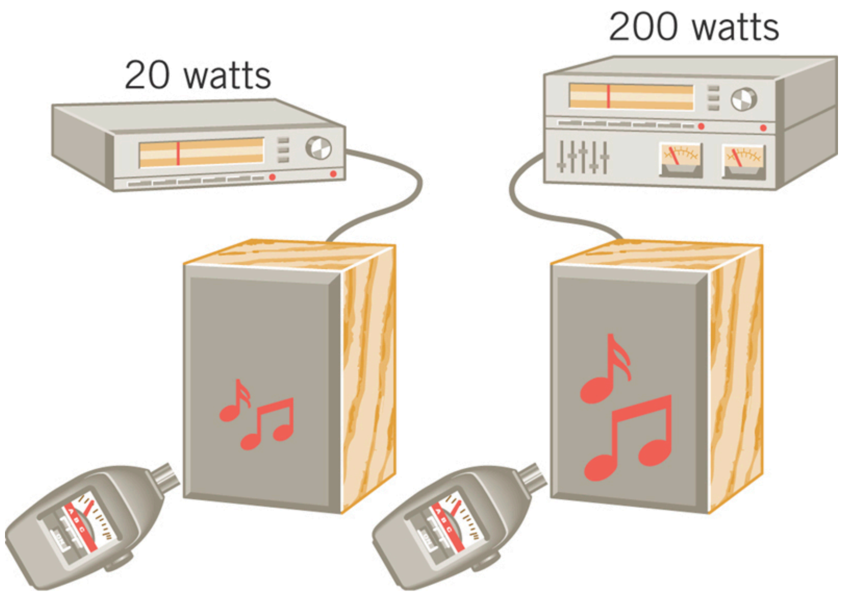


	Intensity I (W/m^2)	Intensity Level β (dB)
Threshold of hearing	1.0×10^{-12}	0
Rustling leaves	1.0×10^{-11}	10
Whisper	1.0×10^{-10}	20
Normal conversation (1 meter)	3.2×10^{-6}	65
Inside car in city traffic	1.0×10^{-4}	80
Car without muffler	1.0×10^{-2}	100
Live rock concert	1.0	120
Threshold of pain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

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



$$90\text{ dB} = (10\text{ dB})\log(I/I_o)$$

$$\log(I/I_o) = 9;$$

$$I = I_o \times 10^{9} = (1\times10^{-12}\text{ W/m}^2)\times10^{9}$$

$$= 1\times10^{-3}\text{ W/m}^2$$

$$93\text{ dB} = (10\text{ dB})\log(I/I_o)$$

$$\log(I/I_o) = 9.3;$$

$$I = I_o \times 10^{9.3} = (1\times10^{-12}\text{ W/m}^2)\times10^{9.3}$$

$$= 1\times10^{-3.3}\text{ W/m}^2 = 1\times10^{-3}(10^{0.3})\text{W/m}^2$$

$$= 1\times10^{-3}(2)\text{W/m}^2 = 2\times10^{-3}\text{W/m}^2$$

$$93\text{dB} = 90\text{dB} + 3\text{dB}$$

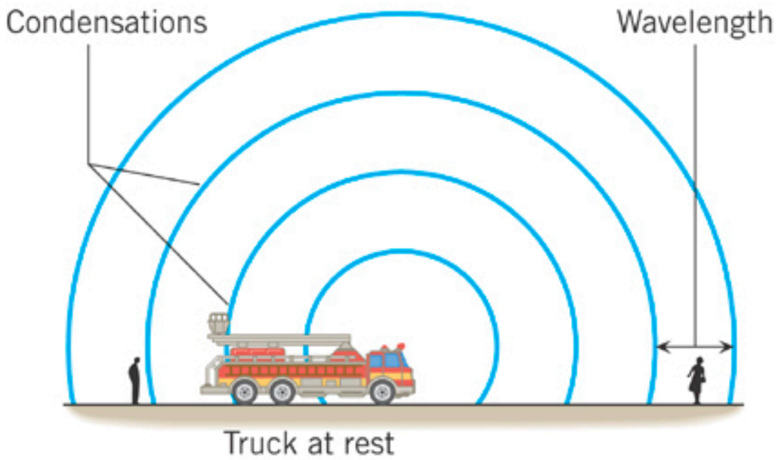
Adding 3dB results in a factor of 2

$$3\text{ dB} = (10\text{dB})\log(I_2/I_1)$$

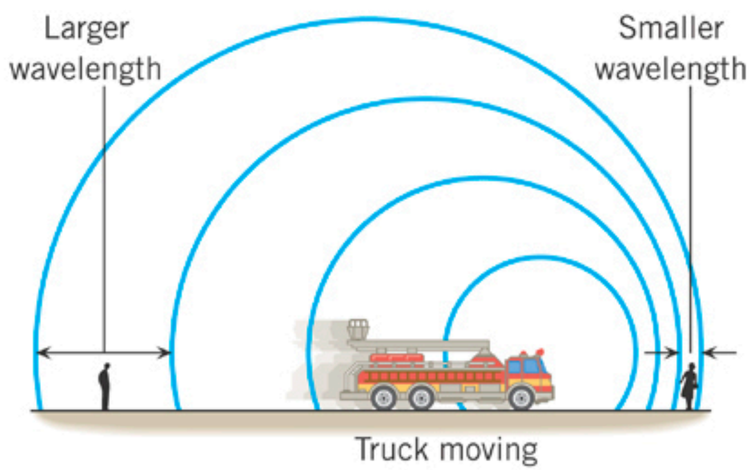
$$0.3 = \log(I_2/I_1);$$

$$I_2 = 10^{0.3} I_1 = 2 I_1$$

16.9 The Doppler Effect



(a)



(b)

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.

SOURCE (*s*) MOVING AT v_s TOWARD OBSERVER (*o*)

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

SOURCE (*s*) MOVING AT v_s AWAY FROM OBSERVER (*o*)

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