WAVES AND SOUND

Chapter 14

Units of Chapter 14

- Types of Waves
- Waves on a String
- Harmonic Wave Functions
- Sound Waves
- Sound Intensity
- The Doppler Effect

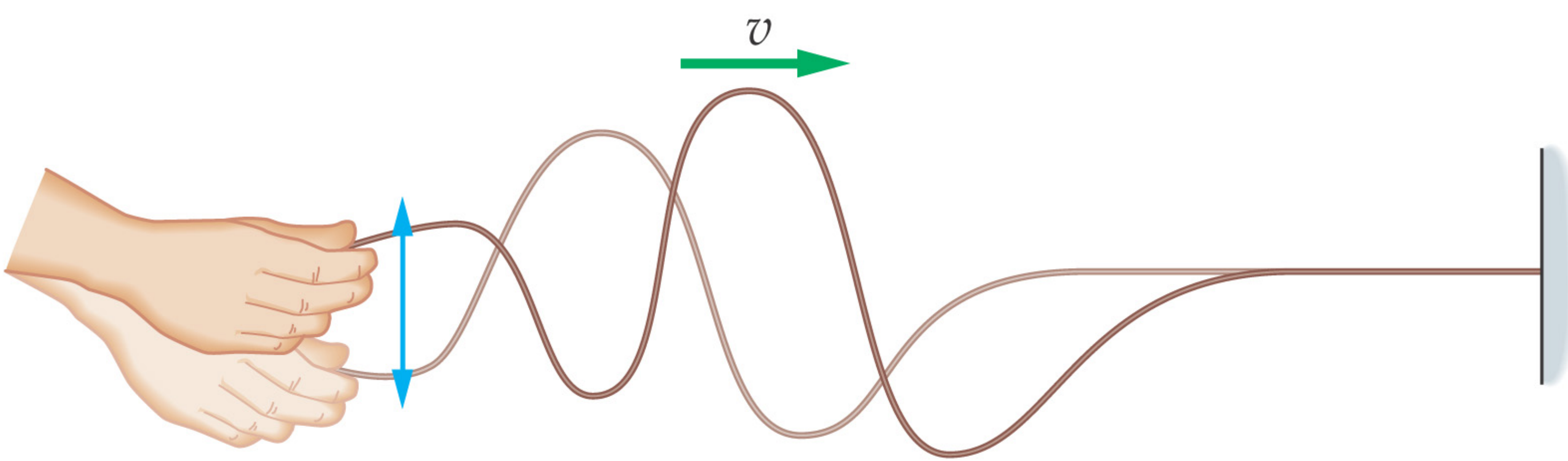
Units of Chapter 14

- Superposition and Interference
- Standing Waves
- Beats

14-1 Types of wave

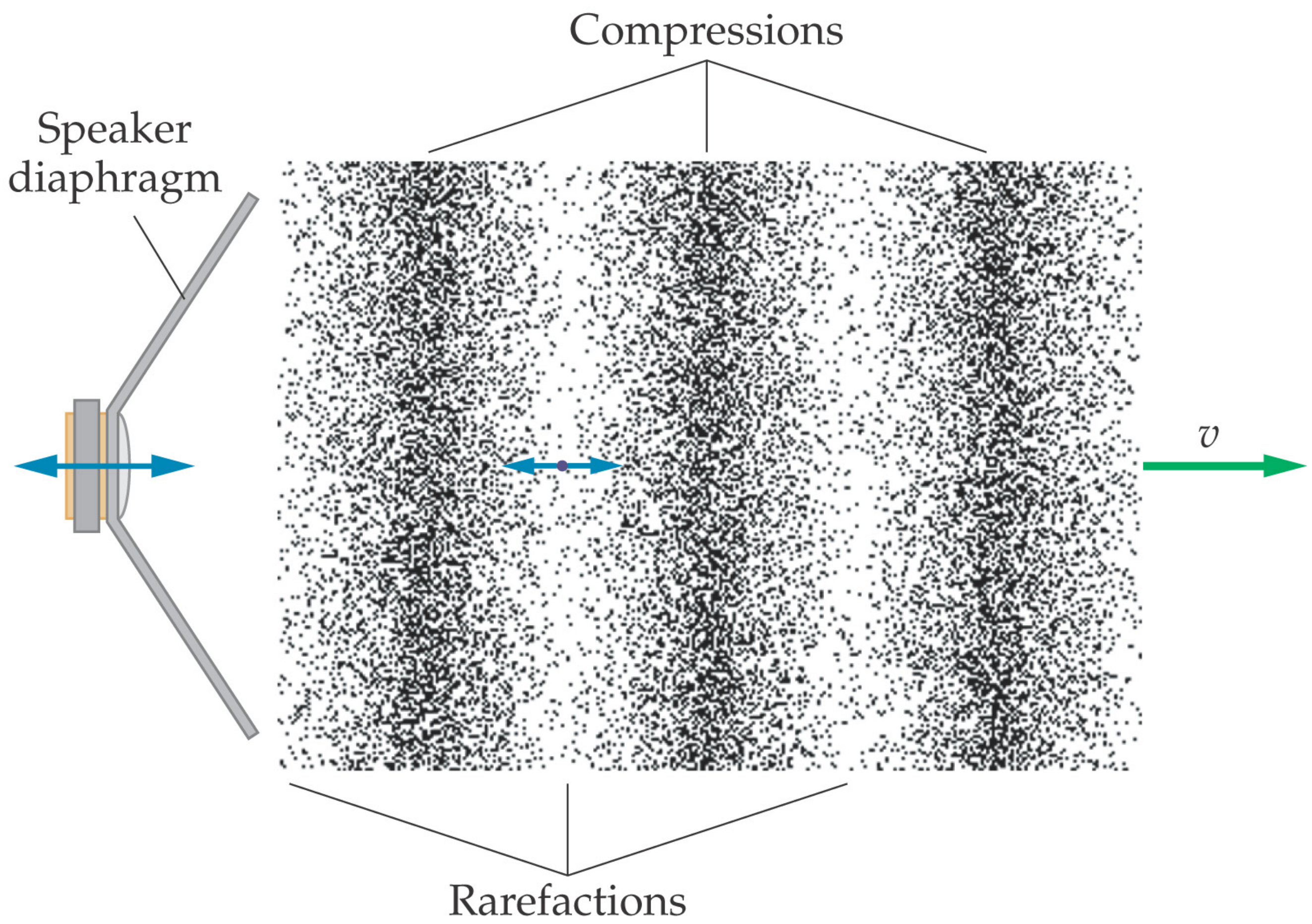
A wave is a disturbance that propagates from one place to another.

The easiest type of wave to visualize is a **transverse wave**, where the displacement of the medium is **perpendicular** to the direction of motion of the wave.



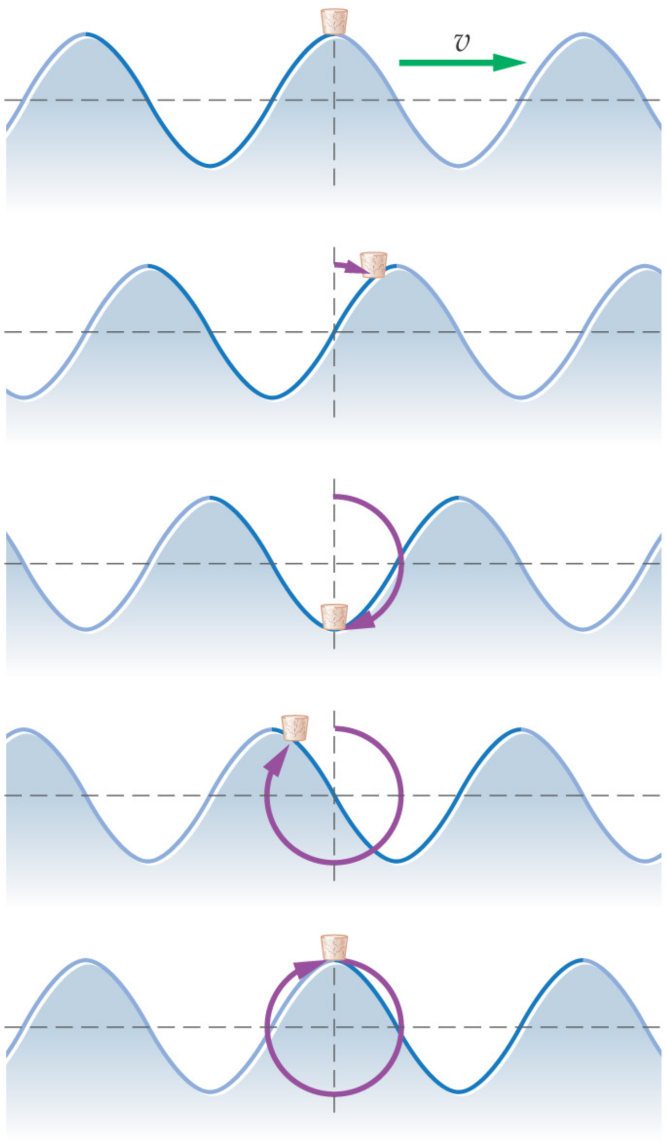
14-1 Types of wave

In a **longitudinal wave**, the displacement is along the direction of wave motion.



14-1 Types of wave

Water waves are a combination of transverse and longitudinal waves.



14-1 Types of wave

Wavelength λ: distance over which wave repeats

Period T: time for one wavelength to pass a given point

Frequency f: $f = 1/T$

Speed of a wave:

$$v = \frac{\text{distance}}{\text{time}} = \frac{\lambda}{T} = \lambda f$$

14-2 Waves on a string

The speed of a wave is determined by the properties of the material through which it propagates.

For a string, the wave speed is determined by:

1. the tension in the string, and

2. the mass of the string.

As the tension in the string increases, the speed of waves on the string increases as well.

14-2 Waves on a string

The total mass of the string depends on how long it is; what makes a difference in the speed is the mass per unit length. We expect that a larger mass per unit length results in a slower wave speed.

Definition of Mass per Length, μ

$$\mu = \text{mass per length} = m/L$$

14-2 Waves on a string

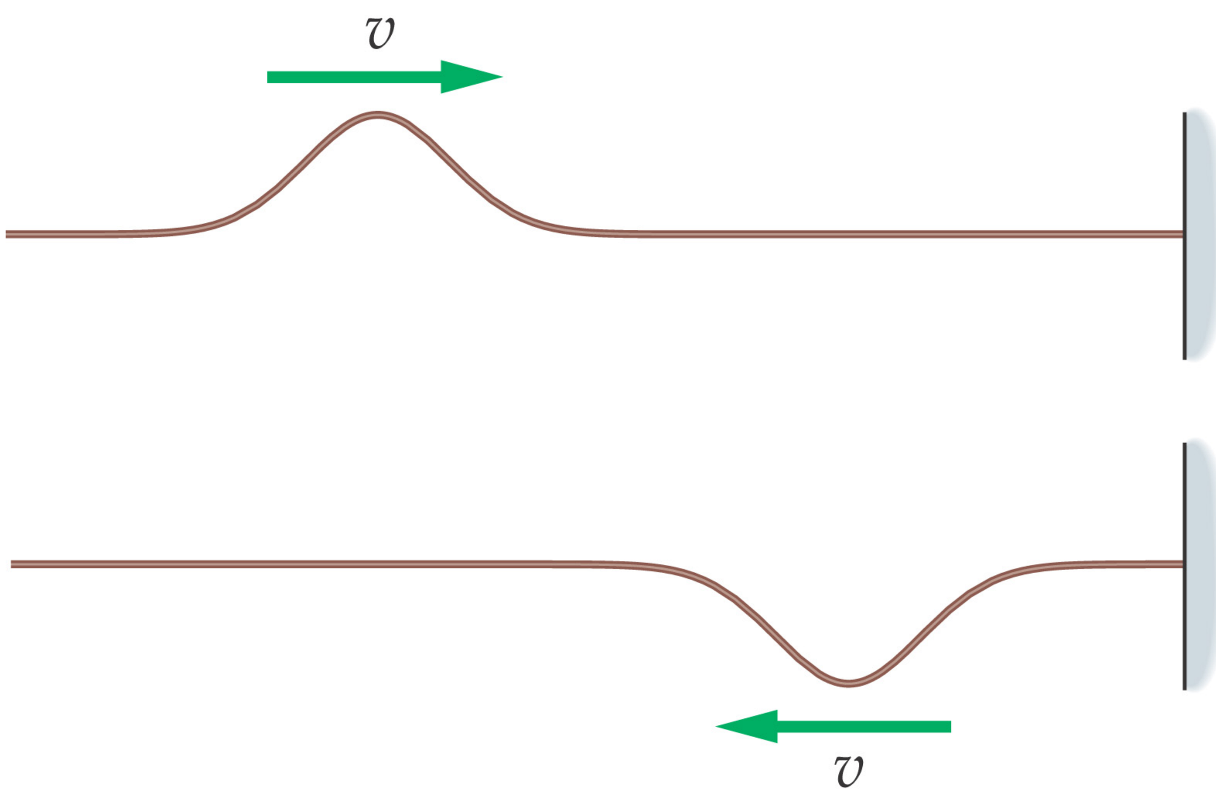
Speed of a Wave on a String, *v*

$$v = \sqrt{\frac{F}{\mu}}$$

As we can see, the speed increases when the force increases, and decreases when the mass increases.

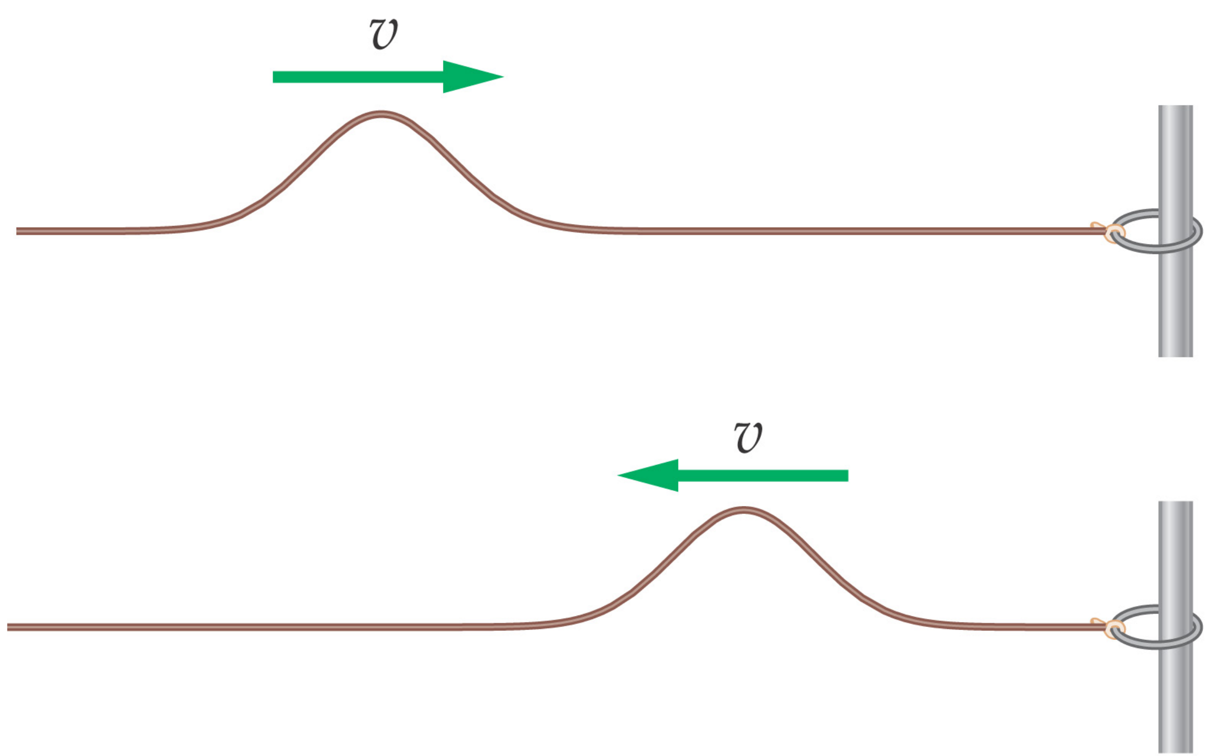
14-2 Waves on a string

When a wave reaches the end of a string, it will be reflected. If the end is fixed, the reflected wave will be inverted:



14-2 Waves on a string

If the end of the string is free to move transversely, the wave will be reflected without inversion.



14-3 Harmonic wave functions

Since the wave has the same pattern at $x + \lambda$ as it does at x, the wave must be of the form

$$y(x) = A\cos\left(\frac{2\pi}{\lambda}x\right)$$

Also, as the wave propagates in time, the peak moves as

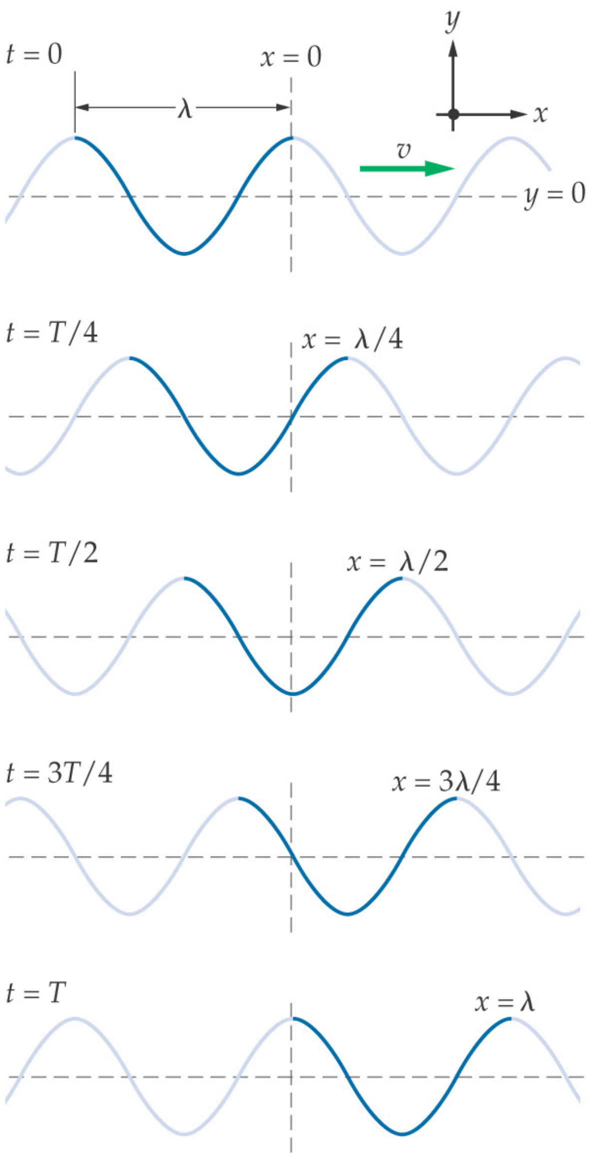
$$x = \lambda\frac{t}{T}$$

14-3 Harmonic wave functions

Combining yields the full wave equation:

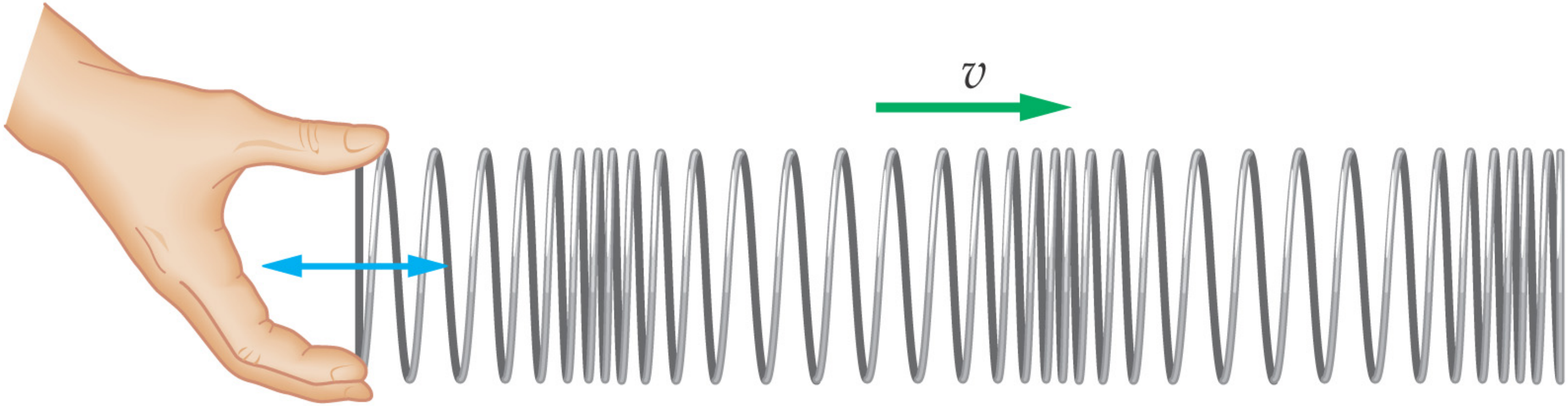
$$y(x,t) = A\cos\left[\frac{2\pi}{\lambda}\left(x - \lambda\frac{t}{T}\right)\right]$$

$$= A\cos\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{T}t\right)$$



14-4 Sound waves

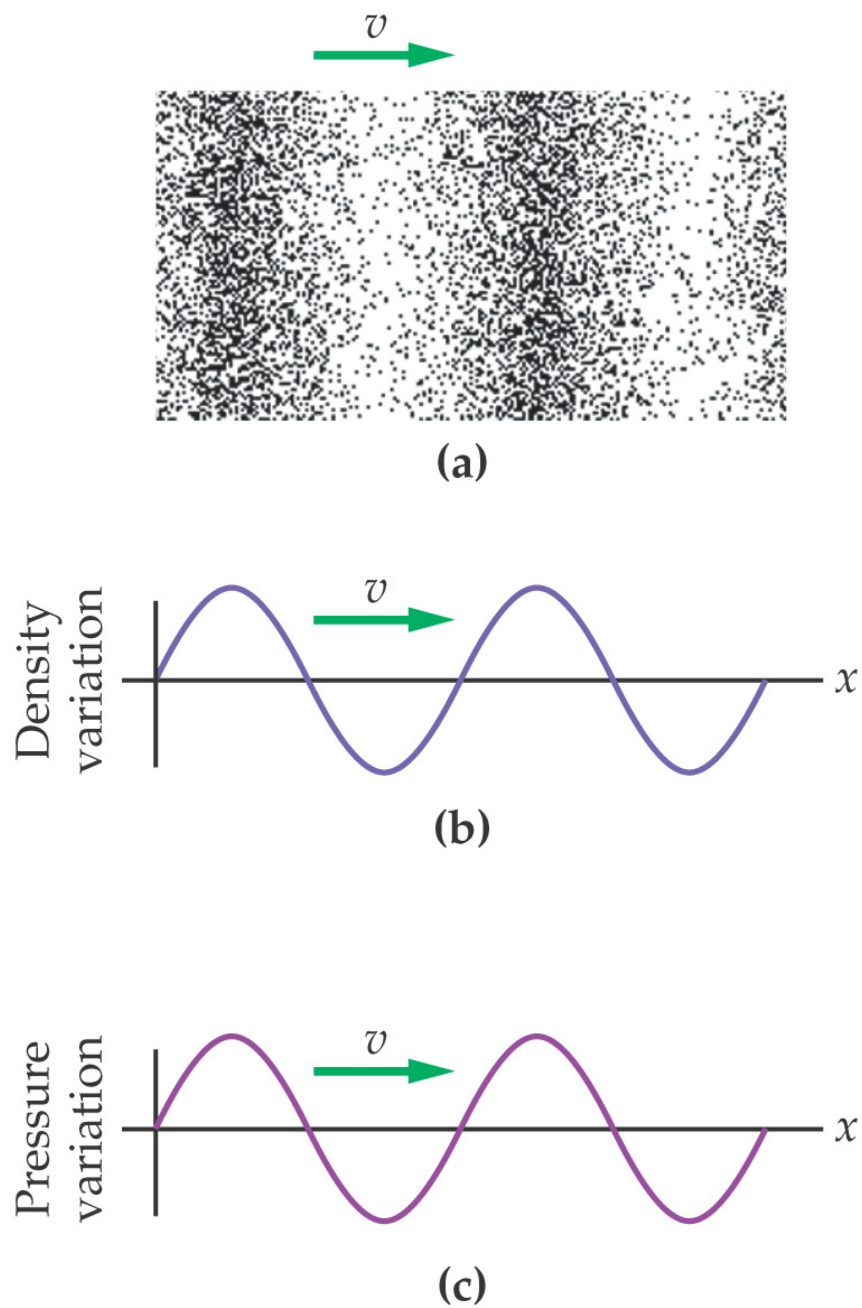
Sound waves are **longitudinal waves**, similar to the waves on a Slinky:



Here, the wave is a series of compressions and stretches.

14-4 Sound waves

In a sound wave, **the density and pressure of the air** (or other medium carrying the sound) are the quantities that **oscillate**.



14-4 Sound waves

The speed of sound is different in different materials; in general, the denser the material, the faster sound travels through it.

TABLE 14–1
Speed of Sound in Various Materials

Material	Speed (m/s)
Aluminum	6420
Granite	6000
Steel	5960
Pyrex glass	5640
Copper	5010
Plastic	2680
Fresh water (20 °C)	1482
Fresh water (0 °C)	1402
Hydrogen (0 °C)	1284
Helium (0 °C)	965
Air (20 °C)	343
Air (0 °C)	331

14-4 Sound waves

Sound waves can have any frequency; the human ear can hear sounds between about 20 Hz and 20,000 Hz.

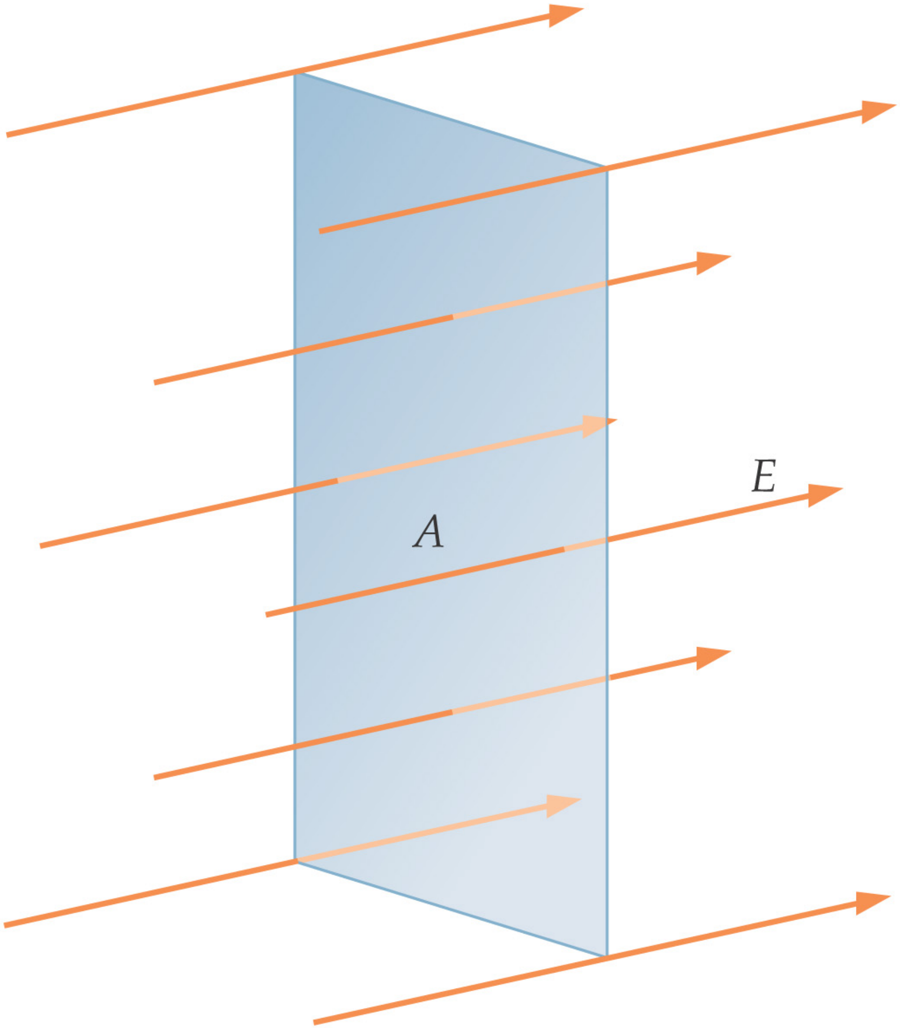
Sounds with frequencies greater than 20,000 Hz are called ultrasonic; sounds with frequencies less than 20 Hz are called infrasonic.

Ultrasonic waves are familiar from medical applications; elephants and whales communicate, in part, by infrasonic waves.

14-5 Sound intensity

The intensity of a sound is the amount of energy that passes through a given area in a given time.

$$I = \frac{E}{At}$$



14-5 Sound intensity

Expressed in terms of power,

Definition of Intensity, *I*

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

SI unit: $\mathrm{W/m^2}$

14-5 Sound intensity

Sound intensity from a point source will decrease as the square of the distance.

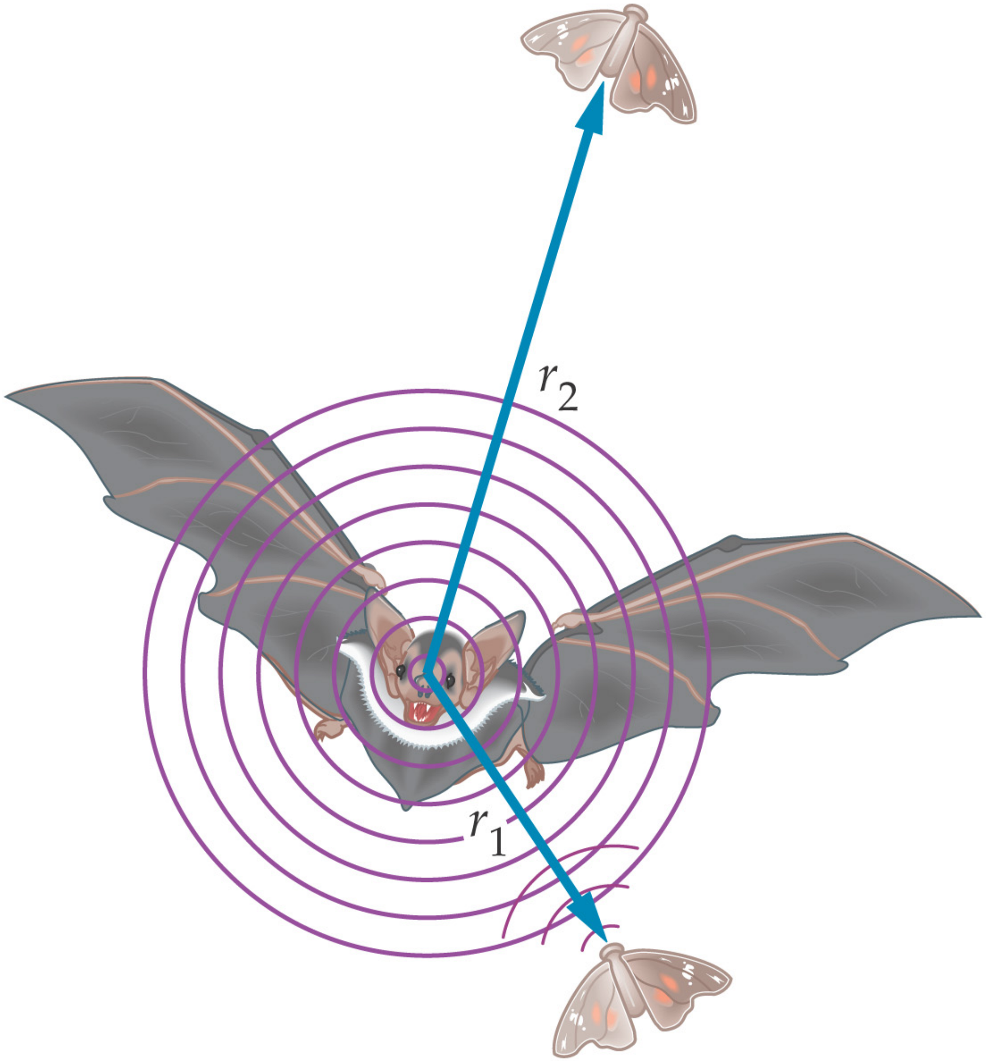
Intensity with Distance from a Point Source

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

SI unit: W/m^2

14-5 Sound intensity

Bats can use this decrease in sound intensity to locate small objects in the dark.



14-5 Sound intensity

When you listen to a variety of sounds, a sound that seems twice as loud as another is ten times more intense. Therefore, we use a logarithmic scale to define intensity values.

Definition of Intensity Level, β

$$\beta = 10 \log(I/I_0)$$

SI unit: dimensionless

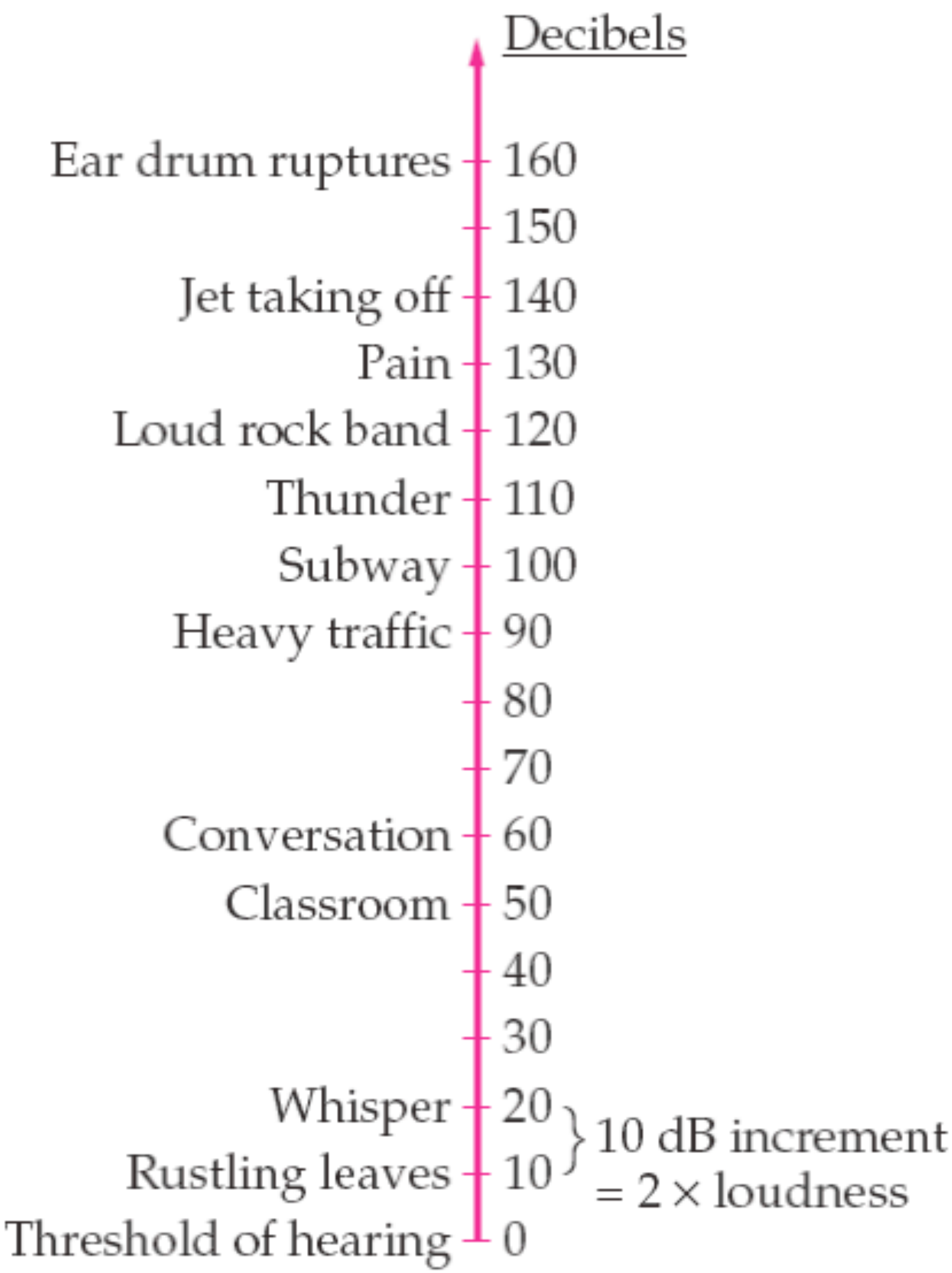
Here, I_0 is the faintest sound that can be heard:

$$I_0 = 10^{-12}\ \mathrm{W/m^2}$$

14-5 Sound intensity

The quantity β is called a bel; a more common unit is the **decibel, dB**, which is a tenth of a bel.

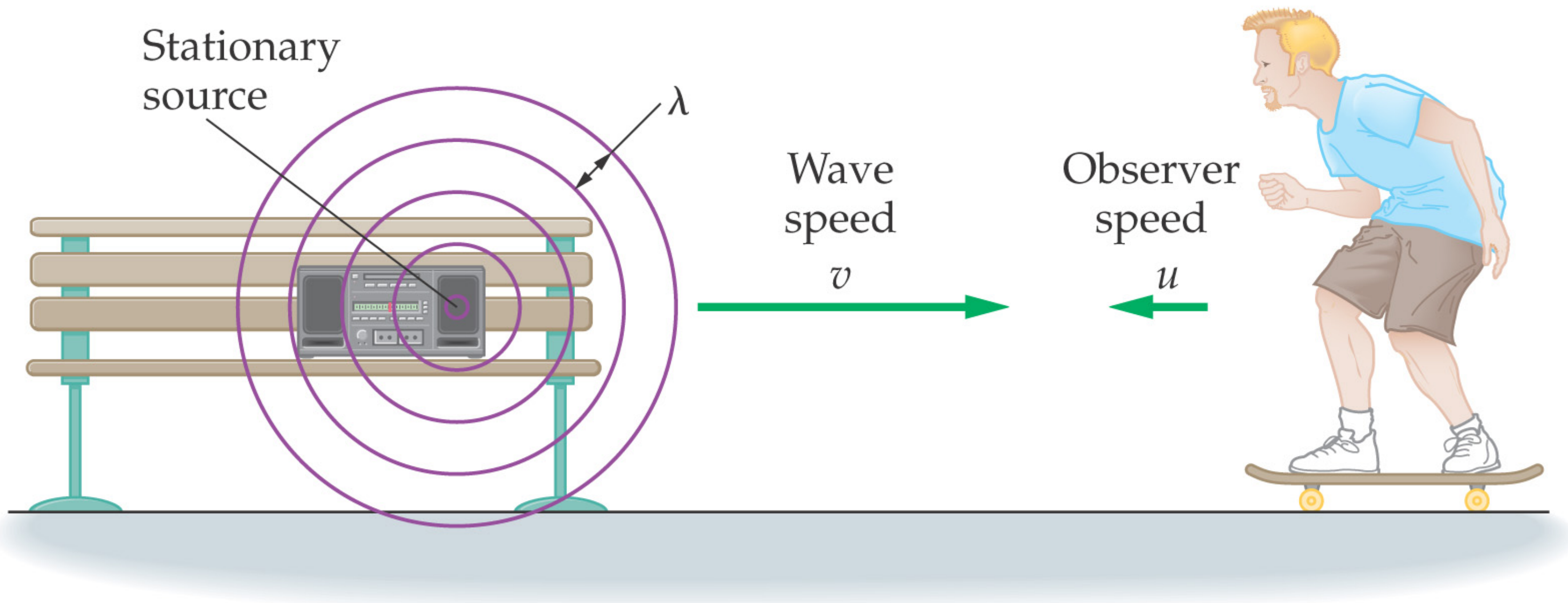
The intensity of a sound doubles with each increase in intensity level of 10 dB.



14-6 Doppler effect

The Doppler effect is the **change in pitch of a sound** when the source and observer are **moving** with respect to each other.

When an observer moves toward a source, the wave speed appears to be higher, and the frequency appears to be higher as well.



14-6 Doppler effect

The new frequency is:

$$f' = \frac{v + u}{(v/f)} = \left(\frac{v + u}{v}\right)f = (1 + u/v)f$$

If the observer were moving away from the source, only the sign of the observer's speed would change:

$$f' = \frac{v'}{\lambda} = \frac{v - u}{\lambda} = (1 - u/v)f$$

14-6 Doppler effect

To summarize:

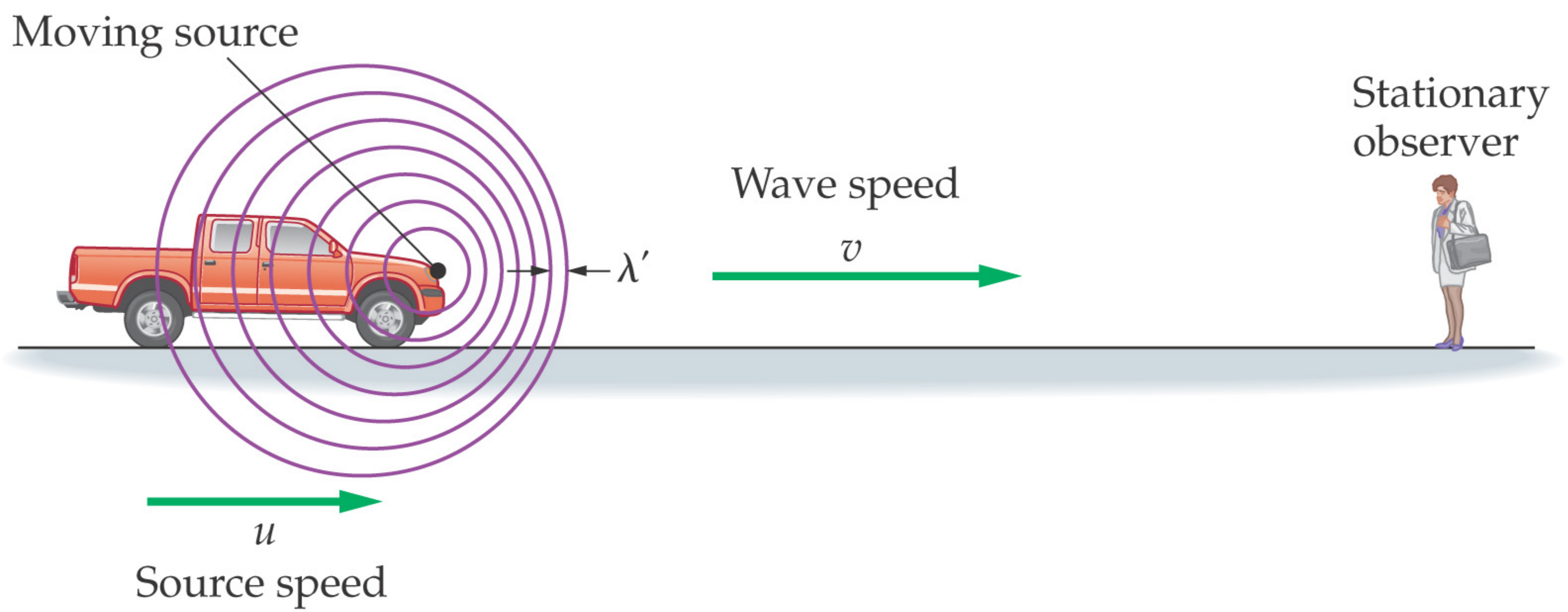
Doppler Effect for *Moving* Observer

$$f' = (1 \pm u/v)f$$

SI unit: $1/s = s^{-1}$

14-6 Doppler effect

The Doppler effect from a **moving source** can be analyzed similarly; now it is the **wavelength** that **appears to change**:



14-6 Doppler effect

We find:

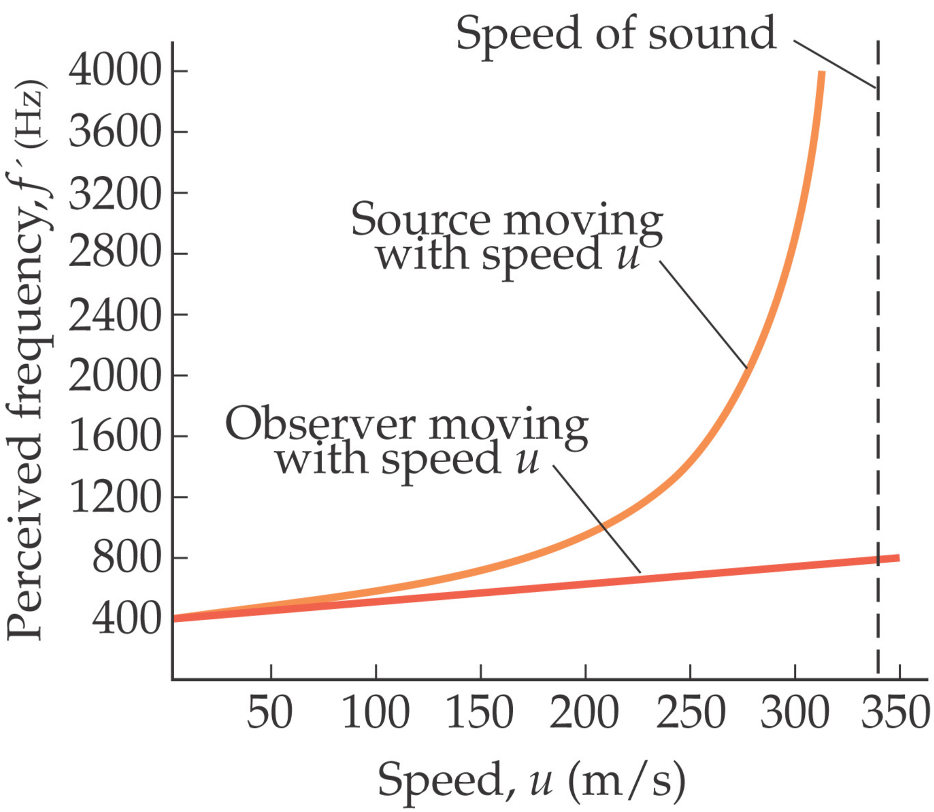
Doppler Effect for *Moving* Source

$$f' = \left(\frac{1}{1 \mp u/v}\right)f$$

SI unit: $1/\text{s} = \text{s}^{-1}$

14-6 Doppler effect

Here is a comparison of the Doppler shifts for a moving source and a moving observer. The two are similar for low speeds but then diverge. If the source moves faster then the speed of sound, a sonic boom is created.



14-6 Doppler effect

Combining results gives us the case where **both observer and source are moving**:

Doppler Effect for Moving Source and Observer

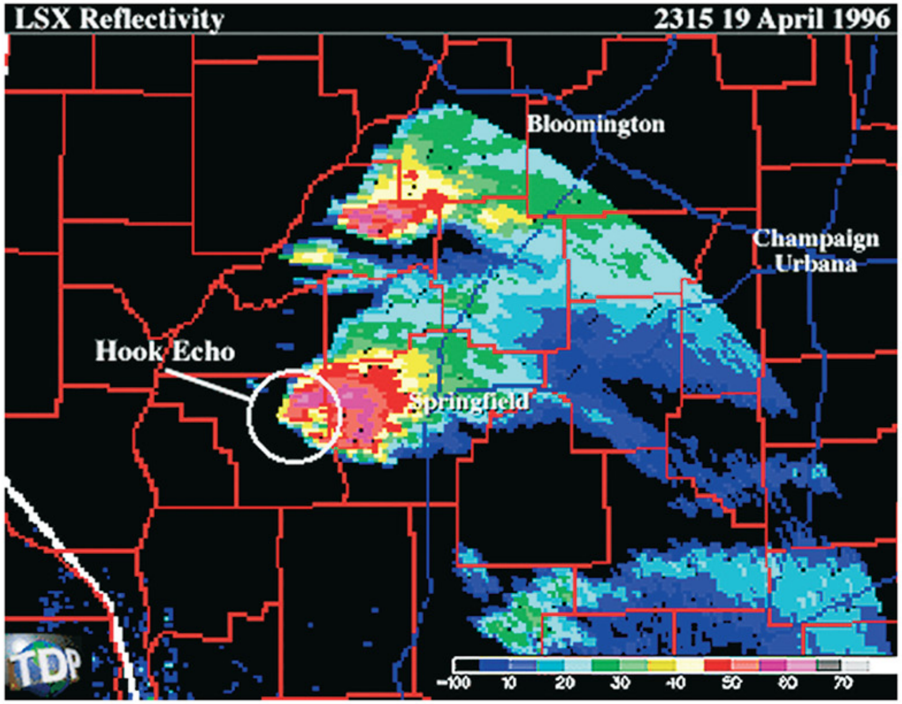
$$f' = \left(\frac{1 \pm u_o/v}{1 \mp u_s/v}\right)f$$

SI unit: $1/s = s^{-1}$

The Doppler effect has many practical applications: weather radar, speed radar, medical diagnostics, astronomical measurements.

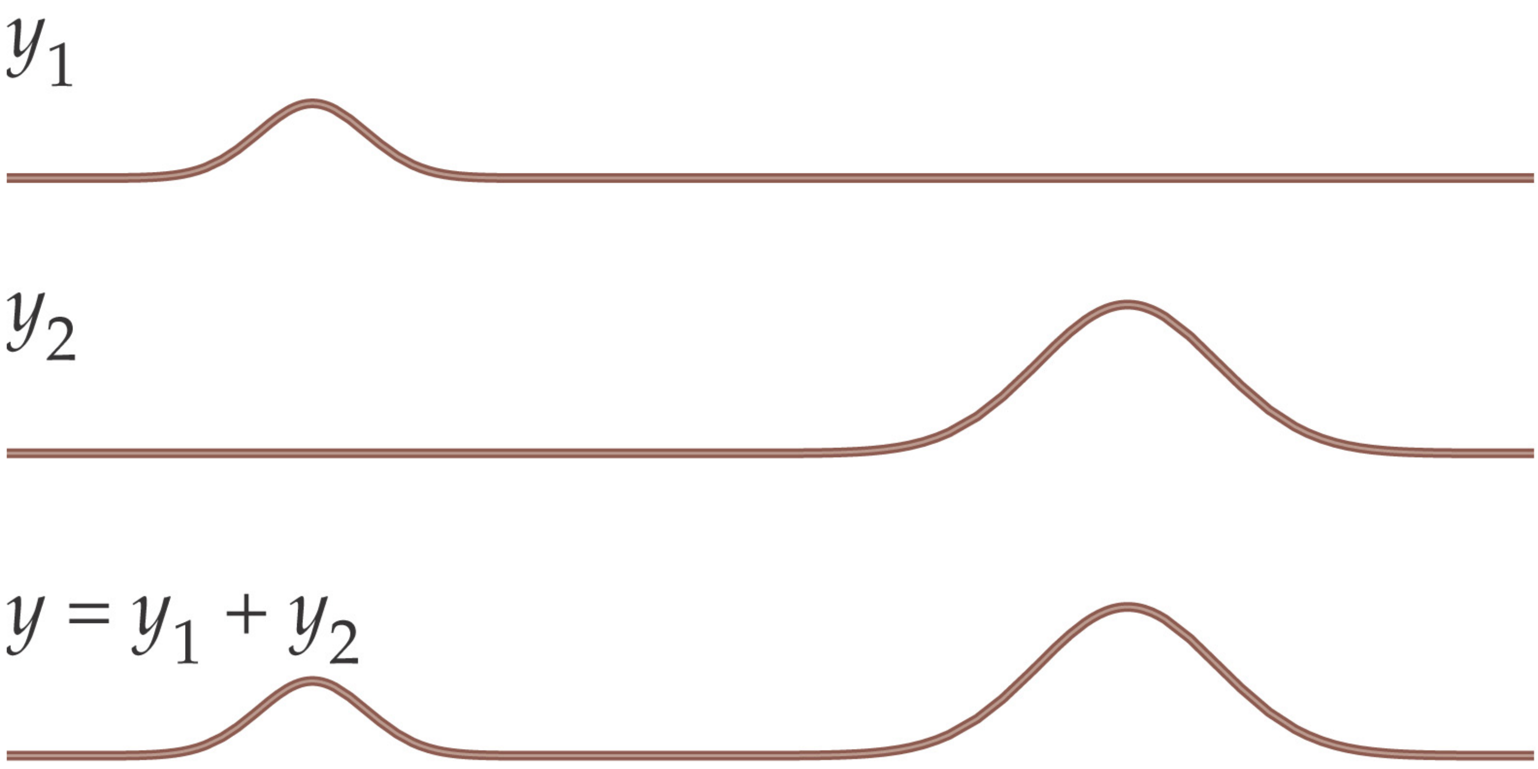
14-6 Doppler effect

At left, a Doppler radar shows the hook echo characteristic of tornado formation. At right, a medical technician is using a Doppler blood flow meter.



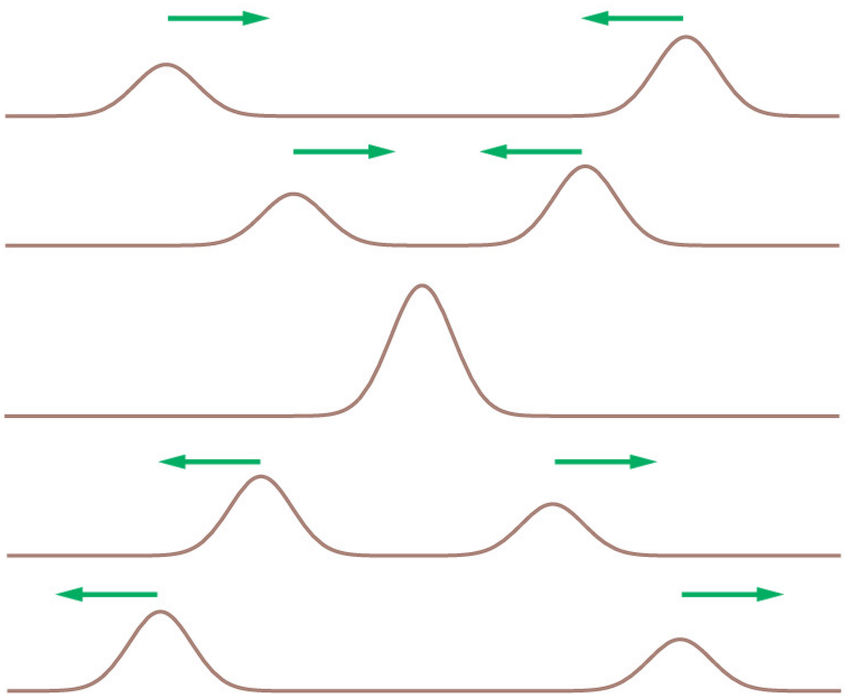
14-7 Superposition and interference

Waves of small amplitude traveling through the same medium **combine**, or superpose, **by simple addition**.

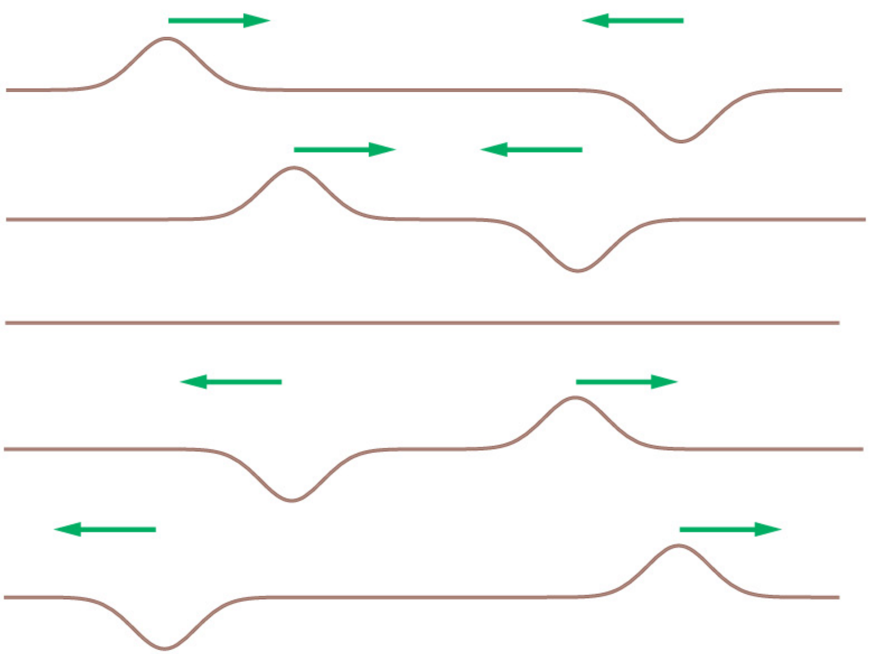


14-7 Superposition and interference

If two pulses combine to give a larger pulse, this is **constructive interference** (left). If they combine to give a smaller pulse, this is **destructive interference** (right).



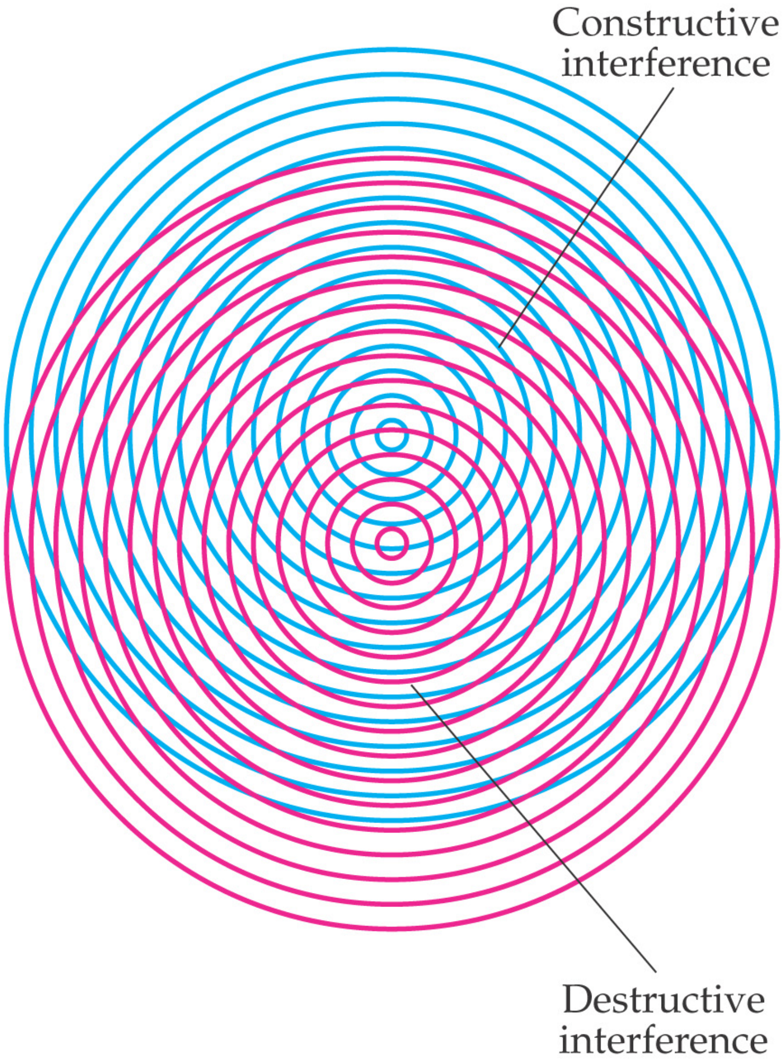
(a)



(b)

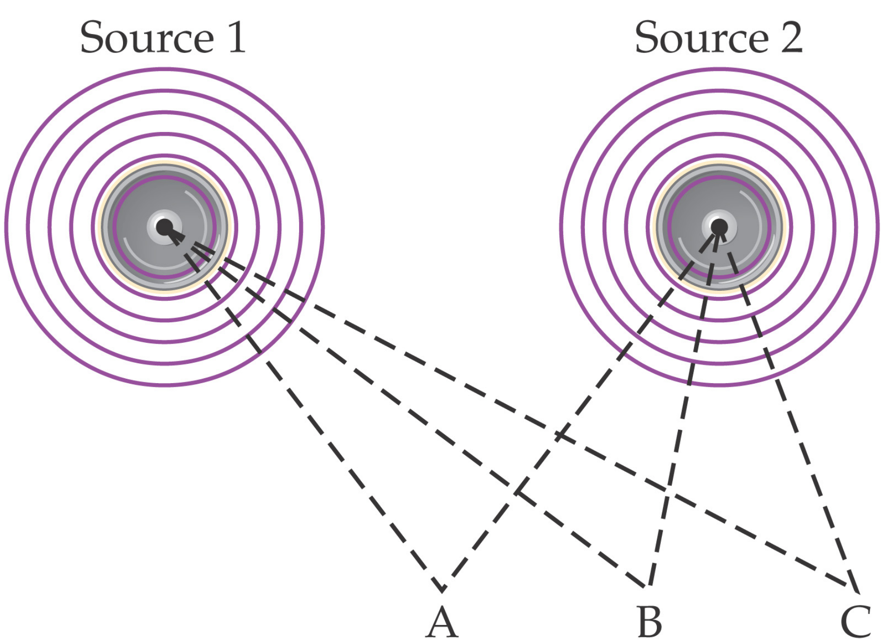
14-7 Superposition and interference

Two-dimensional waves exhibit interference as well. This is an example of an interference pattern.



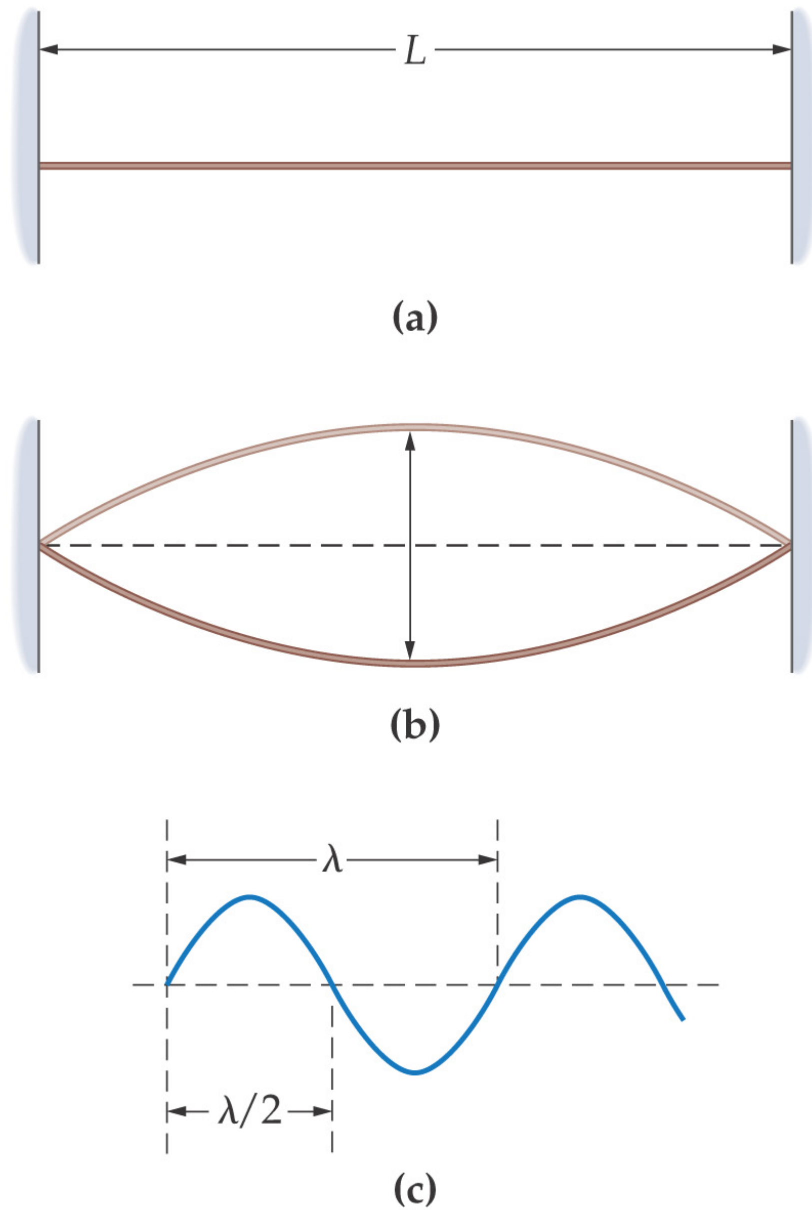
14-7 Superposition and interference

Here is another example of an interference pattern, this one from two sources. If the sources are in phase, points where the distance to the sources differs by an equal number of wavelengths will interfere constructively; in between the interference will be destructive.



14-8 Standing waves

A standing wave is **fixed in location**, but **oscillates with time**. These waves are found on strings with both ends fixed, such as in a musical instrument, and also in vibrating columns of air.



14-8 Standing waves

The fundamental, or lowest, frequency on a fixed string has a **wavelength twice the length of the string**. Higher frequencies are called **harmonics**.

Standing Waves on a String

Fundamental frequency and wavelength:

$$f_1 = \frac{v}{2L}$$

$$\lambda_1 = 2L$$

Frequency and wavelength of the n^{th} harmonic, with $n = 1, 2, 3, \ldots$:

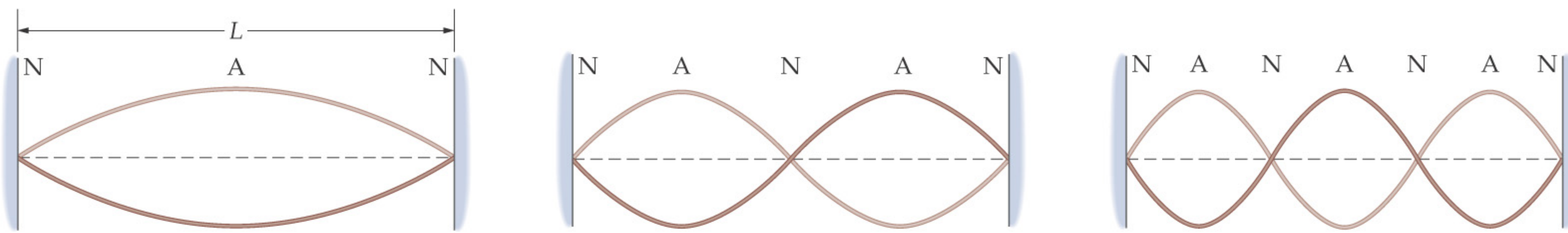
$$f_n = nf_1 = n\frac{v}{2L}$$

$$\lambda_n = \lambda_1/n = 2L/n$$

14-8 Standing waves

There must be an **integral number of half-wavelengths on the string**; this means that only certain frequencies are possible.

Points on the string which never move are called **nodes**; those which have the maximum movement are called **antinodes**.

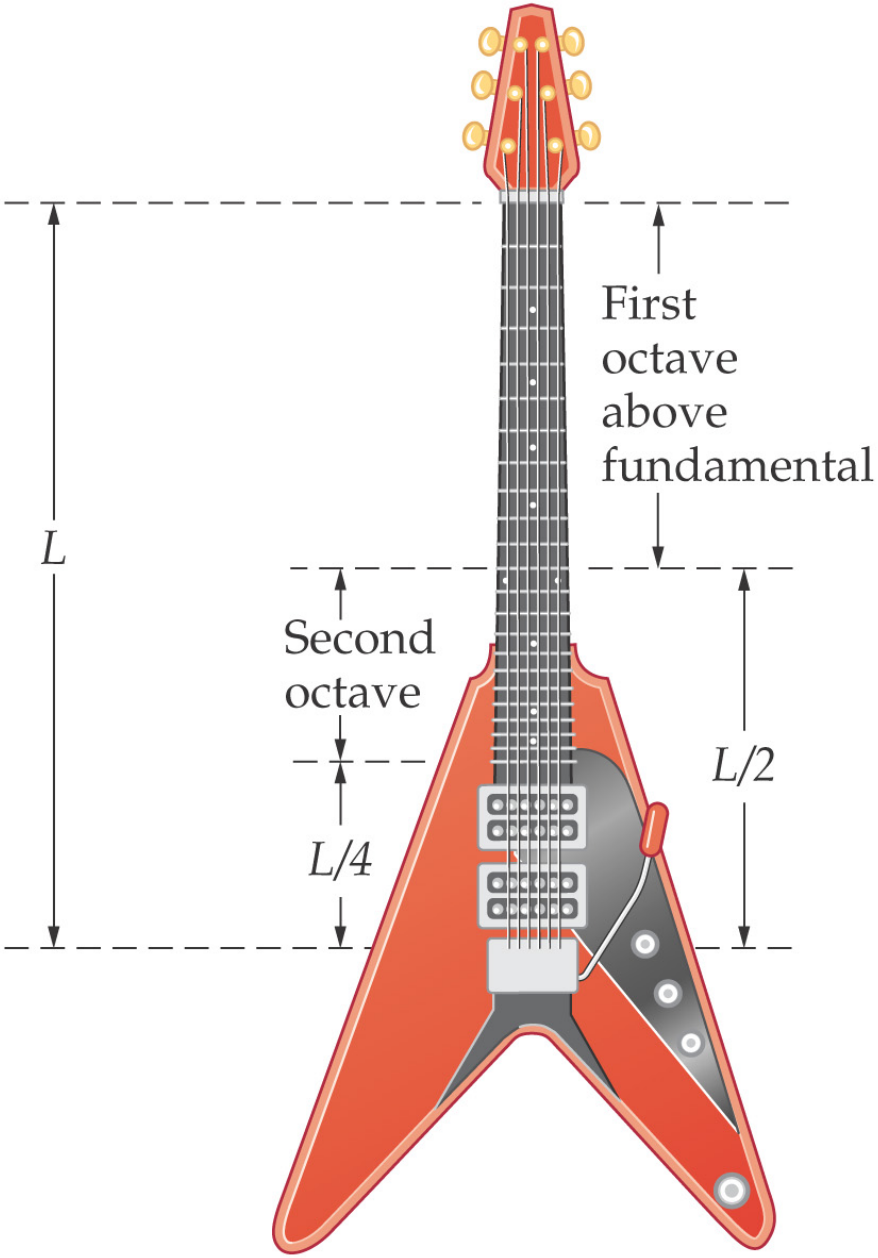


(a) (b) (c)

14-8 Standing waves

In order for different strings to have different fundamental frequencies, they must differ in **length** and/or **linear density**.

A guitar has strings that are all the same length, but the density varies.



14-8 Standing waves

In a piano, the strings vary in both length and density. This gives the sound box of a grand piano its characteristic shape.

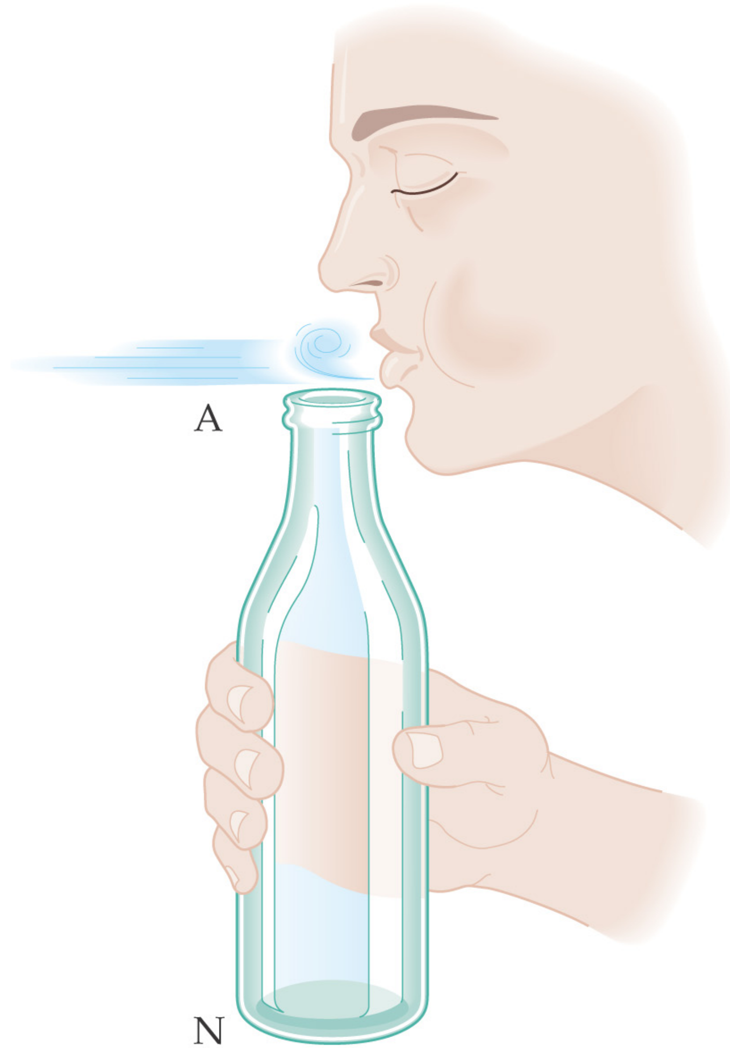
Once the length and material of the string is decided, individual strings may be tuned to the exact desired frequencies by changing the tension.

Musical instruments are usually designed so that the variation in tension between the different strings is small; this helps prevent warping and other damage.

14-8 Standing waves

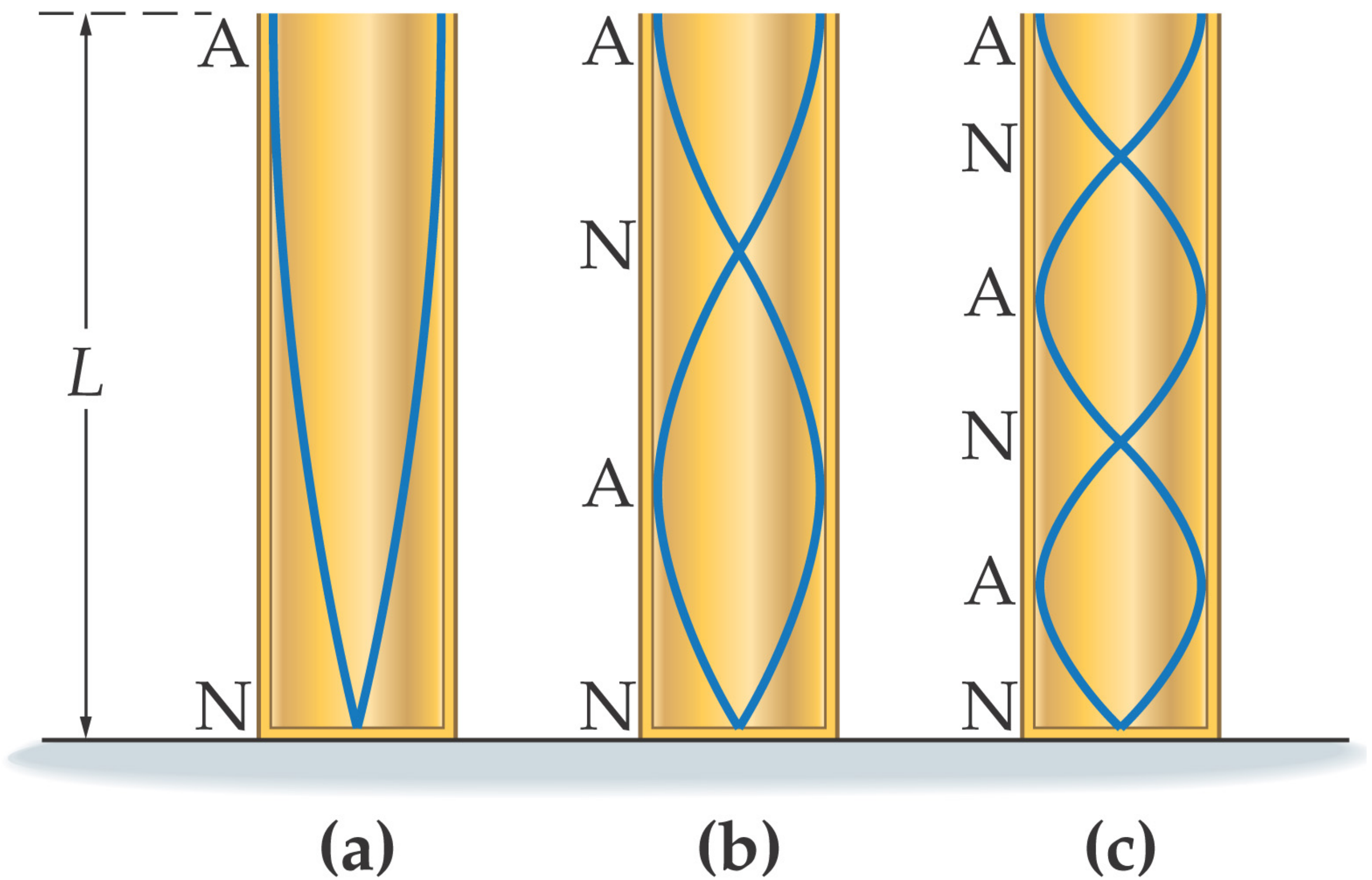
Standing waves can also be excited in **columns of air**, such as soda bottles, woodwind instruments, or organ pipes.

As indicated in the drawing, one end is a node (N), and the other is an antinode (A).



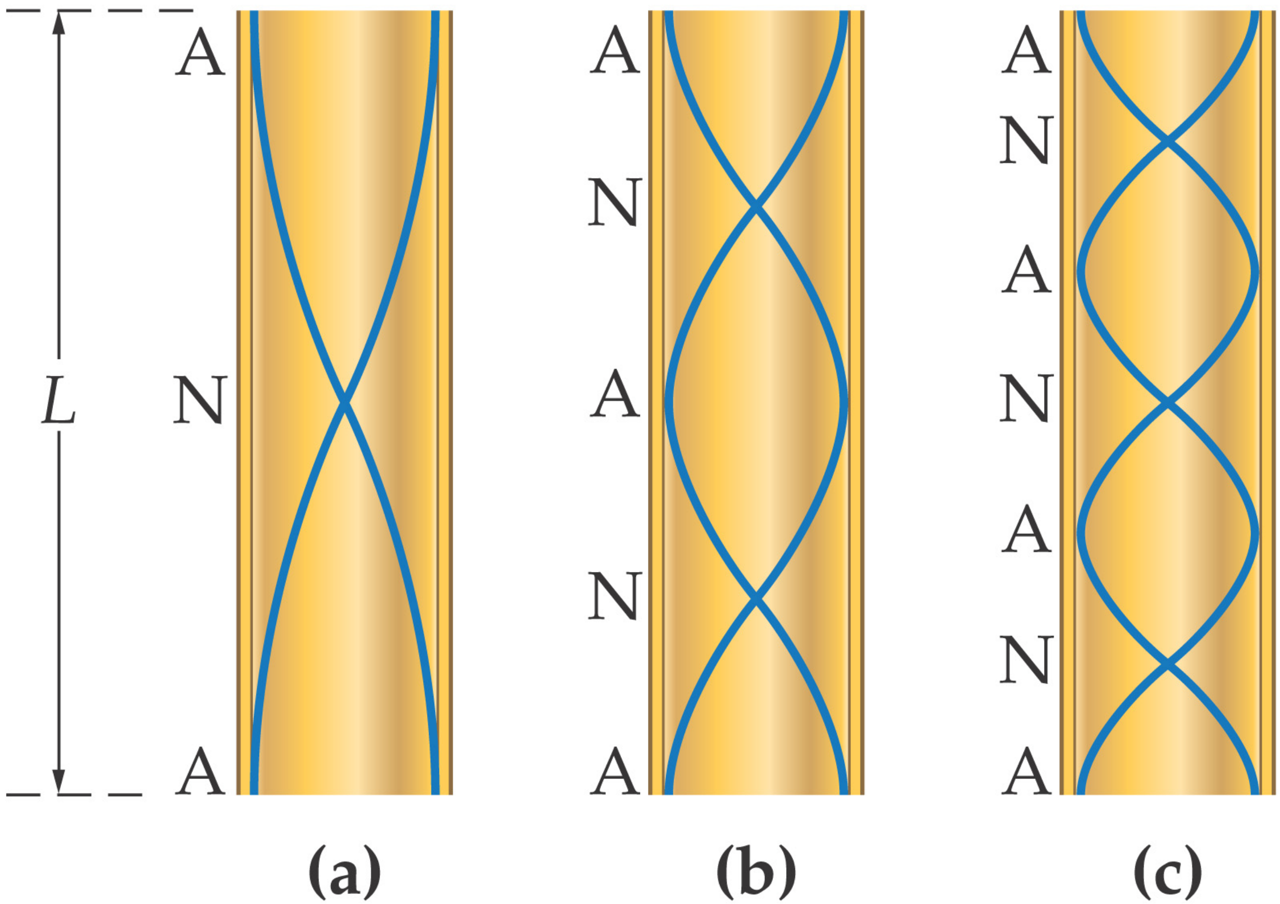
14-8 Standing waves

In this case, the fundamental wavelength is **four times** the length of the pipe, and only **odd-numbered harmonics** appear.



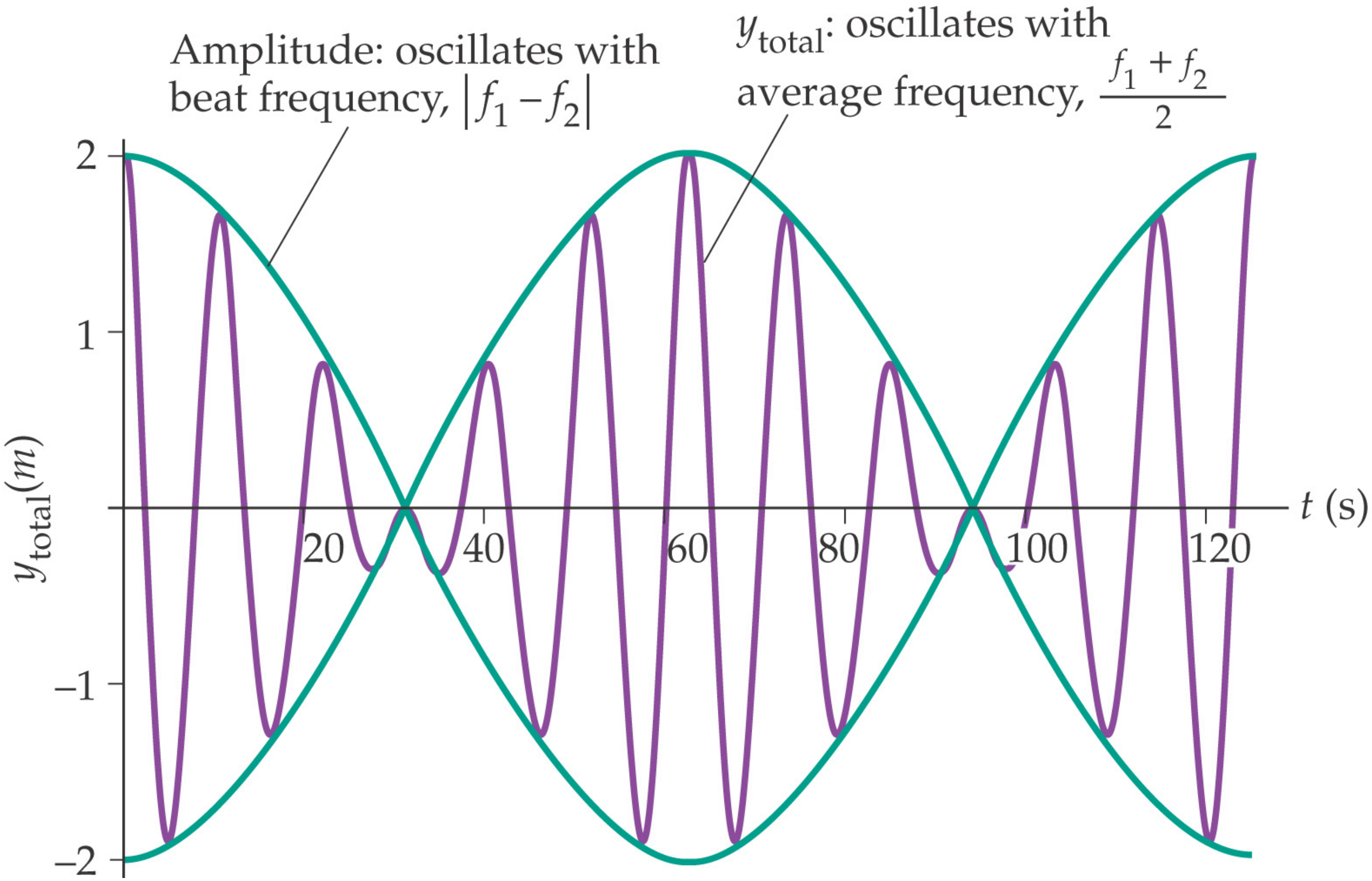
14-8 Standing waves

If the tube is **open at both ends**, both ends are **antinodes**, and the sequence of harmonics is the same as that on a string.



14-9 Beats

Beats are an **interference pattern in time**, rather than in space. If two sounds are very close in frequency, their sum also has a periodic time dependence, although with a much lower frequency.



Summary of Chapter 14

- A wave is a propagating disturbance.
- Transverse wave: particles move at right angles to propagation direction
- Longitudinal wave: particles move along propagation direction
- Wave speed: $v = \lambda f$
- Speed of a wave on a string: $v = \sqrt{\frac{F}{\mu}}$

Summary of Chapter 14

- If the end of a string is fixed, the wave is inverted upon reflection.
- If the end is free to move transversely, the wave is not inverted upon reflection.
- Wave function for a harmonic wave:

$$y(x,t) = A\cos\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{T}t\right)$$

- A sound wave is a longitudinal wave of compressions and rarefactions in a material.

Summary of Chapter 14

- High-pitched sounds have high frequencies; low-pitched sounds have low frequencies.
- Human hearing ranges from 20 Hz to 20,000 Hz.
- Intensity of sound:

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

- Intensity a distance r from a point source of sound:

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

Summary of Chapter 14

- When the intensity of a sound increases by a factor of 10, it sounds twice as loud to us.
- Intensity level, measured in decibels:

$$\beta = 10 \log(I/I_0)$$

- Doppler effect: change in frequency due to relative motion of sound source and receiver
- General case (both source and receiver moving):

$$f' = \left(\frac{1 \pm u_o/v}{1 \mp u_s/v}\right) f$$

Summary of Chapter 14

- When two or more waves occupy the same location at the same time, their displacements add at each point.
- If they add to give a larger amplitude, interference is constructive.
- If they add to give a smaller amplitude, interference is destructive.
- An interference pattern consists of constructive and destructive interference areas.
- Two sources are in phase if their crests are emitted at the same time.

Summary of Chapter 14

- Two sources are out of phase if the crest of one is emitted at the same time as the trough of the other.
- Standing waves on a string:

$$f_n = nf_1 = n(v/2L)$$

$$\lambda_n = \lambda_1/n = 2L/n$$

- Standing waves in a half-closed column of air:

$$f_n = nf_1 = n(v/4L) \qquad n = 1, 3, 5, \ldots$$

$$\lambda_n = \lambda_1/n = 4L/n$$

Summary of Chapter 14

- Standing waves in a fully open column of air:

$$f_n = nf_1 = n(v/2L) \qquad n = 1, 2, 3, \ldots$$

$$\lambda_n = \lambda_1/n = 2L/n$$

- Beats occur when waves of slightly different frequencies interfere.
- Beat frequency: $f_{\text{beat}} = |f_1 - f_2|$