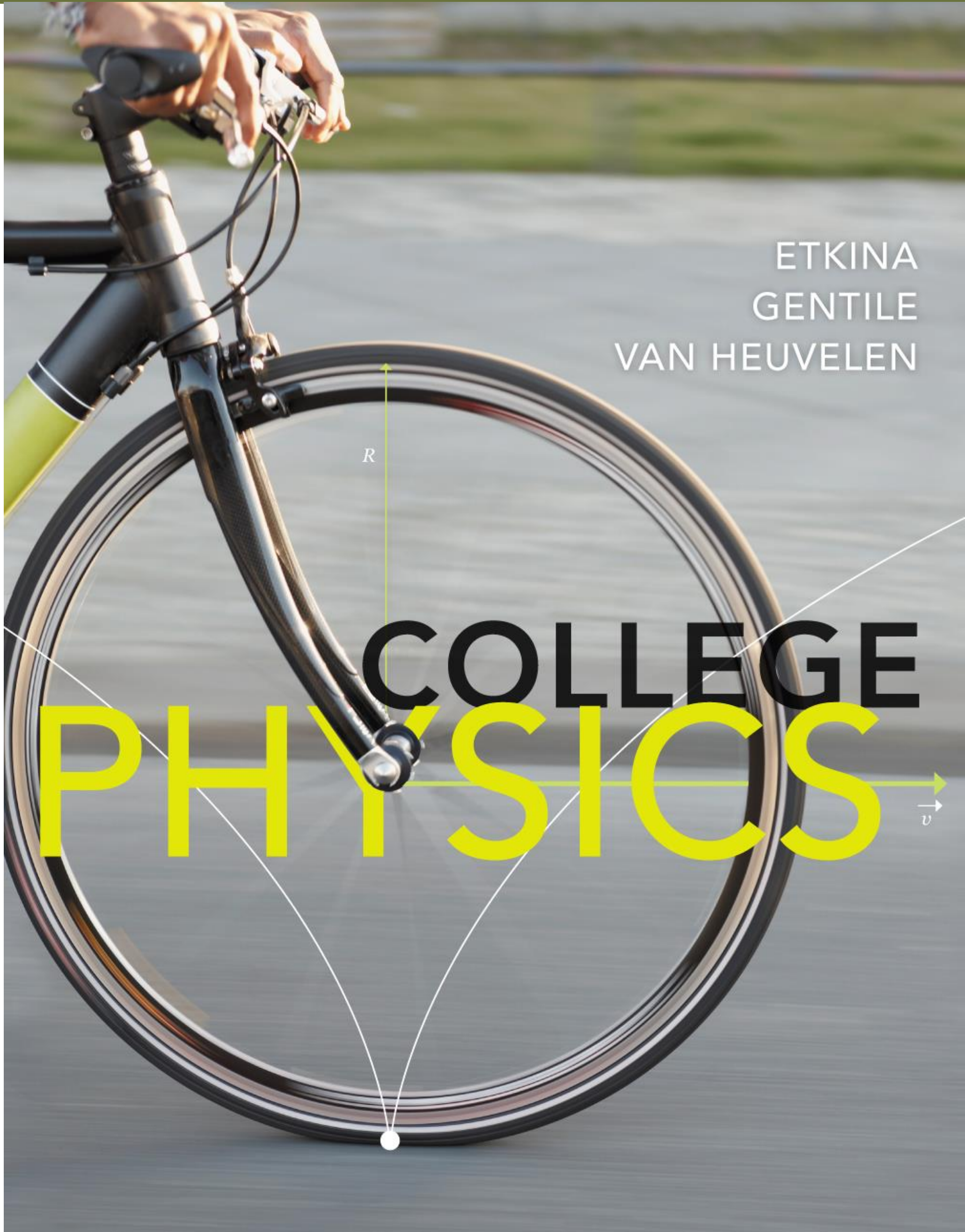

Mechanical Waves

Prepared by
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Mechanical Waves

- How do bats "see" in the dark?
- How can you transmit energy without transmitting matter?
- Why does the pitch of a train whistle change as it passes you?

Be sure you know how to:

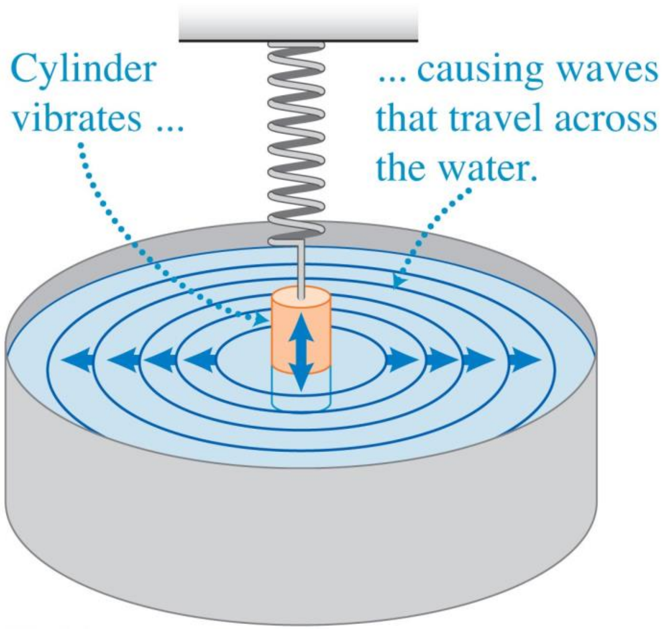
- Describe simple harmonic motion verbally, graphically, and algebraically (Section 19.3).
- Determine the period and amplitude of vibrations using a graph (Section 19.3).
- Determine the power of a process (Section 6.8).

What's new in this chapter

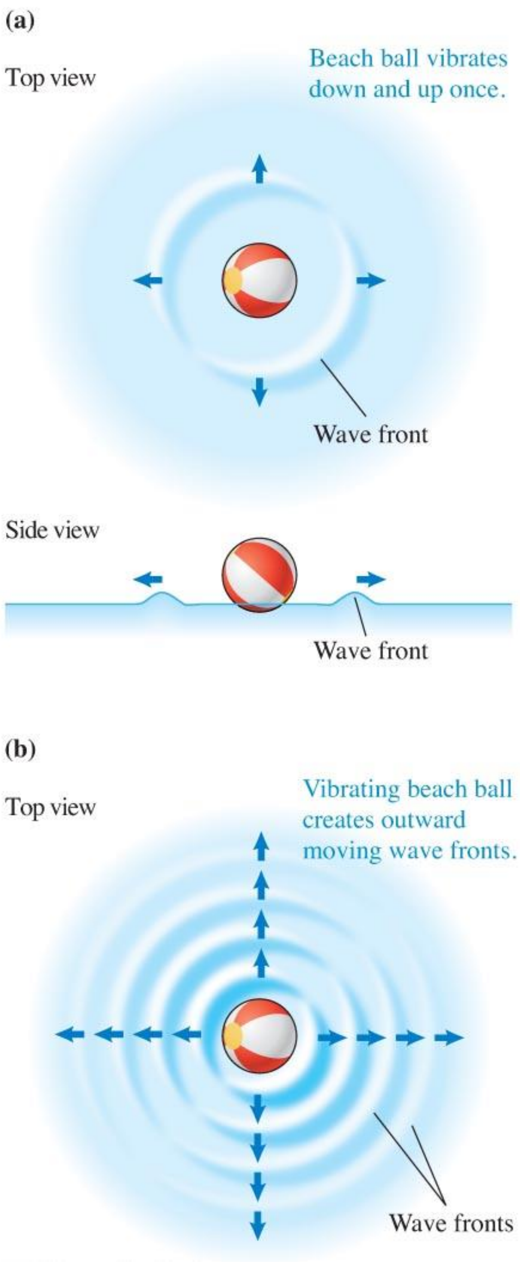
- So far we have looked at the vibrational motion of a single object, such as a pendulum.
  - We have not considered what happens to the environment that is in contact with the vibrating object.
- In this chapter we focus on the effect that the vibrating object has on the medium that surrounds it.
  - An example of such an effect is the propagation of sound.

Observations: Pulses and wave motion

- When an object vibrates, it also disturbs the medium surrounding it.
  - Place a heavy metal cylinder attached to a spring so that the cylinder is partially submerged in a tub with water. Push down on the cylinder a little and release it. The vibrating cylinder (the source) sends ripples (waves) across the tub.



Waves and wave fronts

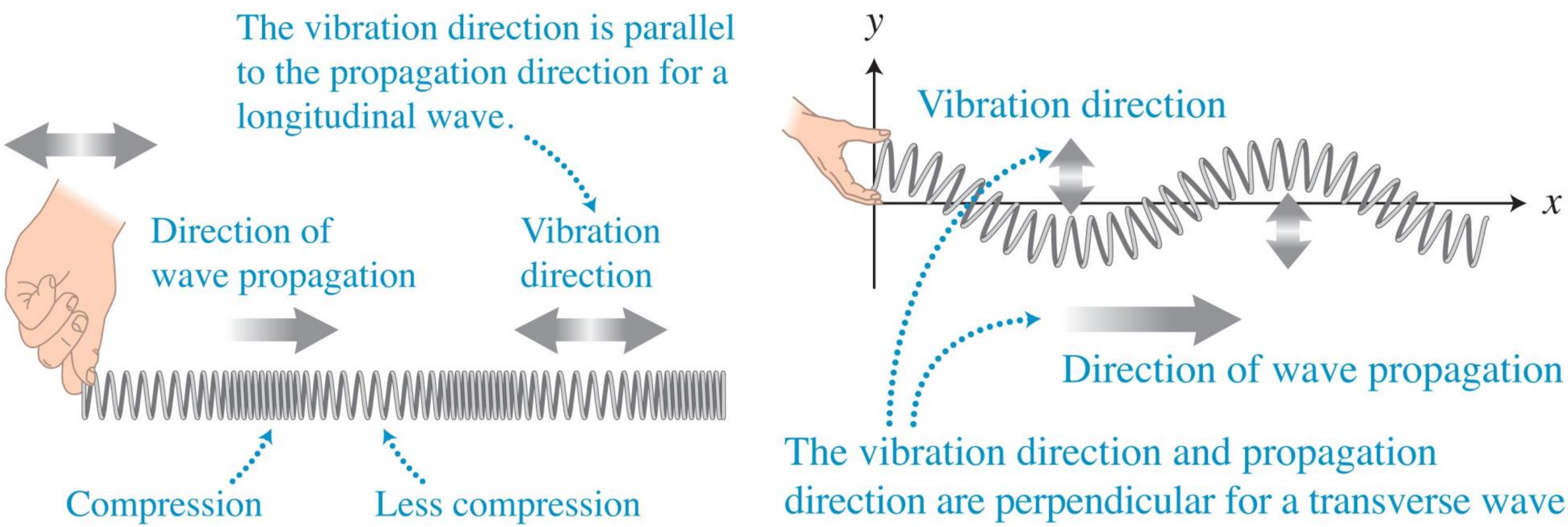


Wave motion

Wave motion involves a disturbance produced by a vibrating object (a source). The disturbance moves, or propagates, through a medium and causes points in the medium to vibrate. When the disturbed medium is physical matter (solid, liquid, or gas), the wave is called a **mechanical wave.**

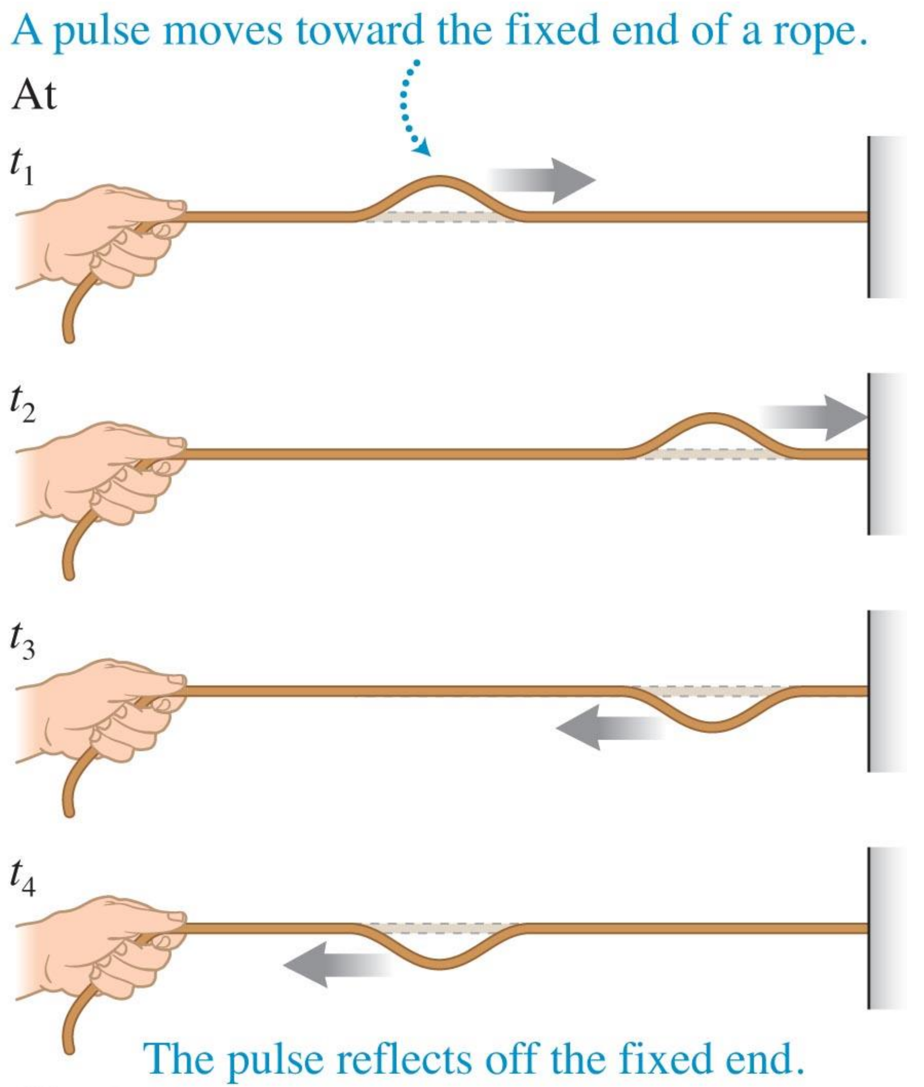
Two kinds of waves

Longitudinal and transverse waves In a *longitudinal wave* the vibrational motion of the particles or layers of the medium is parallel to the direction of propagation of the disturbance. In a *transverse wave* the vibrational motion of the particles or layers of the medium is perpendicular to the direction of propagation of the disturbance.



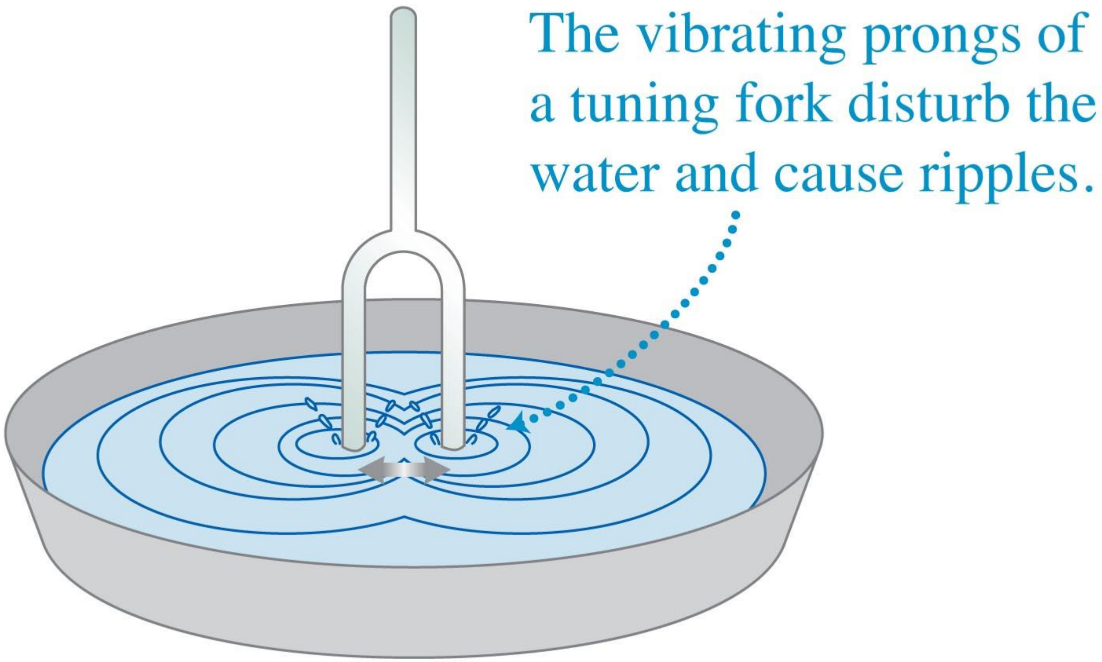
Reflection of waves

- When a wave reaches the wall of the container or the end of the Slinky or rope, it reflects off the end and moves in the opposite direction.
  - When a wave encounters any boundary between different media, some of the wave is reflected back.
  - http://www.acs.psu.edu/drussell/Demos/reflect/reflect.html
  - https://phet.colorado.edu/en/simulation/wave-on-a-string



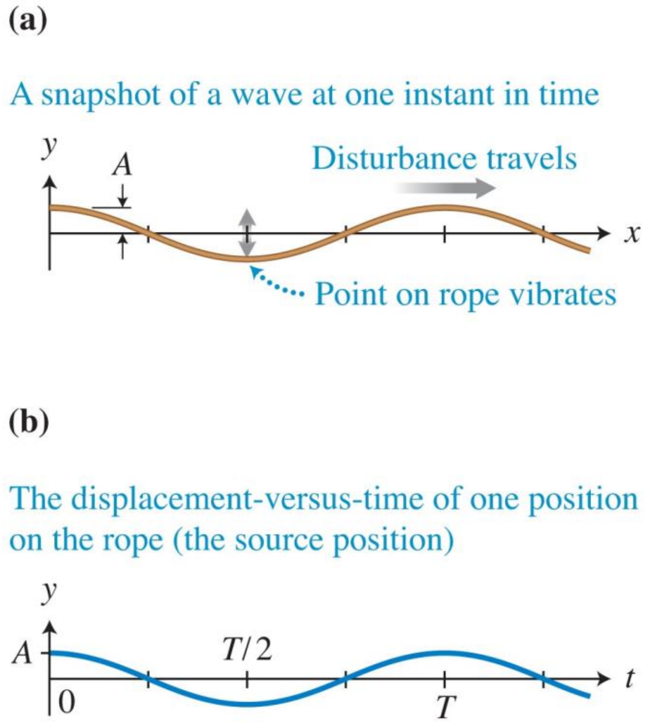
Sound waves

- If you strike a tuning fork, you hear sound.
- You can feel the vibrations of the prongs if you touch them.
- If you place the vibrating prongs in water, you see ripples going out.



Mathematical descriptions of a wave

- A wave can be created in a rope by a motor that vibrates the end of a rope up and down, producing a transverse wave.



- The displacement is described by a sinusoidal function of time:

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

Mathematical descriptions of a wave

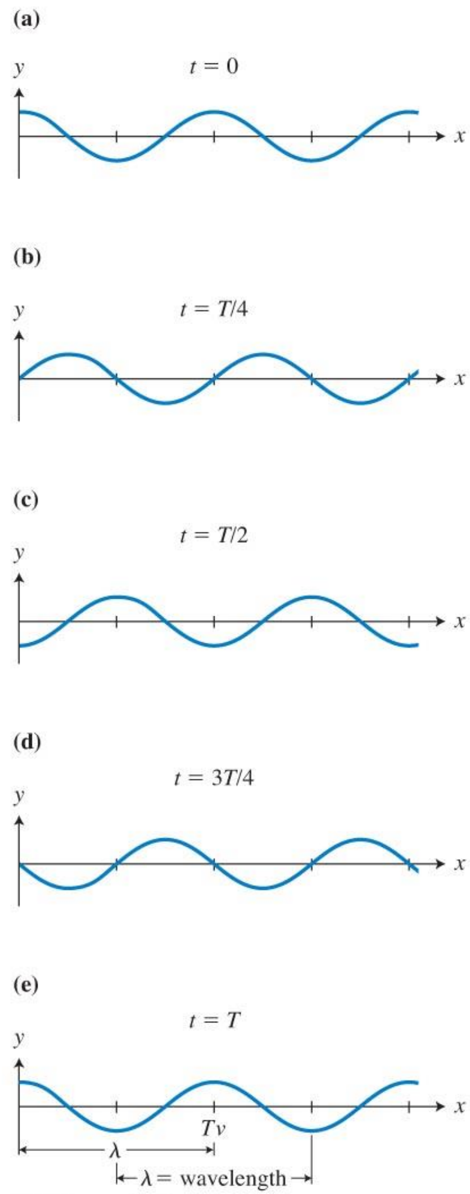
Period T in seconds is the time interval for one complete vibration of a point in the medium anywhere along the wave's path.

Frequency f in Hz (s^{-1}) is the number of vibrations per second of a point in the medium as the wave passes.

Amplitude A is the maximum displacement of a point of the medium from its equilibrium position as the wave passes.

Speed v in m/s is the distance a disturbance travels during a time interval, divided by that time interval.

The shape of a transverse wave at five consecutive times



Mathematical description of a traveling sinusoidal wave

- We know the source oscillates up and down with a vertical displacement given by:

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

- We can mathematically describe the disturbance $y(x, t)$ of a point of the rope at some positive position x to the right of the source (at $x = 0$) by:

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

Wavelength

Wavelength λ equals the distance between two nearest points on a wave that at any clock reading have exactly the same displacement and shape (slope). It is also the distance between two consecutive wave fronts:

$$\lambda = T\nu = \frac{\nu}{f} \tag{20.3}$$

Tip

TIP You can think of a wavelength as the distance that the wave propagates during one period.

Mathematical description of a traveling sinusoidal wave

Mathematical description of a traveling sinusoidal wave The displacement from equilibrium y of a point at location x at time t when a wave of period T travels at speed v in the positive x-direction through a medium is described by the function

$$y = A\cos\left[2\pi\left(\frac{t}{T} - \frac{x}{\lambda}\right)\right] \tag{20.4}$$

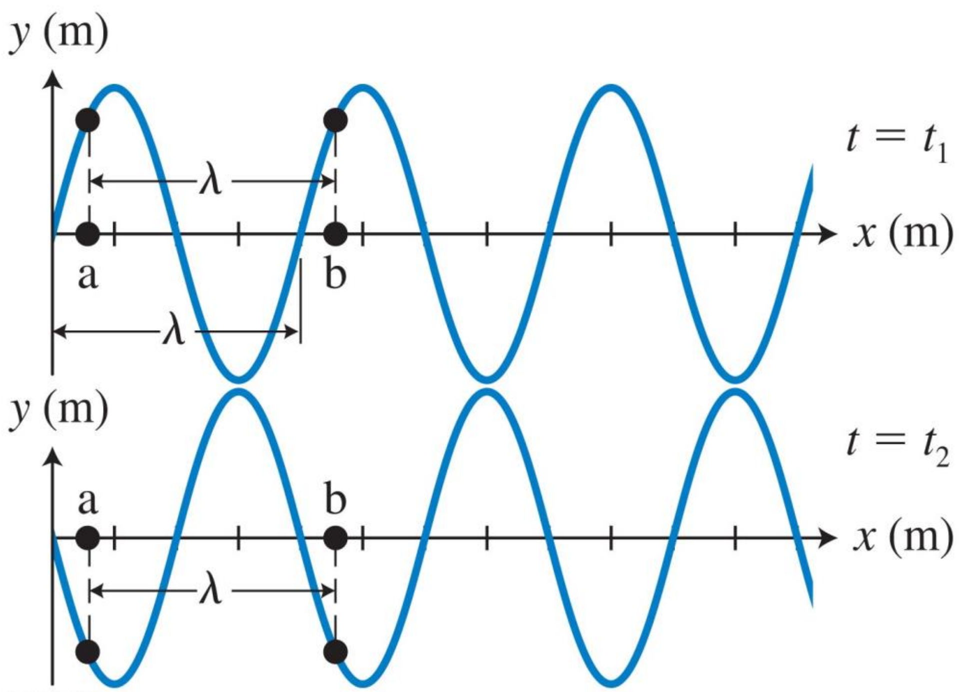
The wavelength λ of this wave equals $\lambda = Tv$.

Tip

TIP Notice that Eq. (20.4) is mathematically symmetric with respect to the period of the wave and its wavelength (the terms in which each appears have the same form). This is because there are two repetitive processes in a wave. If the location x is fixed, that point in the medium vibrates in time with period T. If the time t is fixed (as in a photograph), the space has a wavelike appearance with wavelength λ (see Figure 20.8). We replaced the notation for the function $y(x, t)$ with just y for simplicity.

Phase

- Two points in a medium are "in phase" if at every clock reading, their displacements are exactly the same.
  – Two points separated by a distance equal to an integer multiple of wavelengths are always in phase.



Tip

TIP Because Eq. (20.4) is a function of two variables, when we represent waves graphically we need two graphs, such as those in the figures in Exercise 20.1—one showing how one point of the medium changes its position with time (y versus t; $x =$ constant) and the other one showing the displacements of multiple points of the medium at the same clock reading—a snapshot of the wave (y versus x; $t =$ constant).

Dynamics of wave motion: Speed and the medium

- We have defined the speed of a wave as the distance that a disturbance travels in the medium during a time interval divided by that time interval.
  – This operational definition of speed tells us how to determine the speed but does not explain why a particular wave has a certain speed.
- Our goal is to investigate what determines the wave speed.

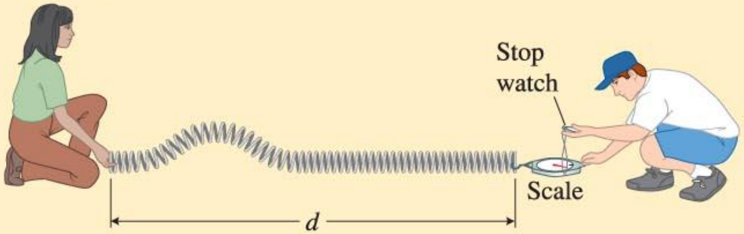
Observational experiment

OBSERVATIONAL EXPERIMENT TABLE

20.2 What affects wave speed?

VIDEO 20.2

Observational experiment	Analysis
Two people are holding the ends of a Slinky. The person on the left starts a pulse on the Slinky. The person on the right measures the force pulling on the Slinky and the time interval Δt for the pulse to travel the distance d. They vary the amplitude, frequency, and pulling force one at a time.	Assume that the speed of a pulse is the same as the speed of a wave and that the pulse does not slow down or speed up as it travels. The speed of the pulse is $v = \frac{\text{distance}}{\text{time interval}} = \frac{d}{\Delta t} = \frac{(4.0\text{ m})}{(1.0\text{ s})} = 4.0\text{ m/s}$



Distance (m)	Time Interval (s)
4.0	1.0

Observational experiment

OBSERVATIONAL EXPERIMENT TABLE

20.2 What affects wave speed? *(Continued)*

VIDEO 20.2

Observational experiment	Analysis

Effect of amplitude Change the amplitude of the pulses:

Amplitude (m)	Distance (m)	Time Interval (s)	Speed (m/s)
0.1	4.0	1.0	4.0
0.2	4.0	1.0	4.0
0.3	4.0	1.0	4.0

Effect of frequency Change the frequency of the pulses (we send several pulses one after another):

Frequency (Hz)	Distance (m)	Time Interval (s)	Speed (m/s)
2.0	4.0	1.0	4.0
4.0	4.0	1.0	4.0
6.0	4.0	1.0	4.0

Effect of force Change the force pulling on the end of the Slinky (the length of the Slinky also changes):

Force (N)	Distance (m)	Time Interval (s)	Speed (m/s)
2	4.0	1.0	4.0
4	8.0	1.0	8.0
6	12.0	1.0	12.0

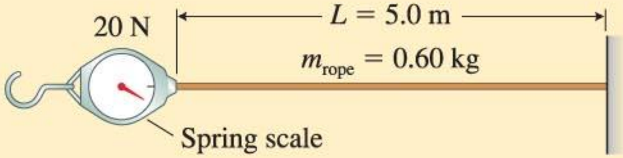
Patterns

- The speed of a pulse *does not depend* on either the amplitude or frequency.
- The speed *does depend* on the magnitude of force exerted on the end.

Testing experiment

TESTING EXPERIMENT TABLE

20.3 Testing the expression for wave speed.

Testing experiment	Prediction	Outcome
Predict the time interval for a pulse to travel from one end of a 0.60-kg rope to the other end and back again. The rope is pulled by a spring scale. Since the pulse travels very fast, to minimize experimental uncertainty we will count 10 trips. 	The wave speed is $v = \sqrt{\frac{F_{\text{S on R}}}{m/L}} = \sqrt{\frac{20\text{ N}}{0.60\text{ kg}/5.0\text{ m}}} = 13\text{ m/s}$ The time interval should be $\Delta t = \frac{2L}{v} = 2(5.0\text{ m})/(13\text{ m/s}) = 0.77\text{ s}.$ We predict that 10 round trips will take 7.7 s.	We conduct the experiment several times and measure the time as 7.7 ± 0.5 s. The predicted outcome lies within this interval.

Conclusion

The outcome is consistent with the prediction. We did not disprove that the speed of a wave depends on the properties of the medium.

Wave speed

Wave speed The speed v of a wave on a string or in some other one-dimensional medium depends on how hard the string or medium is pulled $F_{\text{M on M}}$ (one part of the medium pulling on an adjacent part) and on the mass per unit length $\mu = m/L$ of the medium:

$$v = \sqrt{\frac{F_{\text{M on M}}}{\mu}} \quad (20.5)$$

Tip

TIP Note two mathematical expressions for the speed of the pulse:

$$v = d/\Delta t \text{ and } v = \sqrt{\frac{F_{\text{M on M}}}{\mu}}.$$

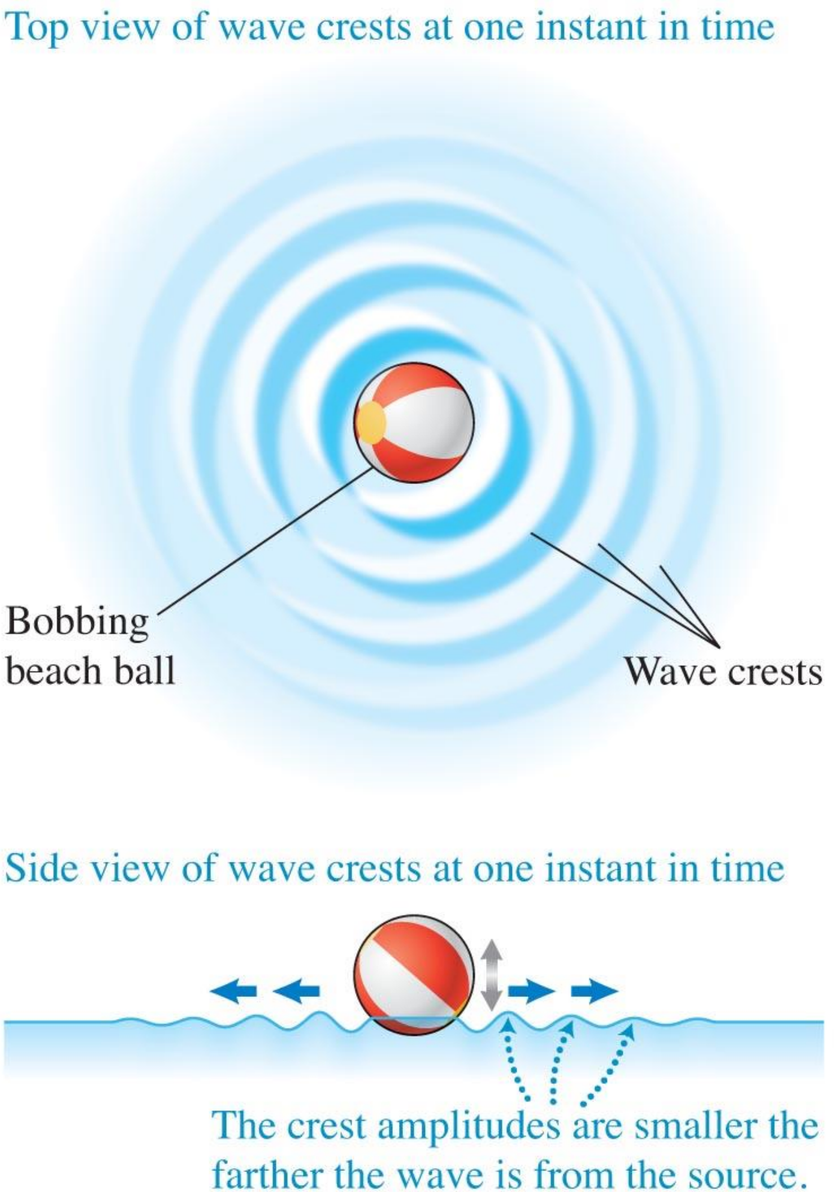
The first expression is an operational definition for speed, while the second is a cause-effect relationship.

Tip

TIP The equation $\lambda = Tv = v/f$ is a cause-effect relationship for the wavelength.

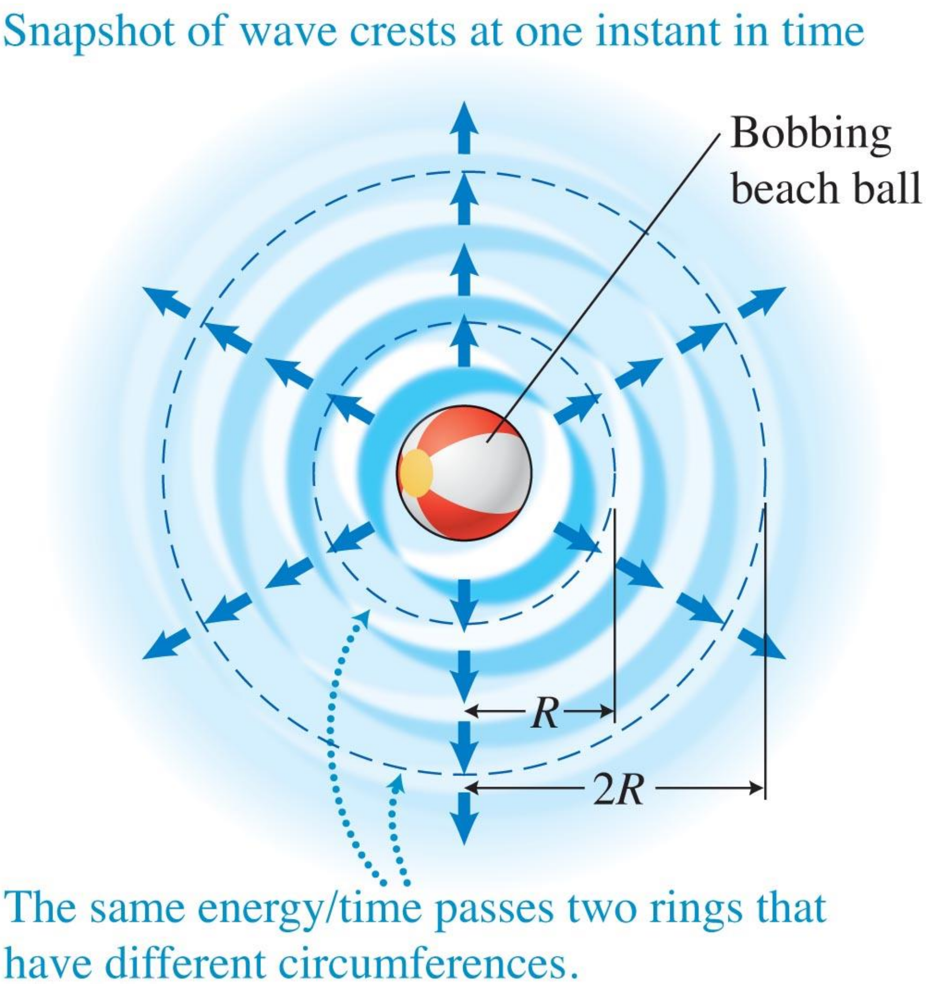
Wave amplitude and energy in a two-dimensional medium

- A beach ball bobs up and down in water in simple harmonic motion, producing circular waves that travel outward across the water surface in all directions.
  - The amplitudes of the crests decrease as the waves move farther from the source.



Wave amplitude and energy in a two-dimensional medium

- The circumference of the second ring is two times greater than the first, but the same energy per unit time moves through it.
  - The energy per unit circumference length passing through the second ring is one-half that passing through the first ring.



Two-dimensional waves produced by a point source

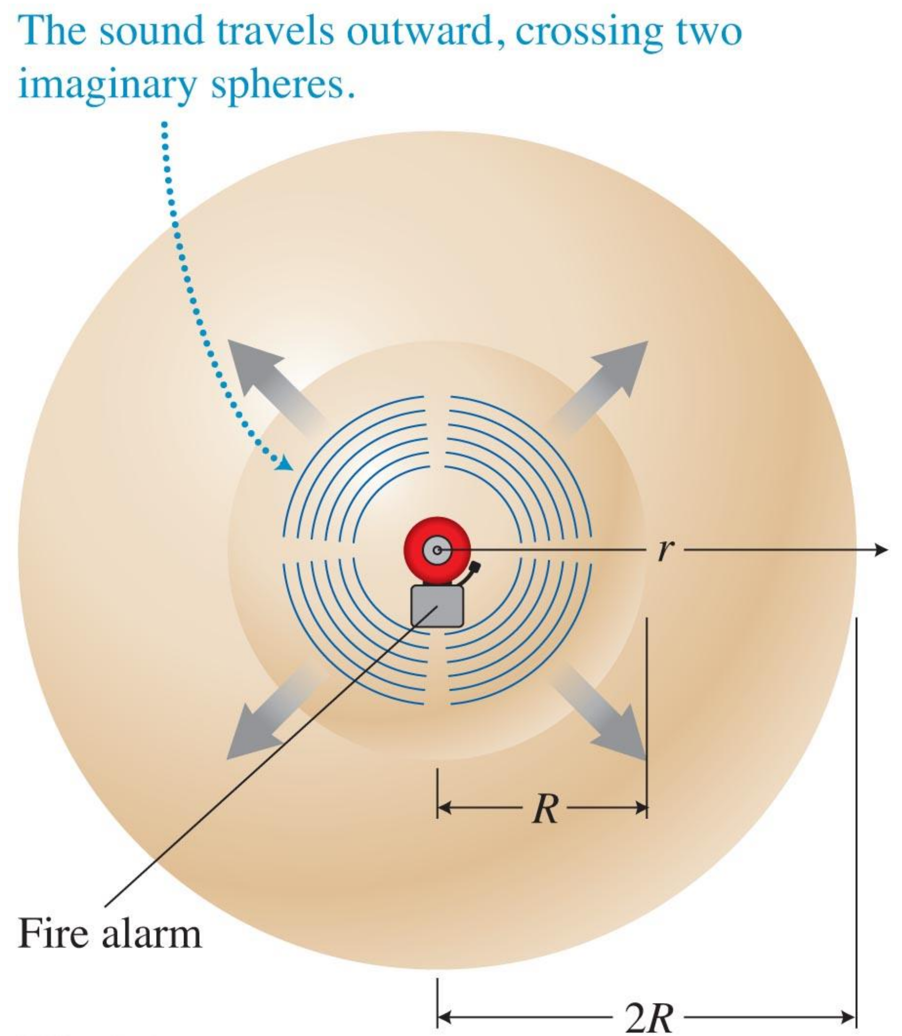
Two-dimensional waves produced by a point source The energy per unit circumference length and per unit time crossing a line perpendicular to the direction that the wave travels decreases as $1/r$, where r is the distance from the point source of the wave.

Example 20.3

- You do a cannonball jump off a high board into a pool. The wave amplitude is 50 cm at your friend's location, 3.0 m from where you enter the water. What is the wave amplitude at a second friend's location, 5.0 m from where you enter the water?

Wave amplitude and energy in a three-dimensional medium

- The area of the second sphere is four times the area of the first sphere, but the same energy per unit time moves through it.
  - The energy per unit area through the second sphere is one-fourth that through the first sphere.



Three-dimensional waves produced by a point source

Three-dimensional waves produced by a point source The energy per unit area per unit time passing across a surface perpendicular to the direction that the wave travels decreases as $1/r^2$, where r is the distance from the point source of the wave.

Tip

TIP The symbol for the area and the amplitude of vibrations is the same—A. Make sure you interpret the meaning of A based on the context of the situation.

Wave power and wave intensity

- The intensity of a wave is defined as the energy per unit area per unit time interval that crosses perpendicular to an area in the medium through which it travels:

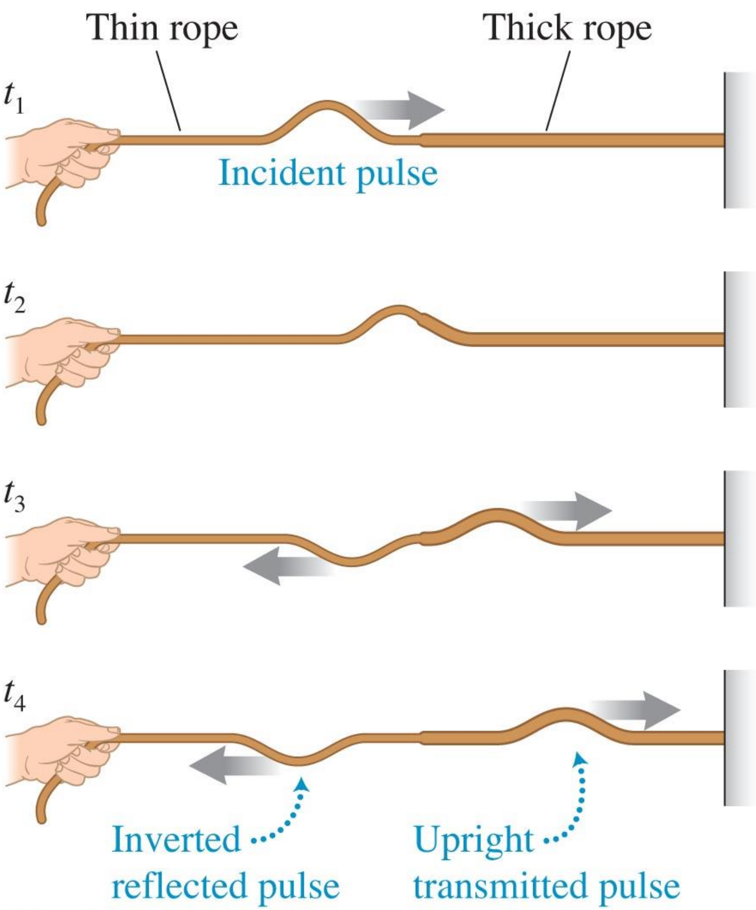
$$\text{Intensity} = \frac{\text{Energy}}{\text{time} \cdot \text{area}} = I = \frac{\Delta U}{\Delta t \cdot A} = \frac{P}{A}$$

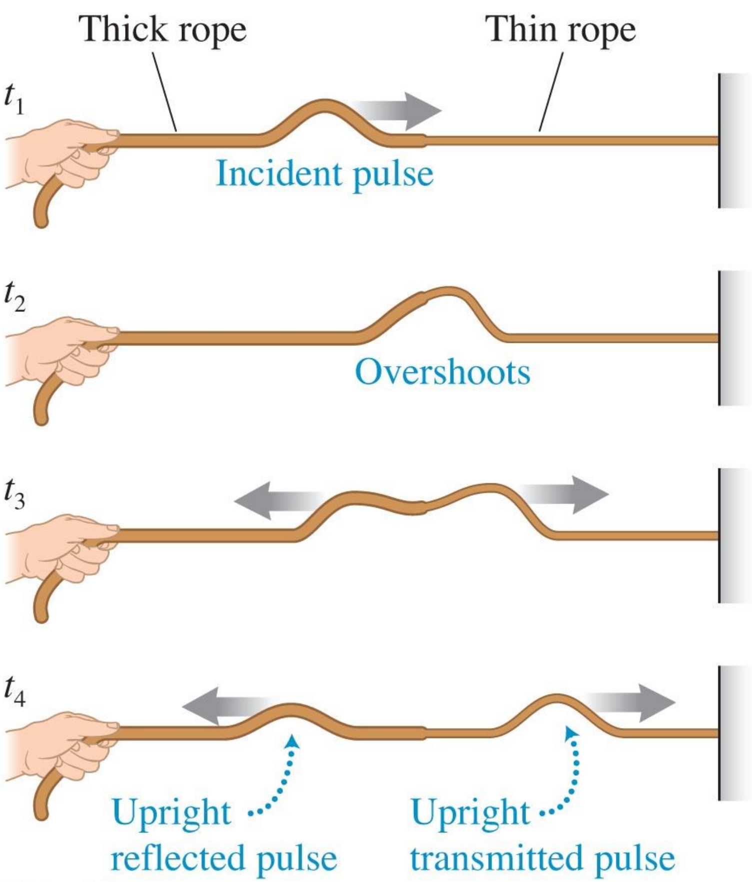
- The unit of intensity *I* is equivalent to joules per second per square meter or watts per square meter.

Reflection and impedance

- If you hold one end of a rope whose other end is fixed and shake it once, you create a transverse traveling incident pulse.
  – When the pulse reaches the fixed end, the reflected pulse bounces back in the opposite direction.
  – The reflected pulse is inverted—oriented downward as opposed to upward.
- What happens to a wave when there is an abrupt change from one medium to another?

Reflection and impedance





Impedance

- Impedance characterizes the degree to which waves are reflected and transmitted at the boundary between different media.
- Impedance is defined as the square root of the product of the elastic and inertial properties of the medium:

$$\text{Impedance} = Z = \sqrt{(\text{Elastic property})(\text{Inertial property})}$$

Ultrasound

- Ultrasound takes advantage of the differing densities of internal structures to "see" inside the body.
  - The impedance of tissue is much greater than that of air. As a result, most of the ultrasound energy is reflected at the air-body interface and does not travel inside the body.
  - To overcome this problem, the area of the body to be scanned is covered with a gel that helps "match" the impedance between the emitter and the body surface.

Superposition principle

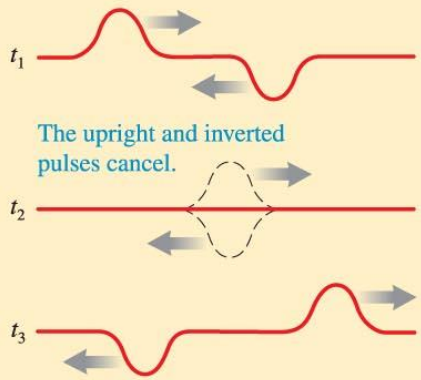
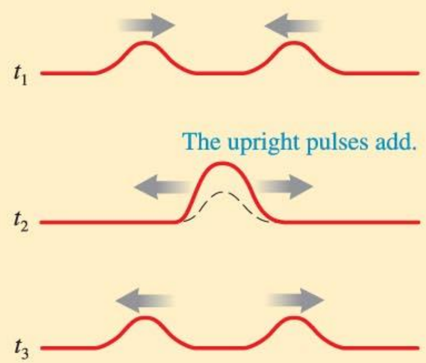
- We have studied the behavior of a single wave traveling in a medium and initiated by a simple harmonic oscillator.
  – Most periodic or repetitive disturbances of a medium are combinations of two or more waves of the same or different frequencies traveling through the same medium at the same time.
- Now we investigate what happens when two or more waves simultaneously pass through a medium.

Observational experiment

OBSERVATIONAL EXPERIMENT TABLE

20.4 Adding two pulses passing through a medium.

VIDEO 20.4

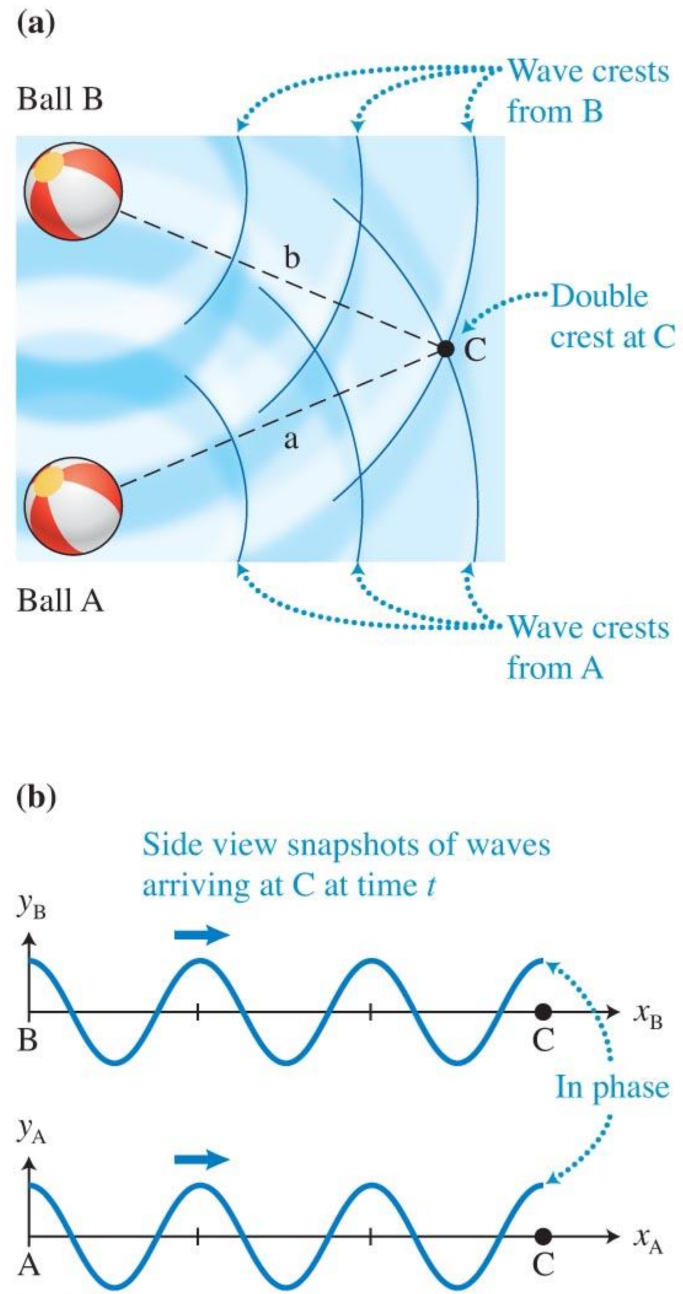
Observational experiment	Analysis
An upright pulse traveling right from the left side of a rope meets an inverted pulse traveling left from the right side of the rope. The rope looks undisturbed as the pulses pass in the middle. After passing, the pulses continue moving in the same direction with the same amplitude as if they had never met. 	The part of the rope where the pulses meet is pulled up by the pulse coming from the left and down by the pulse coming from the right, causing a net zero disturbance.
Two upright pulses travel from each end of the rope toward the center. When the pulses pass the center, the disturbance is twice that if only one pulse was present. After passing the center of the rope, the pulses continue moving in the same direction with the same amplitude as though they had never met. 	The part of the rope where the pulses meet is pulled up by both the right- and left-moving pulses, resulting in a double amplitude disturbance.

Pattern

When pulses meet, the resultant disturbance is the sum of the two.

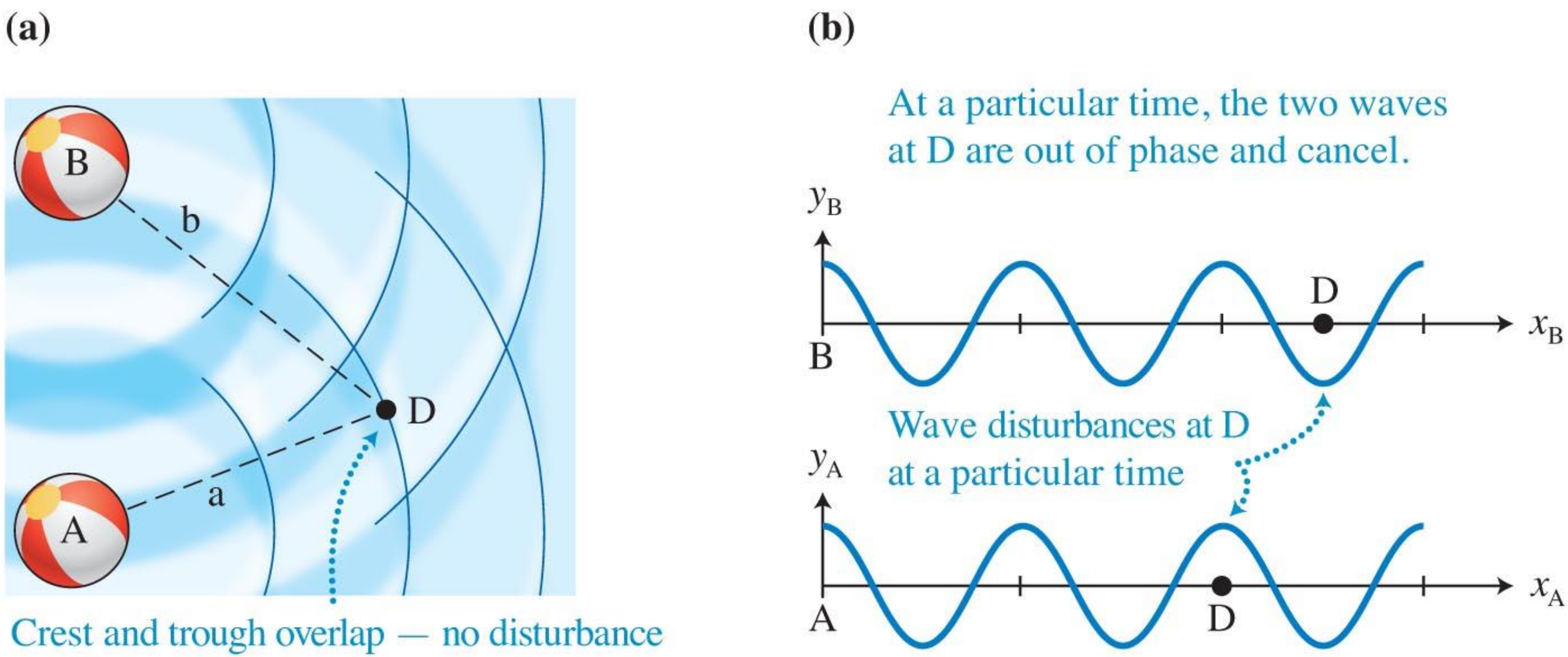
Superposition principle

- Imagine we have two vibrating sources in water, each of which sends out sinusoidal waves.
  - Consider point C in the figure.



Superposition principle

- Imagine we have two vibrating sources in water, each of which sends out sinusoidal waves.
  - Consider point D in the figure.



Skills for analyzing wave processes

- When problem solving:
  - Draw displacement-versus-time or displacement-versus-position graphs to represent the waves if necessary.

Superposition principle for waves

Superposition principle for waves When multiple waves pass through the same medium at the same time, the net displacement at a particular time and location in the medium is the sum of the displacements that would be caused by each wave if it were alone in the medium at that time. Mathematically this statement can be written as

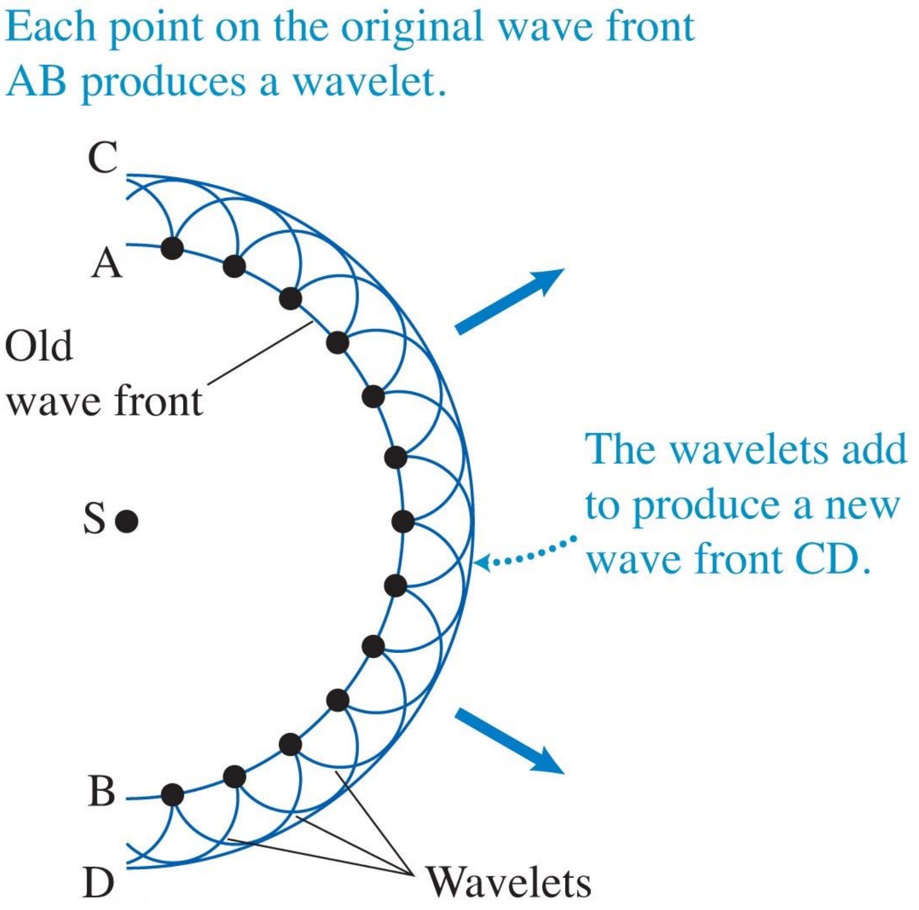
$$y_{\text{net}} = y_1 + y_2 + \ \ldots \tag{20.8}$$

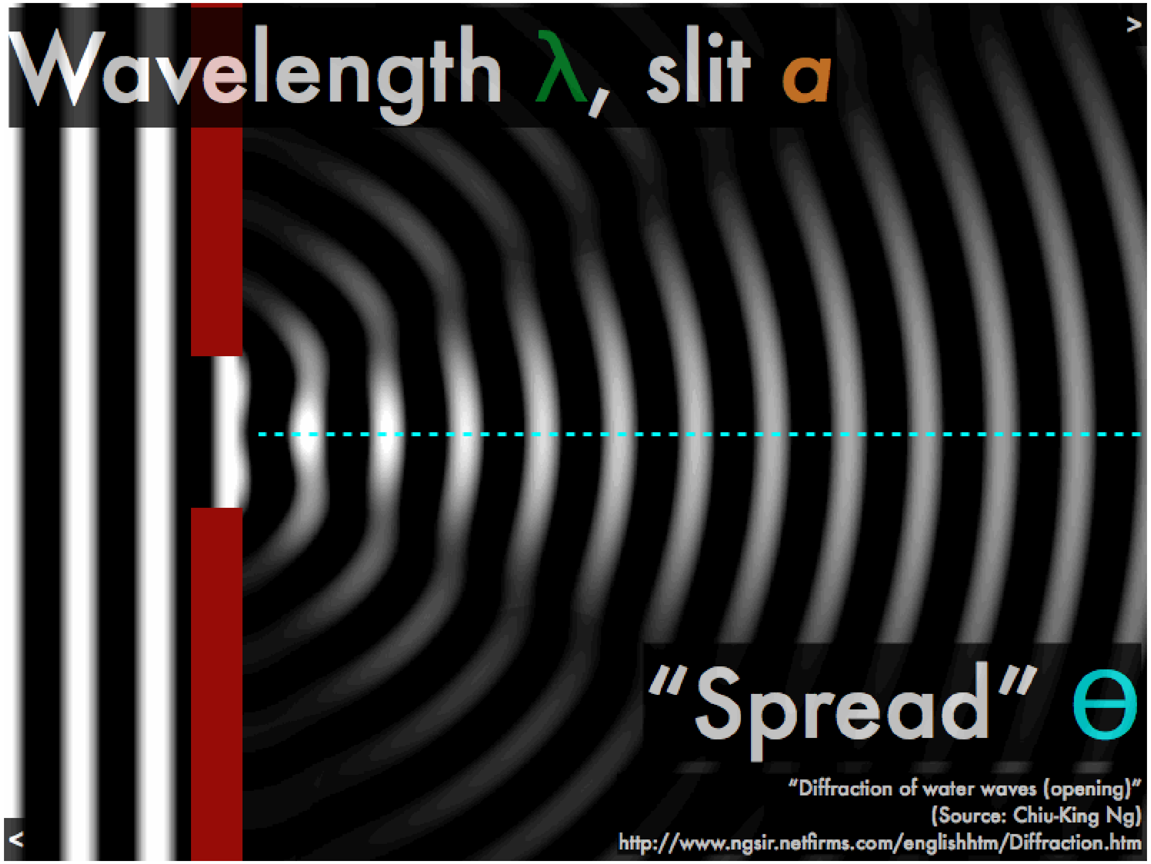
Superposition principle for waves

- The process in which two or more waves of the same frequency overlap is called interference.
  - Places where the waves add to create a larger disturbance are called locations of constructive interference.
  - Places where the waves add to produce a smaller disturbance are called locations of destructive interference.

Huygens' principle

- We can explain the formation of the waves using the superposition principle, first explained by Christiaan Huygens (1629–1695).
  - Each arc represents a wavelet that moves away from a point on the original wave front.



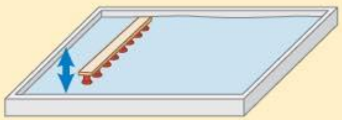
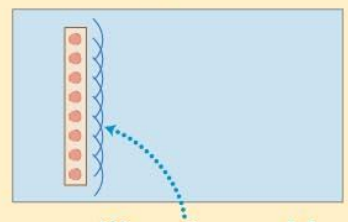
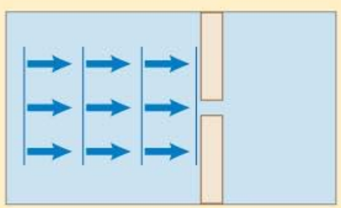
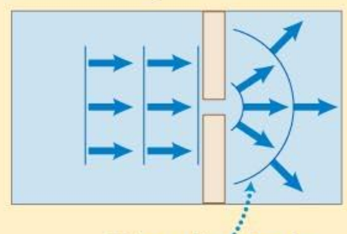

Wavelength λ, slit a
"Spread" θ
"Diffraction of water waves (opening)"
(Source: Chiu-King Ng)
http://www.ngsir.netfirms.com/englishhtm/Diffraction.htm

Testing experiment

TESTING EXPERIMENT TABLE

20.5 Testing Huygens' principle.

VIDEO 20.5

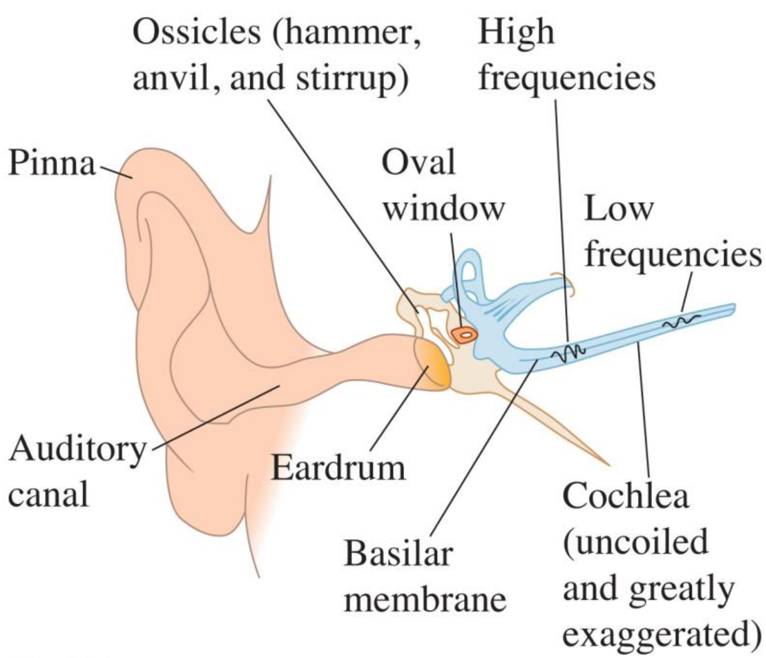
Testing experiment	Prediction	Outcome
Take a strip of cardboard with many closely spaced pushpins pushed through it from the bottom in a line.  Place the cardboard just above the water so that when it vibrates, the pins move up and down, each creating a wavelet in the water. Then shake the cardboard to produce vibrations of the pins in the water.	When added, the wavelets produced by each pin should produce a straight wave front. 	We observe the predicted straight wave front.
Remove the pins from the cardboard and shake the board. When the board vibrates in a tray of water, it creates a wave with wave fronts that look like lines (plane waves). Place a barrier with a narrow slit opening in the path of the plane waves. 	The vibrations of water beyond the narrow slit should be circular wavelets. 	We observe a circular wavelet spreading beyond the narrow slit.

Conclusion

Predictions based on Huygens' principle match the outcomes of the testing experiments. These experiments do not disprove the principle but rather give us more confidence in the principle.

Sound

- We hear sound when pressure variations at the eardrum cause it to vibrate.



- Pressure waves in the frequency range that we can hear are called sound.
- Higher- or lower-frequency pressure waves are called ultrasound or infrasound.

Loudness and intensity

- Loudness is determined primarily by the amplitude of the sound wave: the larger the amplitude, the louder the sound.
  - Equal-amplitude sound waves of different frequencies will not have the same perceived loudness to humans.
- To measure the loudness of a sound, we measure the intensity: the energy per unit area per unit time interval.

intensity level

- Because of the wide variation in the range of sound intensities, a quantity called intensity level is commonly used to compare the intensity of one sound to the intensity of a reference sound.
- Intensity level is defined on a base 10 logarithmic scale as follows:

$$\beta = 10 \log_{10} \frac{I}{I_0}$$

Intensities and intensity levels of common sounds

Table 20.6 **Intensities and intensity levels of common sounds.**

Source of sound	Intensity (W/m^2)	Intensity level (dB)	Description
Large rocket engine (nearby)	10^6	180	
Jet takeoff (nearby)	10^3	150	
Pneumatic riveter; machine gun (nearby)	10	130	
Rock concert with amplifiers (2 m); jet takeoff (60 m)	1	120	Pain threshold
Construction noise (3 m)	10^{-1}	110	
Moving subway train (nearby)	10^{-2}	100	
Heavy truck (15 m)	10^{-3}	90	Constant exposure
Niagara Falls (nearby)	10^{-3}	90	endangers hearing
Noisy office with machines; inside an average factory	10^{-4}	80	
Busy traffic	10^{-5}	70	
Normal conversation (1 m)	10^{-6}	60	
Quiet office	10^{-7}	50	Quiet
Library	10^{-8}	40	
Soft whisper (5 m)	10^{-9}	30	
Rustling leaves	10^{-10}	20	Barely audible
Normal breathing	10^{-11}	10	
	10^{-12}	0	Hearing threshold

Quantitative Exercise 20.6

- The sound in an average classroom has an intensity of 10^{-7} W/m^2.
  1. Determine the intensity level of that sound.
  2. If the sound intensity doubles, what is the new sound intensity level?

Tip

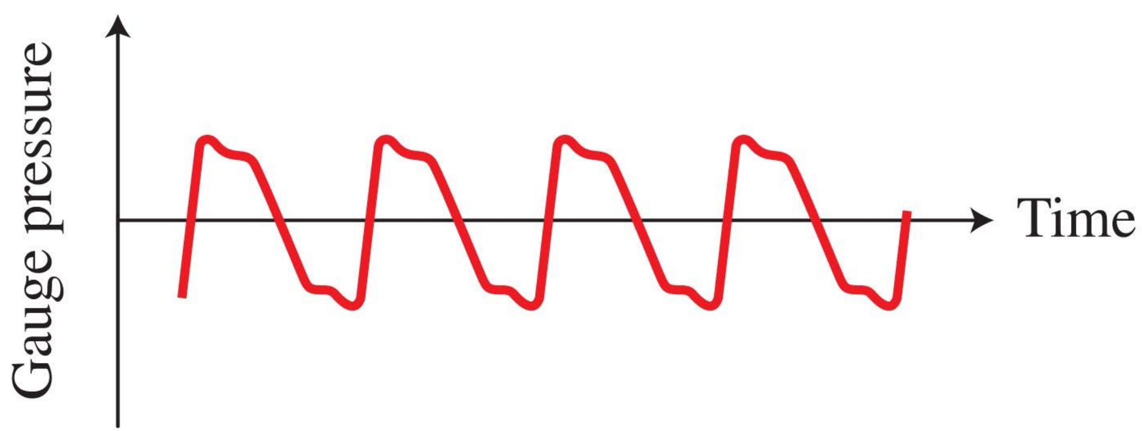
TIP Remember that a 60-dB sound has 10 times the intensity of a 50-dB sound, which has 10 times the intensity of a 40-dB sound, and so on.

Pitch, frequency, and complex sounds

- Pitch is the perception of the frequency of a sound.
  - Tuning forks of different sizes produce sounds of approximately the same intensity, but we hear each as having a different pitch.
  - The shorter the length of the tuning fork, the higher the frequency and the higher the pitch.
- Like loudness, pitch is not a physical quantity but rather a subjective impression.

Complex sounds, waveforms, and frequency spectra

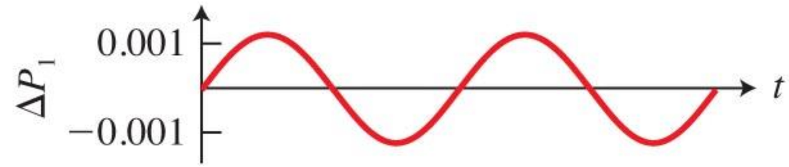
- An oboe and a violin playing concert A equally loudly at 440 Hz sound very different.
  - Which other property of sound causes this different sensation to our ears?
  - Musical notes from instruments have a characteristic frequency, but the wave is not sinusoidal.



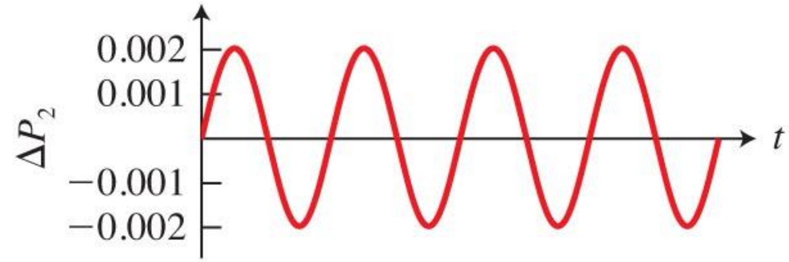
Waveforms

- Superposition causes the sound from two tuning forks to create a complex pattern.
- This complex pattern is called a waveform: a combination of two or more waves of different frequencies and possibly different amplitudes.

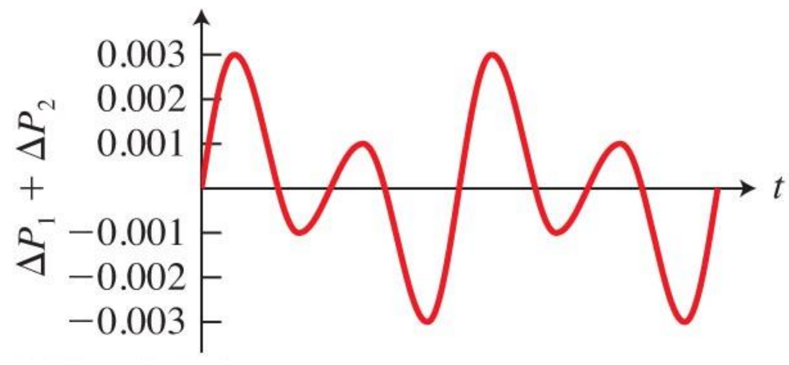
(a) Wave 1 produced by sound from the first tuning fork



(b) Wave 2 produced by sound from the second tuning fork



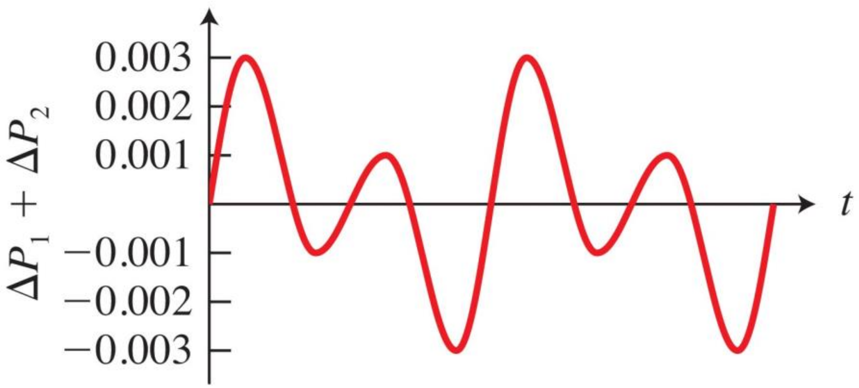
(c) Combined wave produced by both tuning forks

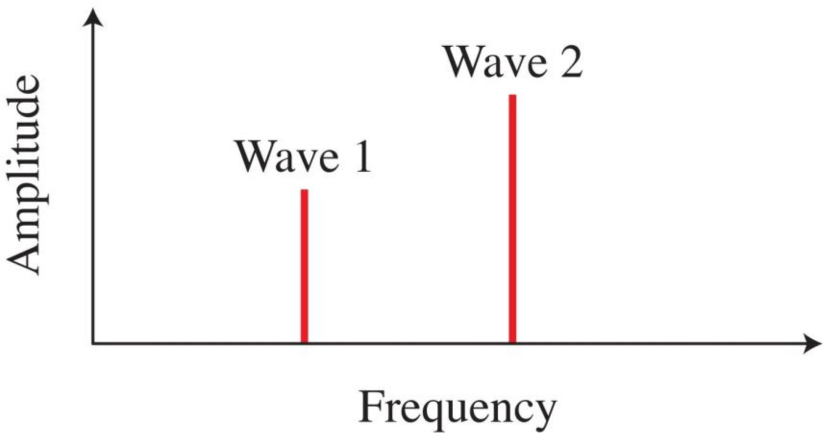


Frequency spectrum

- A spectrum analyzer decomposes a complex waveform into its component frequencies.
- The frequency spectrum plots the amplitude of each component versus the frequency.

(c) Combined wave produced by both tuning forks



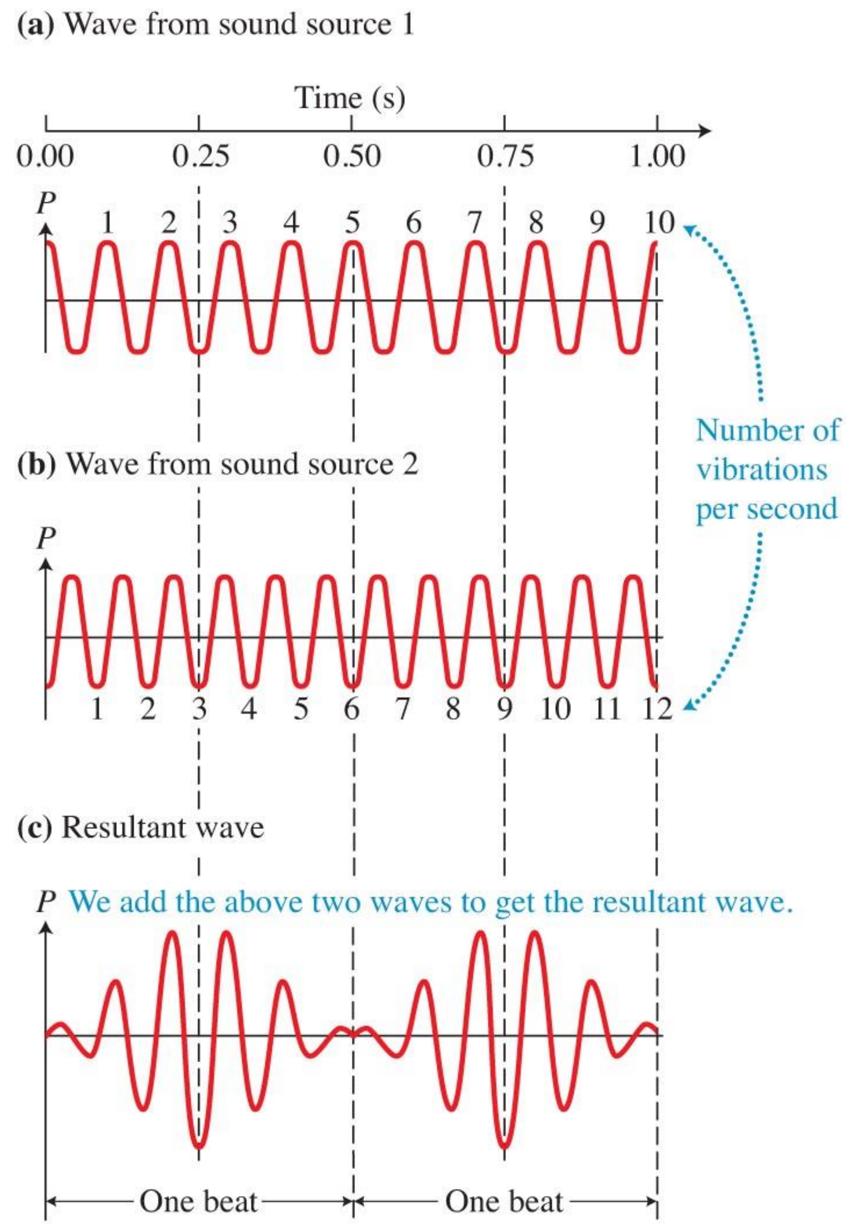


Fundamental and harmonics

- The lowest frequency of a complex wave is called the fundamental.
- Higher-frequency components that are whole-number multiples of the fundamental are called harmonics.
  - We usually identify the pitch as the fundamental frequency.
  - The complexity of the waveform (the number of harmonics) contributes to the quality of the sound we associate with specific instruments.

Beat and beat frequencies

- Two sound sources of similar (but not the same) frequency are equidistant from a microphone that records the air pressure variations due to the two sound sources as a function of time.



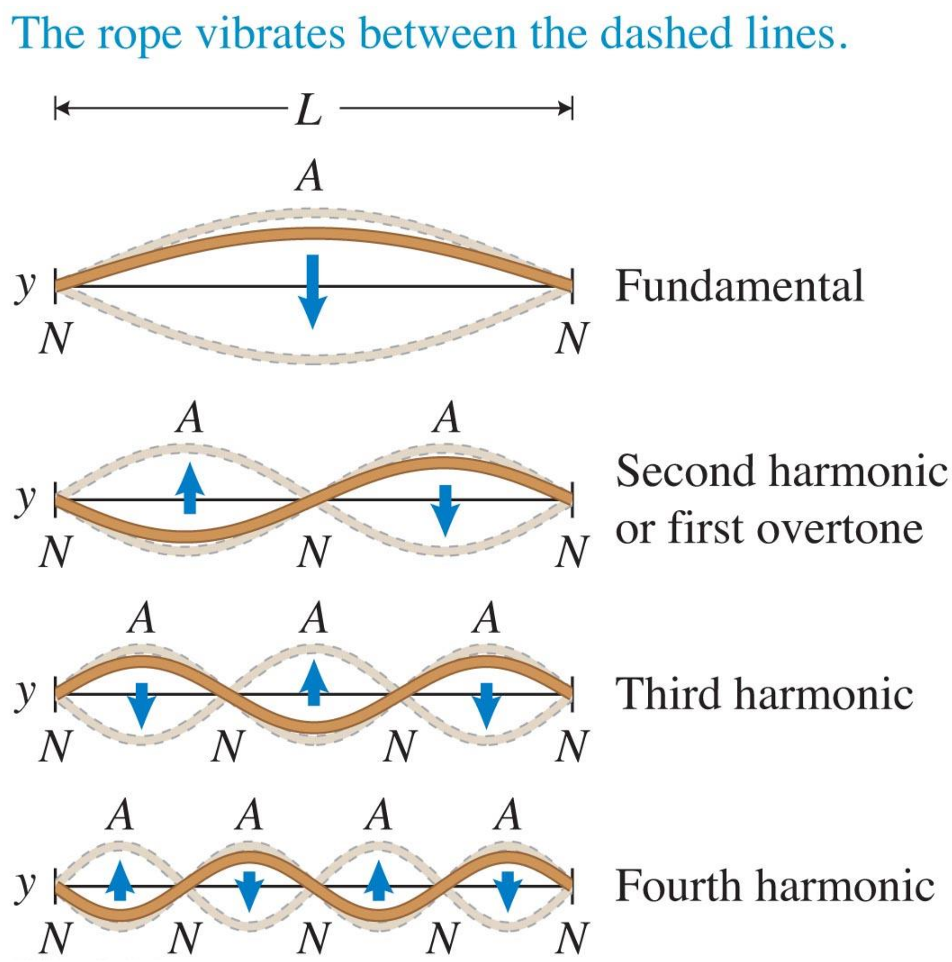
Beat and beat frequencies

A **beat** is a wave that results from the superposition of two waves of about the same frequency. The beat (the net wave) has a frequency equal to the average of the two frequencies and has variable amplitude. The frequency with which the amplitude of the net wave changes is called the **beat frequency** f_{beat}; it equals the difference in the frequencies of the two waves:

$$f_{beat} = |f_1 - f_2| \qquad (20.10)$$

Standing waves on strings

- You shake the end of a rope that is attached to a fixed support.
  - At specific frequencies, you notice that the rope has large-amplitude sine-shaped vibrations that appear not to be traveling.



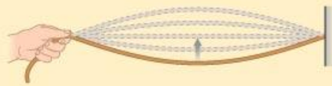
Observational experiment

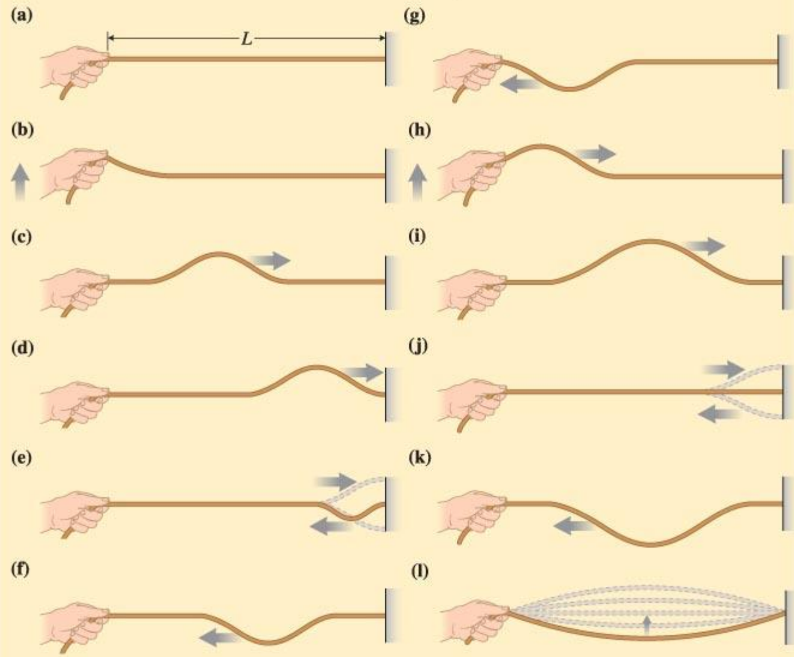
OBSERVATIONAL EXPERIMENT TABLE

20.7 Producing the first standing wave vibration.

VIDEO 20.7

Observational experiment	Analysis
You shake a rope that is fixed at one end at a relatively low frequency and observe the large-amplitude vibration.	A pulse starts moving to the right (b–d). When it reaches the fixed end, the upward pulse is reflected and inverted to a downward pulse traveling back toward your hand (e–g). When it reaches your hand, it once again reflects and inverts to an upward pulse (h). To make this pulse bigger, you begin another upward shake, timing the shake so that it adds to the previous upward pulse that has just been reflected (h).





Active Learning Guide›

Pattern

- You must shake the rope upward each time a previous pulse returns. The amplitude of the disturbance traveling along the rope grows.
- You need one up and down shake during the time interval $(2L/v)$ that it takes for the pulse to travel down the string and back:

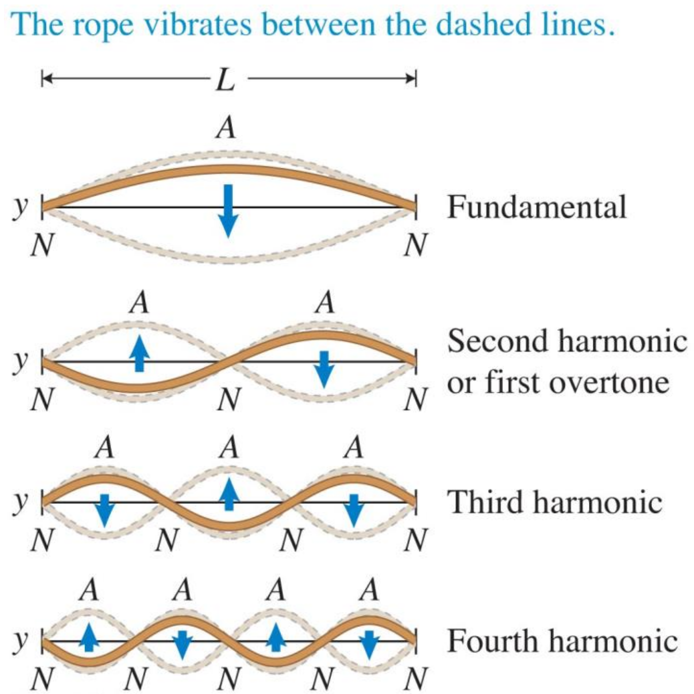
$$f_1 = \frac{1\ \text{vibration}}{\frac{2L}{v}} = \frac{v}{2L}$$

Standing waves on a string

- The lowest-frequency vibration of the rope is one up-and-down shake per time interval:

$$f_1 = \frac{1}{\tau} = \frac{1}{\dfrac{2L}{v}} = \frac{v}{2L}$$

- This frequency is called the fundamental frequency.



Testing experiment

TESTING EXPERIMENT TABLE

20.8 Fundamental vibration frequency.

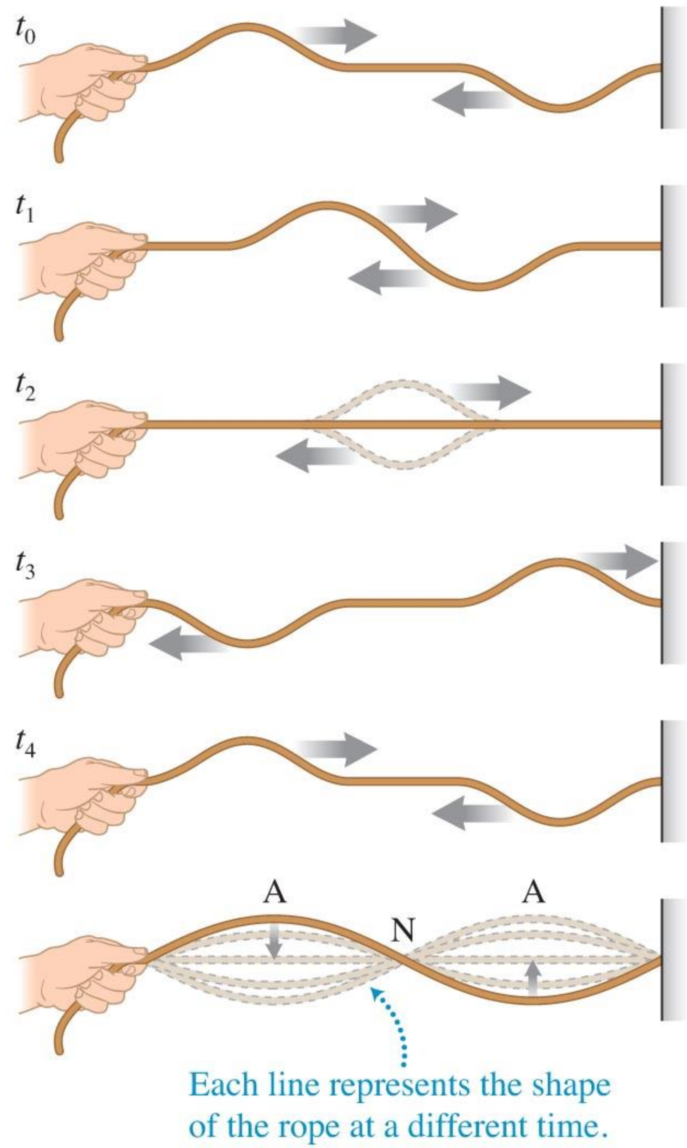
Testing experiment	Prediction	Outcome
Predict the fundamental vibration frequency of a banjo D string. The mass of the string is 0.252 g, its length is 0.690 m, and the wooden peg pulls on its end exerting a 60.0-N force.	The speed of a wave in the string is $v = \left[\frac{F_{\text{Peg on String}}}{(m_{\text{string}}/L_{\text{string}})}\right]^{1/2} = \left[\frac{(60.0\ \text{N})}{(0.252 \times 10^{-3}\ \text{kg})/(0.690\ \text{m})}\right]^{1/2} = 405\ \text{m/s}$ Consequently, we predict that the fundamental frequency should be $f_1 = \frac{v}{2L} = \frac{405\ \text{m/s}}{2(0.690\ \text{m})} = 294\ \text{s}^{-1} = 294\ \text{Hz}$	When we pluck a banjo D string and compare it to the frequency of a tuning fork, we find $f_1 = 294$ Hz.

Conclusion

The agreement is excellent. We've built confidence in the expression for fundamental frequency.

Standing waves on a string

- Consider the vibration that produces a standing wave on the rope at twice the frequency of the fundamental vibration.
  - Vibrate the rope so that your hand has two up-and-down shakes during the time interval needed for a pulse to make a round trip.



Standing wave frequencies on a string

Standing wave frequencies on a string The frequencies f_n at which a string with fixed ends can vibrate are

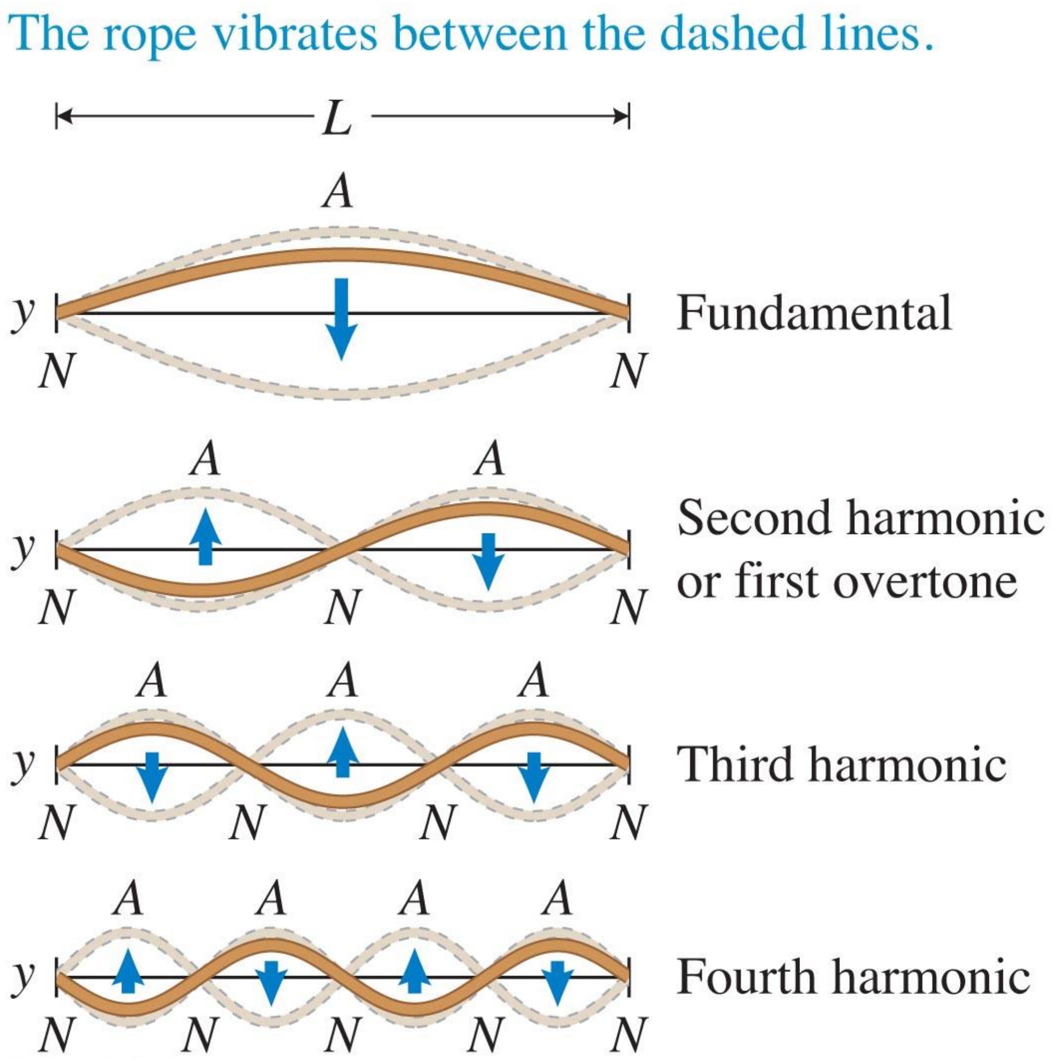
$$f_n = n\left(\frac{v}{2L}\right) \text{ for } n = 1, 2, 3, \ldots \qquad (20.12)$$

where v is the speed of the wave on the string and L is the string length.

- We can write this expression in terms of the wavelengths:

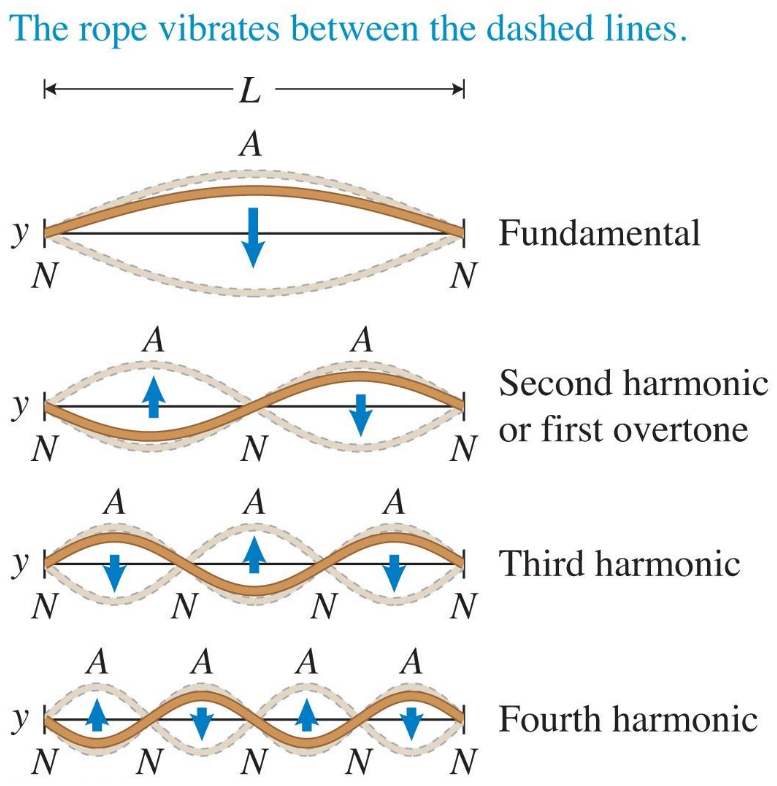
$$\lambda_n = \frac{v}{f_n} = \frac{v}{n\left(\frac{v}{2L}\right)} = \frac{2L}{n} \text{ for } n = 1, 2, 3, \ldots$$

Standing wave frequencies on a string (Cont'd)



Standing waves on a string

- In a standing wave, only the antinodes reach the maximum displacement.
- The nodes do not vibrate at all.
  - All of the points vibrate in phase.

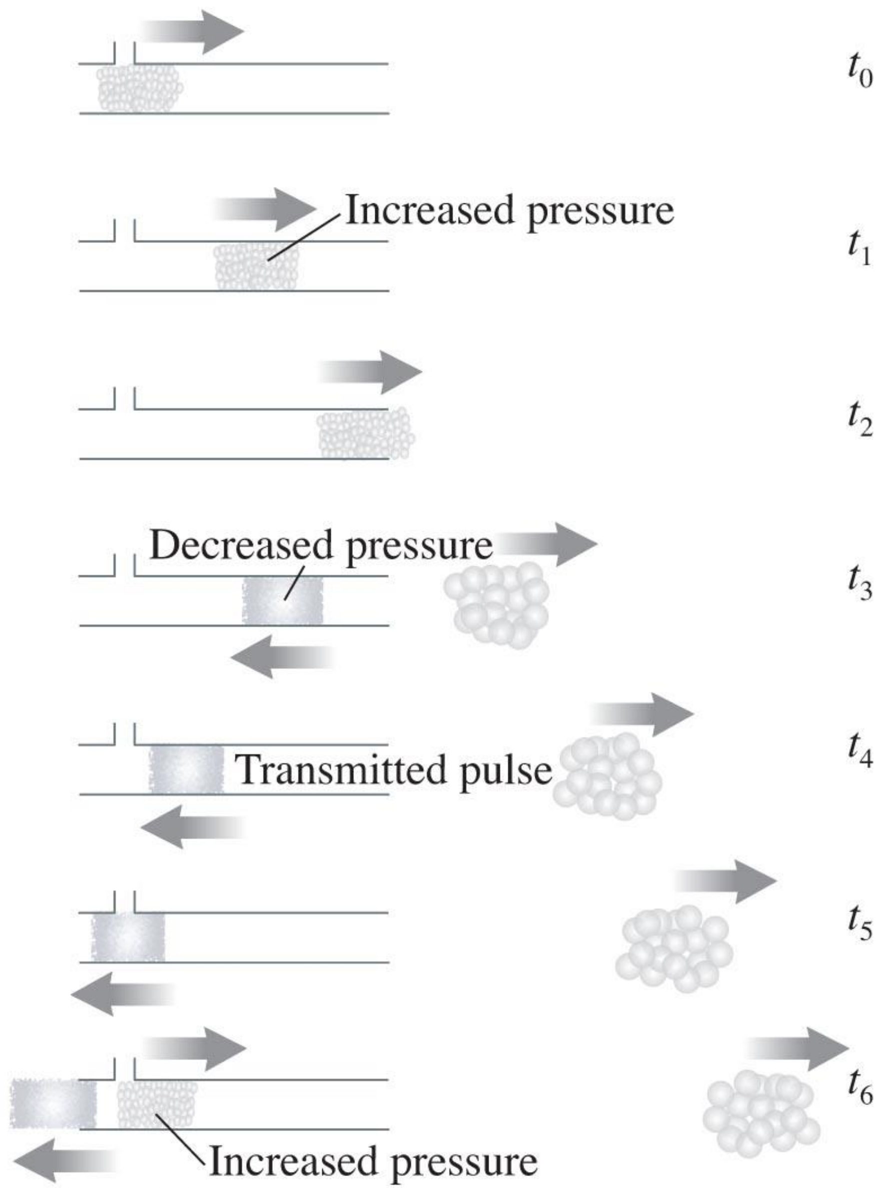


Example 20.7

- A banjo D string is 0.69 m long and has a fundamental frequency of 294 Hz. Shortening the string (by holding the string down over a fret) causes it to vibrate at a higher fundamental frequency. Where should you press to play the note F-sharp, which has a fundamental frequency of 370 Hz?

Standing waves in open-open pipes

- A flute is a wind instrument that is an example of an open-open pipe, so called because it is open on both ends.
  - Blowing into the open-open pipe initiates pressure pulses at that end of it.
  - Visualize: http://www.physicsclassroom.com/class/sound/Lesson-5/Open-End-Air-Columns?_sm_au_=iVV0NvPfWZ07fN6H



Standing wave vibration frequencies in open-open pipes

Standing wave vibration frequencies in open-open pipes The resonant frequencies f_n of air in an open-open pipe of length L in which sound travels at speed v are

$$f_n = n\left(\frac{v}{2L}\right) \text{ for } n = 1, 2, 3, \ldots \qquad (20.14)$$

where v is the speed of sound in the medium that fills the pipe.

Standing waves in one-end-closed pipes: An open-closed pipe

- Visualize: http://www.physicsclassroom.com/class/sound/Lesson-5/Closed-End-Air-Columns
- Consider a pipe that is closed at one end and open at the other end.
  - Examples of this type of open-closed pipe include a clarinet, a trumpet, and the human throat.
  - Blowing into the reed or mouthpiece initiates a high-pressure pulse near the closed end of the pipe.

Standing wave vibration frequencies in open-closed pipes

Standing wave vibration frequencies in open-closed pipes The resonant frequencies f_n of air in an open-closed pipe of length L in which sound travels at speed v are

$$f_n = n\left(\frac{v}{4L}\right) \text{ for } n = 1, 3, 5, \ldots \qquad (20.15)$$

Exciting the sound and changing the pitch of a wind instrument

- In clarinets and saxophones, the sources of vibrations are the reeds. In trumpets, trombones, and French horns, the sources of vibrations are the vibrating lips and mouthpiece.
  - The vibrations produced by the reeds and mouthpieces are pressure pulses at a variety of frequencies.
  - The pipes attached to the reeds and mouthpieces reinforce only those input frequency vibrations that are at resonant frequencies of the instruments.

Testing our understanding of standing waves in pipes

- If our reasoning is correct that sound in pipe-like instruments is due to standing waves inside of them, then changing the medium (which changes the wave speed) inside a pipe should change the fundamental frequency produced by the pipe, even though the length of the pipe has not changed.

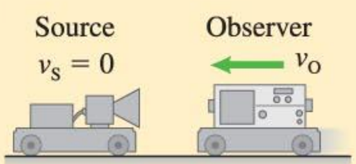
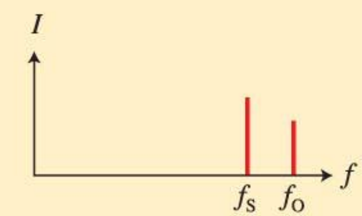
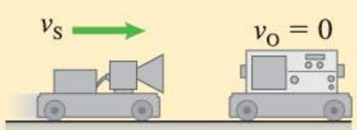
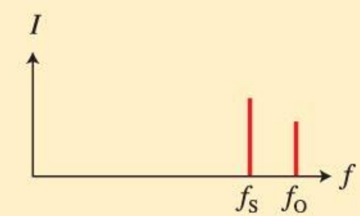
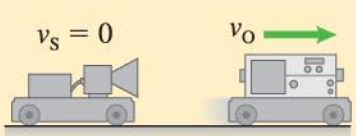
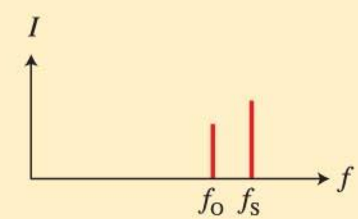
The Doppler effect: Putting it all together

- When you hear the sound from a horn of a passing car, its pitch is noticeably higher than normal as it approaches, but noticeably lower than normal as it moves away.
  - This phenomenon is an example of the Doppler effect.
  - The Doppler effect occurs when a source of sound and an observer move with respect to each other and/or with respect to the medium in which the sound travels.

Observational experiment

OBSERVATIONAL EXPERIMENT TABLE

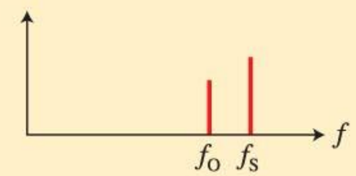
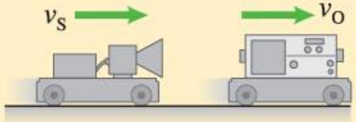
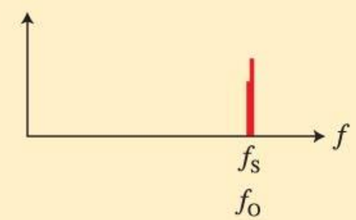
20.9 Effects of motion on observed frequency.

Observational experiment	Analysis
Place a battery-powered whistle (the source) on one cart and an observer with a spectrum analyzer on another cart. The carts can move toward or away from each other. **(a) Source** stationary with respect to the ground **Observer** moving toward source 	The frequency spectrum for the signal emitted by the source (f_S) and heard by the observer (f_O) $f_S < f_O$ 
(b) Source moving toward observer **Observer** stationary with respect to the ground 	The frequency spectrum: $f_S < f_O$ 
(c) Source stationary with respect to the ground **Observer** moving away from source 	The frequency spectrum: $f_S > f_O$ 

Observational experiment

OBSERVATIONAL EXPERIMENT TABLE

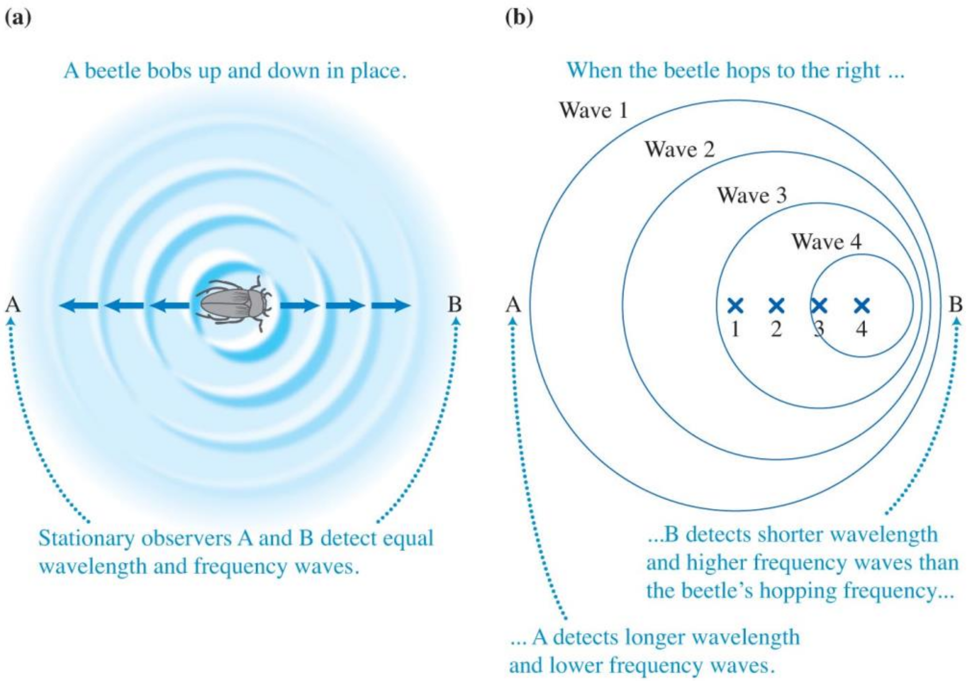
20.9 **Effects of motion on observed frequency.** ***(Continued)***

Observational experiment	Analysis
(d) Source moving away from observer **Observer** stationary  	The frequency spectrum: $f_S > f_O$ 
(e) Source moving with respect to the ground **Observer** moving at the same speed in the same direction  	The frequency spectrum: $f_S = f_O$ 

Patterns

- (a) and (b) Source and/or observer are moving *toward* each other: the observed frequency is *greater than* the emitted source frequency.
- (c) and (d) Source and/or observer are moving *away from* each other: the observed frequency is *less than* the source frequency.
- (e) There is no relative motion: the observed and emitted frequencies are the same.

Doppler effect for the source moving relative to the medium



$$f_O = f_S \frac{v}{v \mp v_S}$$

– We use the minus sign when the source is moving toward the observer.

– We use the plus sign when the source is moving away from the observer.

Doppler effect for the observer moving relative to the medium

$$f_O = \frac{v \pm v_O}{\lambda} = \frac{v \pm v_O}{v/f_S} = f_S \frac{v \pm v_O}{v}$$

– This equation can be used to calculate the frequency f_O detected by an observer moving at speed v_O toward (plus sign) or away from (minus sign) a stationary source emitting waves at frequency f_S.

Doppler effect for sound

Doppler effect for sound When a sound source and sound observer move relative to each other and/or the medium, the observed sound frequency f_O differs from the source sound frequency f_S:

$$f_O = f_S\left(\frac{v \pm v_O}{v \mp v_S}\right) \tag{20.18}$$

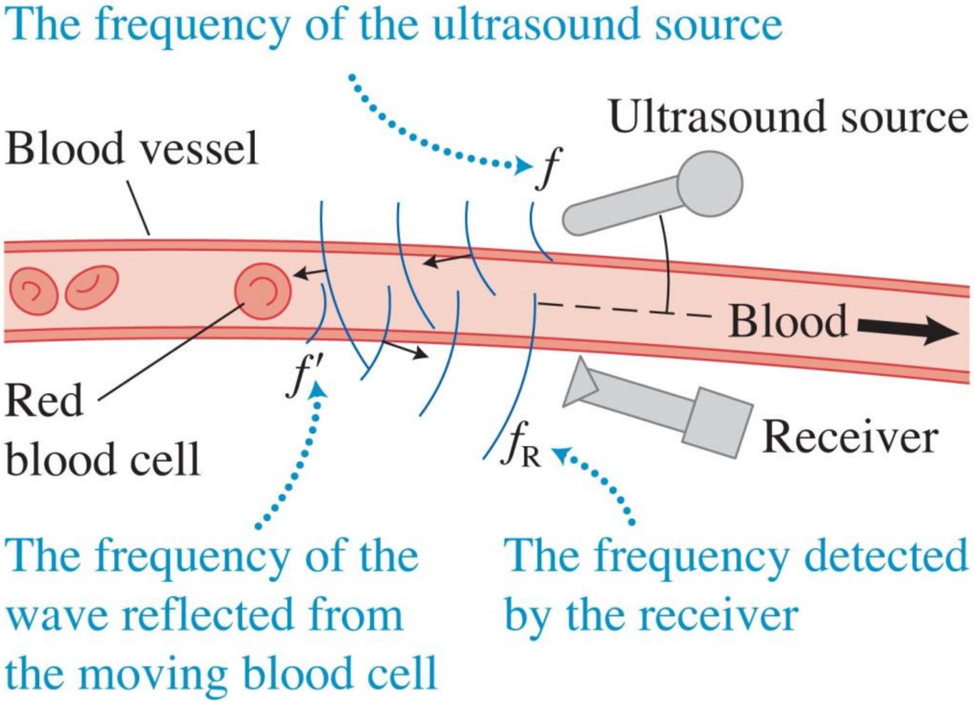
where v is the speed of waves through the medium, v_O is the speed of the observer relative to the medium (use the plus sign if the observer moves toward the source and a minus sign if the observer moves away from the source), and v_S is the speed of the source relative to the medium (use the minus sign if the source moves toward the observer and a plus sign if the source moves away from the observer).

Tip

TIP Once you have chosen which signs to use in Eq. (20.18), check for consistency. When the source and observer are getting closer, $f_O > f_S$, and so on.

Measuring the speed of blood flow in the body

- The Doppler effect is used to measure the speed of blood flow in the body.
  - Ultrasound waves are directed into an artery. The waves are reflected by red blood cells back to the receiver.

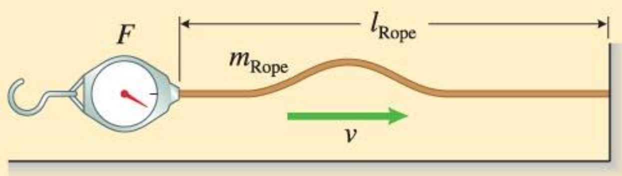
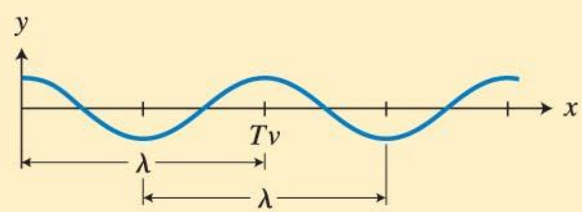


Example 20.9

- A friend with a ball attached to a string stands on the floor and swings the ball in a horizontal circle. The ball has a 400-Hz buzzer in it. When the ball moves toward you on one side, you measure a frequency of 412 Hz. When the ball moves away on the other side of the circle, you measure a frequency of 389 Hz. Determine the speed of the ball.

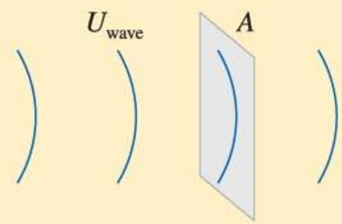
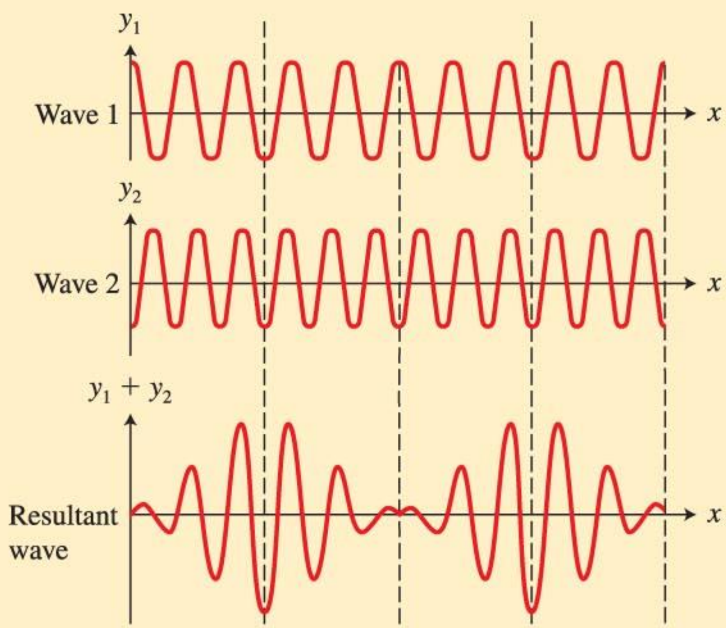
Summary

Summary

Words	Pictorial and physical representations	Mathematical representation
Wave speed v depends on the properties of the medium (such as a force $F_{\text{M on M}}$ that one part of medium exerts on another part and a mass/length quantity $\mu = m/L$). The *wavelength* λ is equal to the shortest distance between two points that vibrate in phase and depends on the frequency f and the wave speed v. (Sections 20.2 and 20.3)		$\lambda = vT = \frac{v}{f}$ Eq. (20.3) $v = \sqrt{\frac{F_{\text{M on M}}}{\mu}}$ Eq. (20.5)
Traveling sinusoidal wave The traveling wave expression allows us to determine the displacement from equilibrium y of a point in the medium at location x at time t when a wave of wavelength λ travels at speed v. In a traveling wave all points vibrate with the same amplitude but have different phases. (Section 20.2)		$y = A\cos\left[2\pi\left(\frac{t}{T} - \frac{x}{\lambda}\right)\right]$ Eq. (20.4)

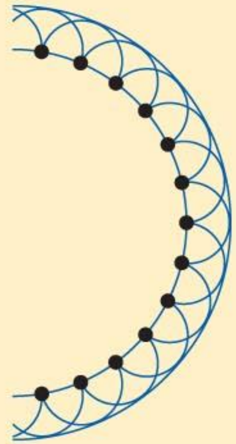
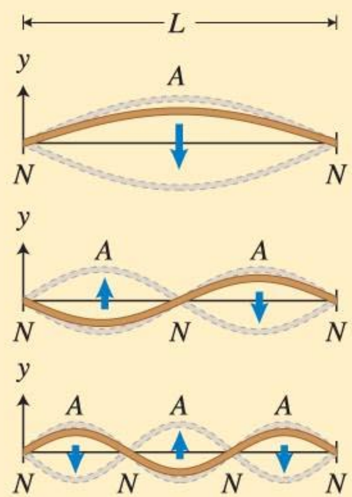
Summary

Summary *(Continued)*

Words	Pictorial and physical representations	Mathematical representation
Intensity I of a wave is the energy per unit area per time interval that crosses an area perpendicular to the direction of travel of the wave. **Intensity level** β is a logarithmic measure of the intensity I relative to reference intensity I_0. (Sections 20.4 and 20.7)		$I = \frac{\Delta U}{\Delta t \cdot A} = \frac{P}{A}$ Eq. (20.6) $\beta = 10 \log_{10}\left(\frac{I}{I_0}\right)$ Eq. (20.9) where for sound $I_0 = 10^{-12}\,\mathrm{J/m^2 \cdot s}$
Superposition principle When two or more waves pass through the same medium at the same time, the net displacement of any point in the medium is the sum of the displacements that would be caused by each wave if alone in the medium. (Section 20.6)		$y_{net} = y_1 + y_2 + y_3 + \ldots$ Eq. (20.8)

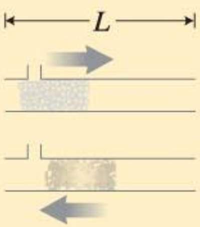
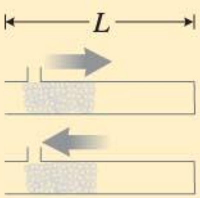
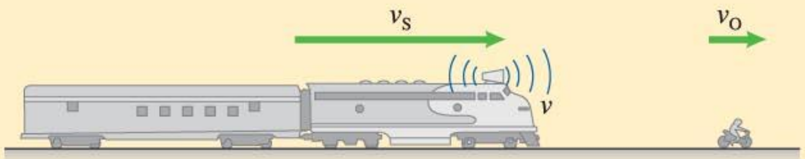
Summary

Summary *(Continued)*

Words	Pictorial and physical representations	Mathematical representation
Huygens' principle Every vibrating point of a medium produces a wavelet surrounded by a circular wave front. The new wave front is the superposition of all wavelets due to the vibrations of all points on the previous wave front. (Section 20.6)		
Standing waves on strings are the result of the constructive interference of reflected transverse waves of frequencies f_n traveling at speed v in both directions on a string of length L. The vibrating points in a standing wave have different amplitudes, but all vibrate in phase. (Section 20.9)		$f_n = n\left(\frac{v}{2L}\right)$ for $n = 1, 2, 3, \ldots$ Eq. (20.12)

Summary

Summary *(Continued)*

Words	Pictorial and physical representations	Mathematical representation
Standing waves in open-open pipes are similar to standing waves on strings except that they are longitudinal pressure waves of frequencies f_n traveling at speed v in a tube of length L with two open ends. (Section 20.10)		$f_n = n\left(\frac{v}{2L}\right)$ for $n = 1, 2, 3, \ldots$ Eq. (20.14)
Standing waves in open-closed pipes are similar to standing waves in open pipes, but with a pipe having one closed end. (Section 20.10)		$f_n = n\left(\frac{v}{4L}\right)$ for $n = 1, 3, 5, \ldots$ Eq. (20.15)
Doppler effect for sound When a sound source and sound observer move relative to each other, the frequency f_O of the observed sound differs from the frequency f_S of the source. v_O and v_S are the observer and source speeds (magnitudes of the velocities) and v is the speed of the wave through the medium. (Section 20.11)		$f_O = f_S\left(\frac{v \pm v_O}{v \mp v_S}\right)$ Eq. (20.18) Use + in front of v_O if observer moves toward source and − if away; use − in front of v_S if source moves toward observer and + if away.