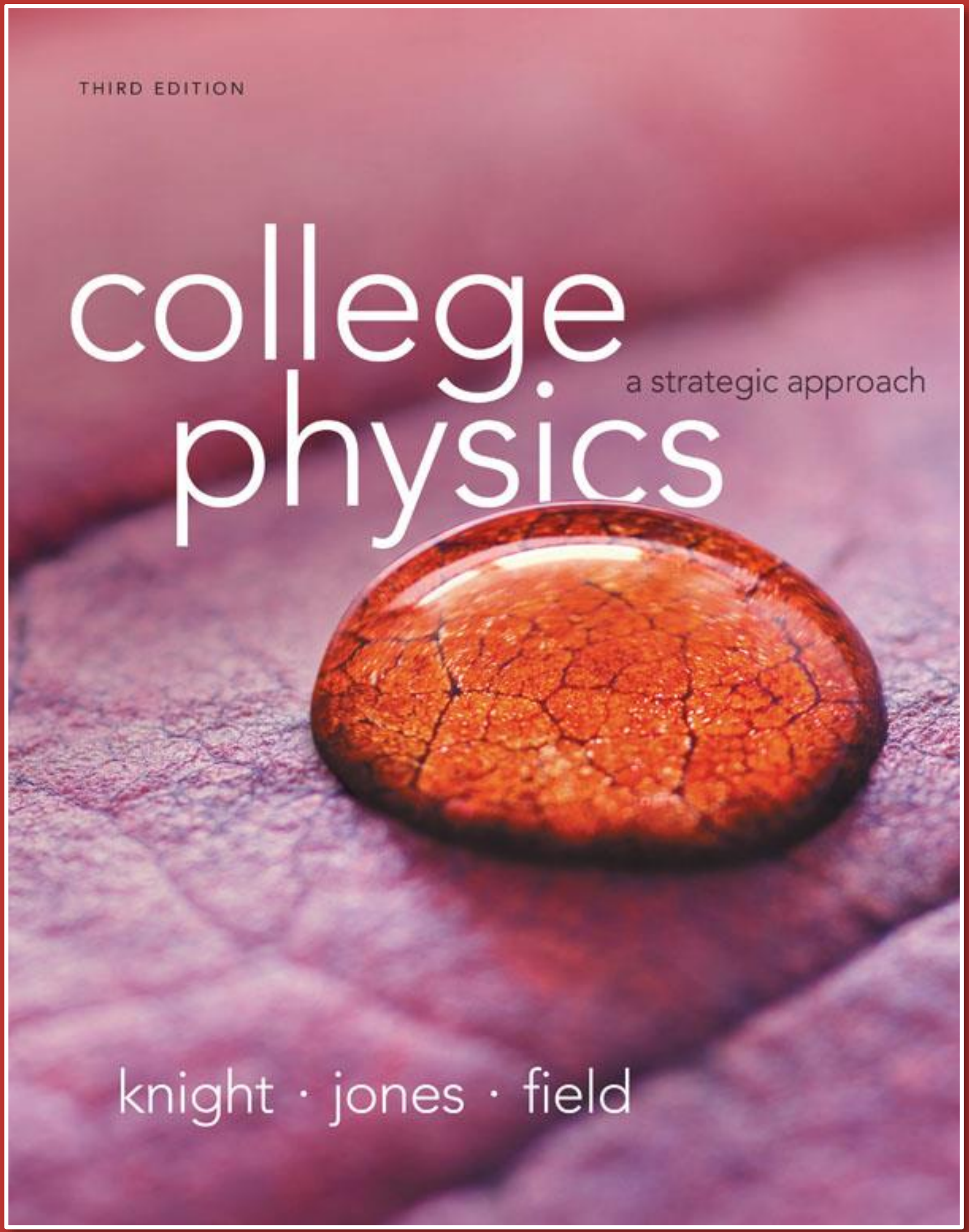


Lecture Presentation

Chapter 15

Traveling Waves and Sound

Suggested Videos for Chapter 15

- **Prelecture Videos**
  - *Wave Motion*
  - *Describing Waves*
  - *Energy and Intensity*
- **Class Videos**
  - *Traveling Waves*
  - *Traveling Waves Problems*
- **Video Tutor Solutions**
  - *Traveling Waves and Sound*

Suggested Simulations for Chapter 15

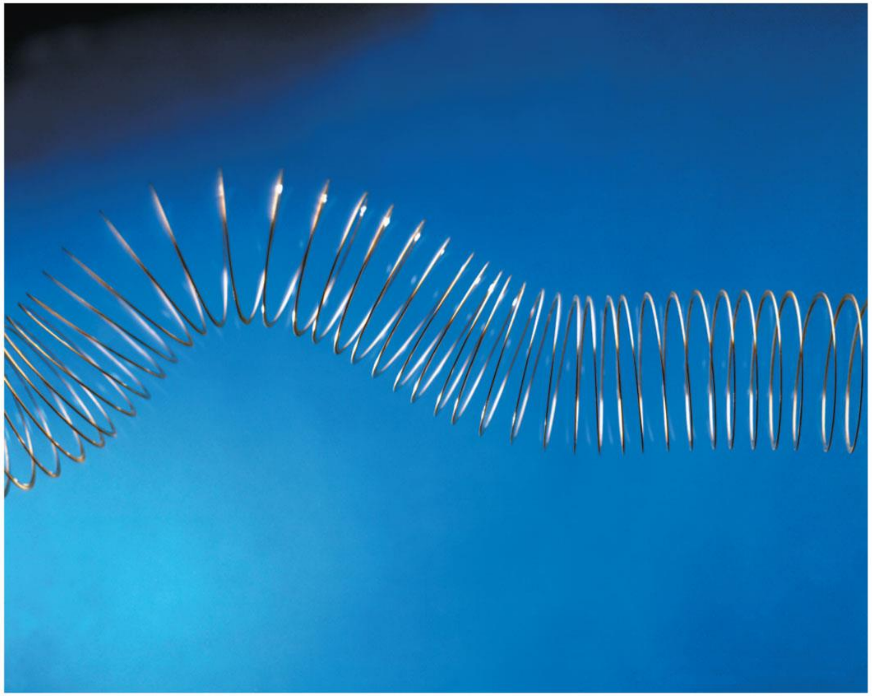
- **ActivPhysics**
  - *10.1–10.3, 10.8, 10.9*
- **PhETs**
  - *Wave Interference*
  - *Wave on a String*
  - *Sound*
  - *Radio Waves and Electromagnetic Fields*

Chapter 15 Traveling Waves and Sound

Chapter Goal: To learn the basic properties of traveling waves.

Chapter 15 Preview
Looking Ahead: Traveling Waves

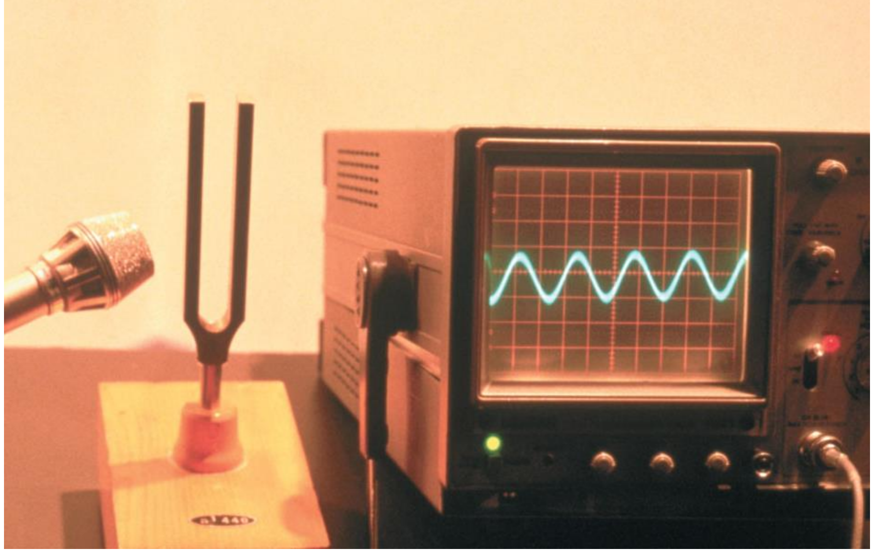
- Shaking one end of the spring up and down causes a disturbance—a wave—to travel along the spring.



- You'll learn the wave model that describes phenomena ranging from light waves to earthquake waves.

Chapter 15 Preview
Looking Ahead: Describing Waves

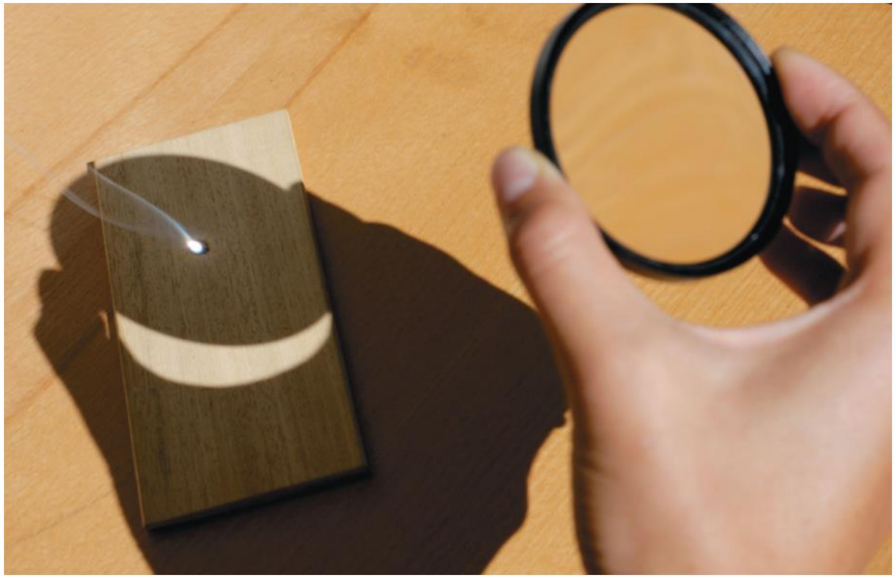
- The microphone picks up the vibrating tuning fork's sound wave. The signal is *sinusoidal*, a form we've seen for oscillations.



- The terms and equations used to describe waves are closely related to those for oscillations, as you'll see.

Chapter 15 Preview
Looking Ahead: Energy and Intensity

- All waves carry energy. The lens focuses sunlight into a small area, where the concentrated energy sets the wood on fire.

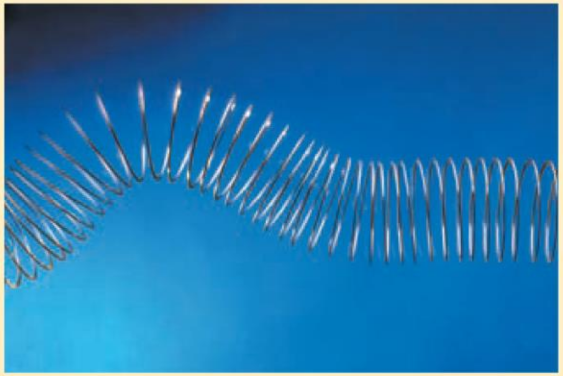


- You'll learn to calculate **intensity**, a measure of how spread out a wave's energy is.

Chapter 15 Preview
Looking Ahead

Traveling Waves

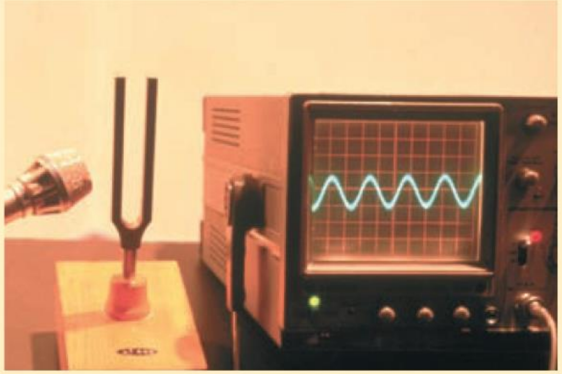
Shaking one end of the spring up and down causes a disturbance—a **wave**—to travel along the spring.



You'll learn the **wave model** that describes phenomena ranging from light waves to earthquake waves.

Describing Waves

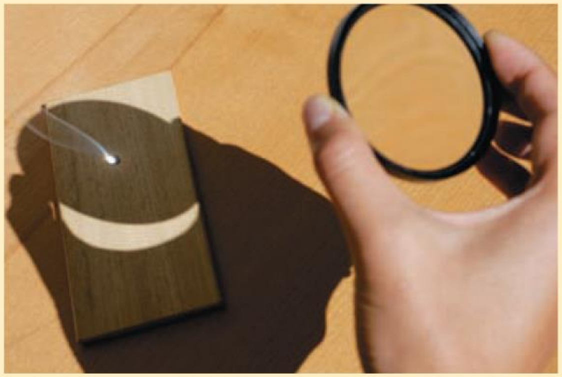
The microphone picks up the vibrating tuning fork's sound wave. The signal is *sinusoidal*, a form we've seen for oscillations.



The terms and equations used to describe waves are closely related to those for oscillations, as you'll see.

Energy and Intensity

All waves carry energy. The lens focuses sunlight into a small area, where the concentrated energy sets the wood on fire.

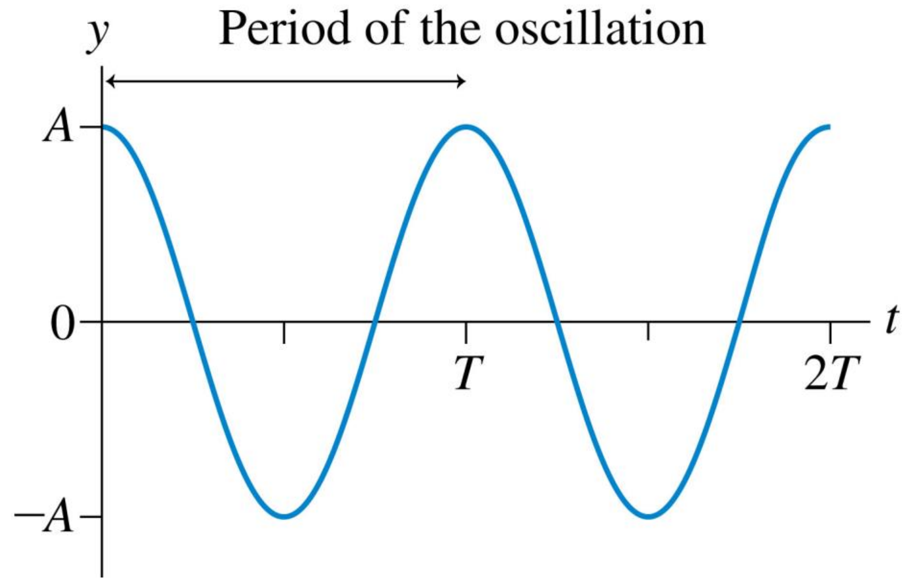


You'll learn to calculate **intensity,** a measure of how spread out a wave's energy is.

Text: p. 470

Chapter 15 Preview
Looking Back: Simple Harmonic Motion

- In Chapter 14, you learned to use the terminology of simple harmonic motion to describe oscillations.
- The terms you learned—such as period, frequency, amplitude—will apply to descriptions of wave motion as well.



Chapter 15 Preview
Stop to Think

A wooden toy hangs from a spring. When you pull it down and release it, it reaches the highest point of its motion after 1.0 s. What is the frequency of the oscillation?

A. 2.0 Hz
B. 1.5 Hz
C. 1.0 Hz
D. 0.5 Hz

Reading Question 15.1

Which of the following is a longitudinal wave?

A. Sound wave
B. Water wave
C. Light wave

Reading Question 15.1

Which of the following is a longitudinal wave?

✔ A. Sound wave
B. Water wave
C. Light wave

Reading Question 15.2

When the particles of a medium move with simple harmonic motion, this means the wave is a

A. Sound wave.
B. Sinusoidal wave.
C. Standing wave.
D. Harmonic wave.
E. Transverse wave.

Reading Question 15.2

When the particles of a medium move with simple harmonic motion, this means the wave is a

A. Sound wave.
✔ B. Sinusoidal wave.
C. Standing wave.
D. Harmonic wave.
E. Transverse wave.

Reading Question 15.3

A 100 Hz sound wave is traveling through the air. If we increase the frequency to 200 Hz, this will _________ the wavelength.

A. Increase
B. Not change
C. Decrease

Reading Question 15.3

A 100 Hz sound wave is traveling through the air. If we increase the frequency to 200 Hz, this will _________ the wavelength.

A. Increase
B. Not change
✔ C. Decrease

Reading Question 15.4

A lens collects light and focuses it into a small spot. This increases the _________ of the light wave.

A. Wavelength
B. Frequency
C. Energy
D. Intensity

Reading Question 15.4

A lens collects light and focuses it into a small spot. This increases the _________ of the light wave.

A. Wavelength
B. Frequency
C. Energy
D. Intensity ✔

Reading Question 15.5

We measure the sound intensity level in units of

A. Watts.
B. Joules.
C. Candelas.
D. Decibels.
E. Hertz.

Reading Question 15.5

We measure the sound intensity level in units of

A. Watts.
B. Joules.
C. Candelas.
✔ D. Decibels.
E. Hertz.

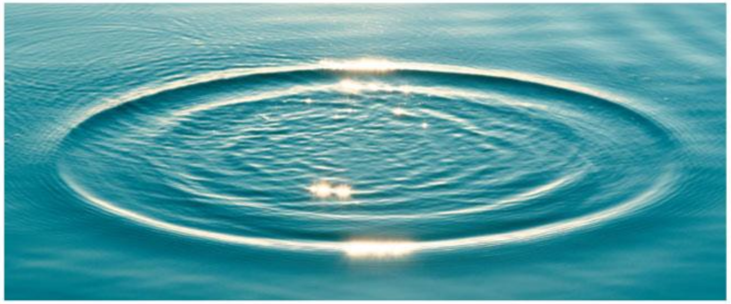
Section 15.1 The Wave Model

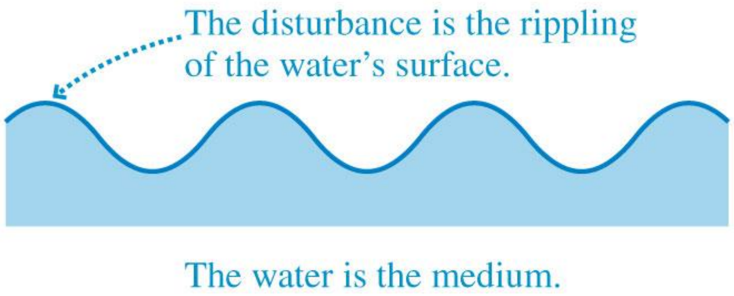
The Wave Model

- The **wave model** describes the basic properties of waves and emphasizes those aspects of wave behavior common to all waves.
- A **traveling wave** is an organized disturbance that travels with a well-defined wave speed.

Mechanical Waves

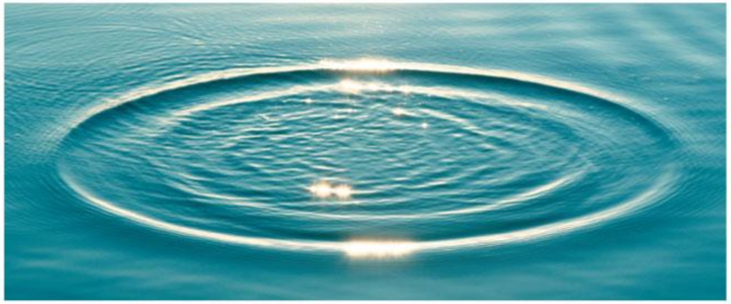
- **Mechanical waves** are waves that involve the motion of the substance through which they move. The substance is the **medium.**
- A **disturbance** is a wave that passes through a medium, displacing the atoms that make up the medium from their equilibrium position.

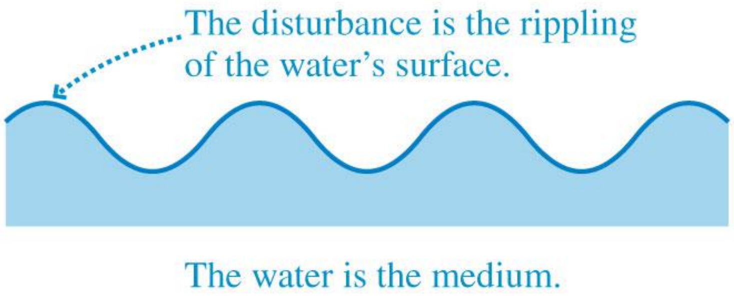




Mechanical Waves

- A wave disturbance is created by a *source*.
- Once created, the disturbance travels outward through the medium at the **wave speed** *v*.
- A wave does transfer *energy*, but **the medium as a whole does not travel.**





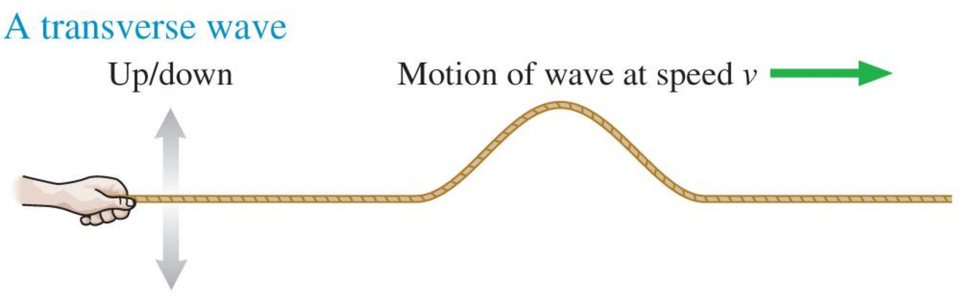
- **A wave transfers energy, but it does not transfer any material or substance outward from the source.**

Electromagnetic and Matter Waves

- **Electromagnetic waves** are waves of an *electromagnetic field*. They include visible light, radio waves, microwaves, and x rays.
- Electromagnetic waves require no material medium and can travel through a vacuum.
- **Matter waves** describe the wave-like characteristics of material particles such as electrons and atoms.

Transverse and Longitudinal Waves

- Most waves fall into two general classes: *transverse* and *longitudinal.*

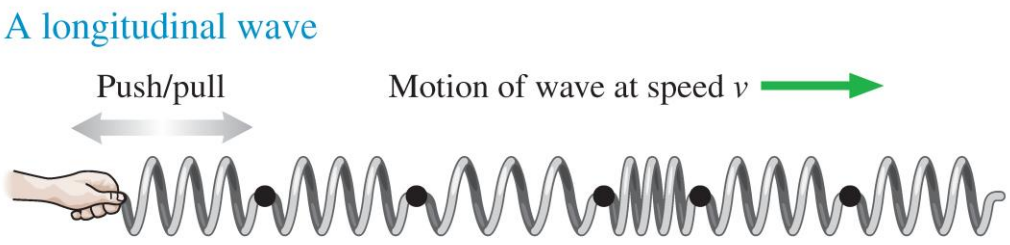


For mechanical waves, a **transverse wave** is a wave in which the particles in the medium move *perpendicular* to the direction in which the wave travels. Shaking the end of a stretched string up and down creates a wave that travels along the string in a horizontal direction while the particles that make up the string oscillate vertically.

Text: p. 472

Transverse and Longitudinal Waves

- Most waves fall into two general classes: *transverse* and *longitudinal.*

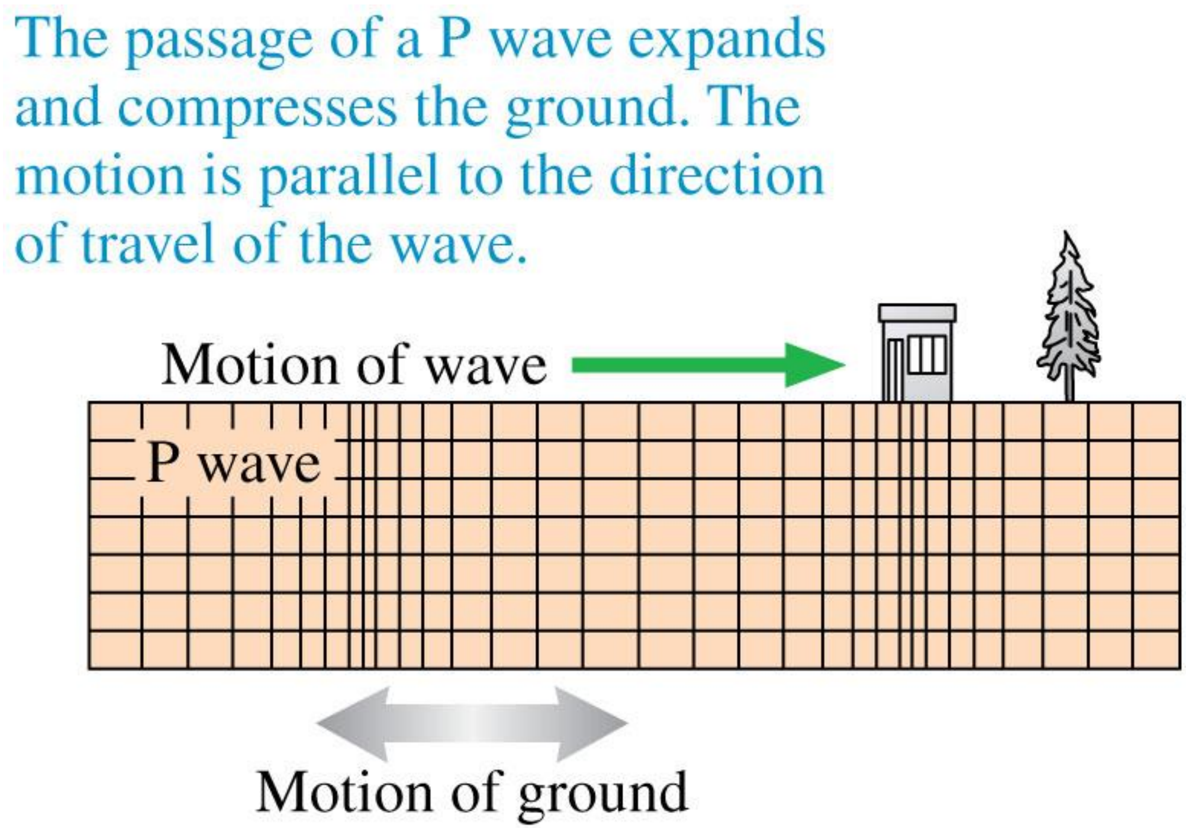


In a **longitudinal wave,** the particles in the medium move *parallel* to the direction in which the wave travels. Here we see a chain of masses connected by springs. If you give the first mass in the chain a sharp push, a disturbance travels down the chain by compressing and expanding the springs.

Text: p. 472

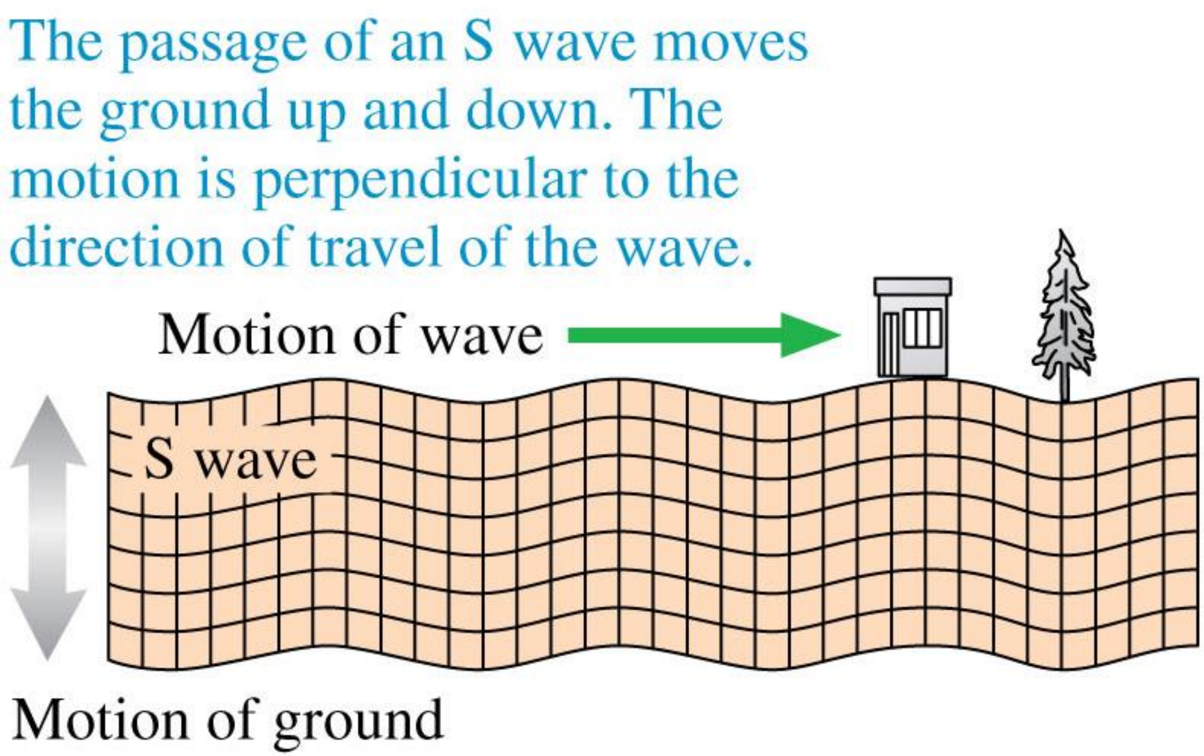
Transverse and Longitudinal Waves

- The two most important types of earthquake waves are S waves (transverse) and P waves (longitudinal).



Transverse and Longitudinal Waves

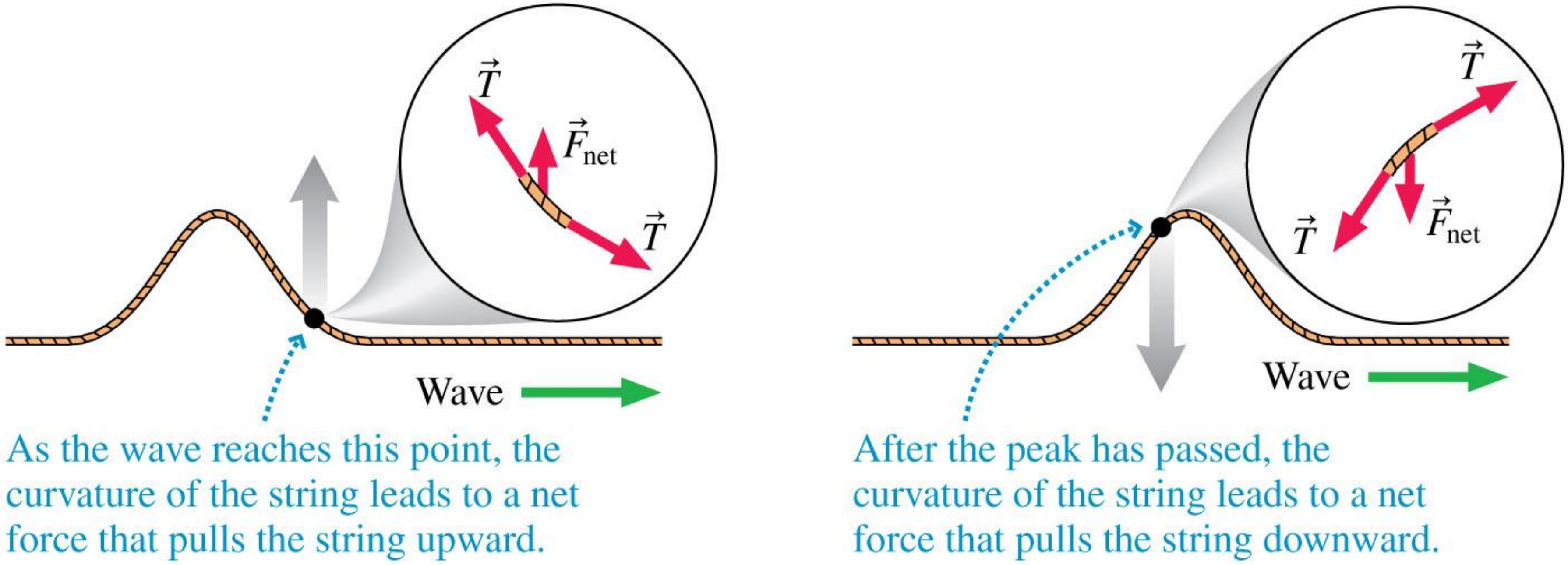
- The P waves are faster, but the S waves are more destructive.



Section 15.2 Traveling Waves

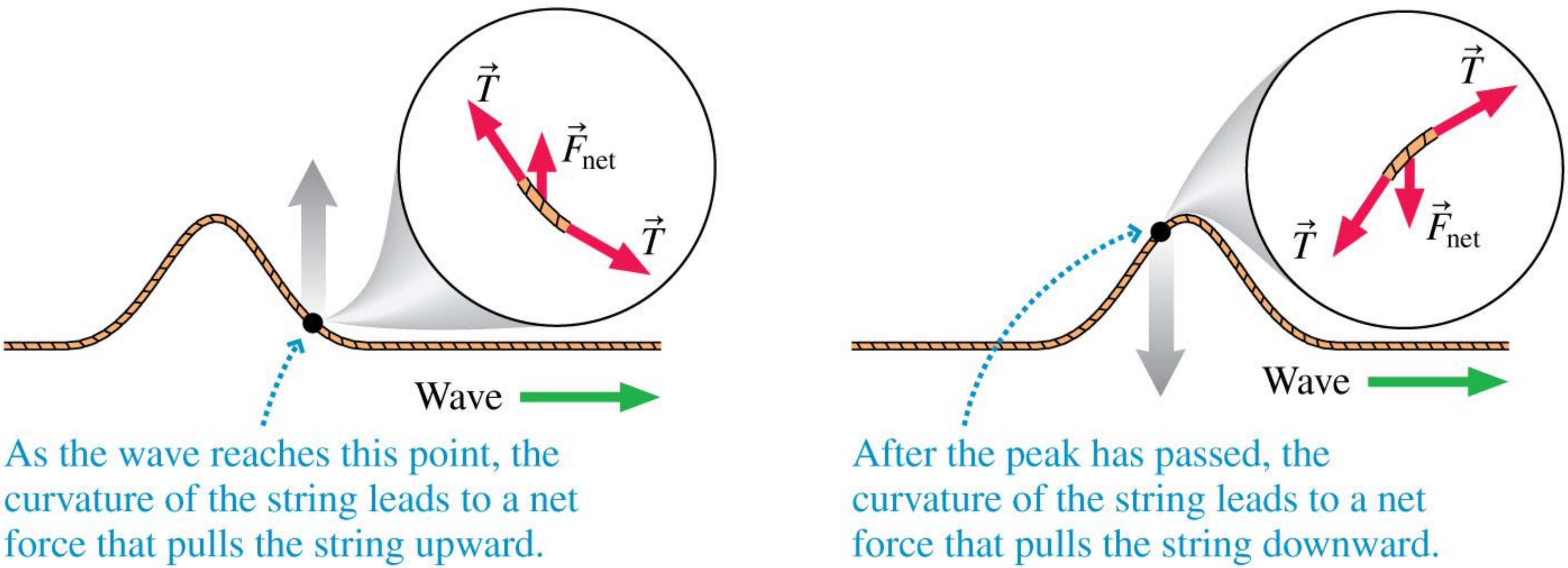
Waves on a String

- A transverse *wave pulse* traveling along a stretched string is shown below.



Waves on a String

- The curvature of the string due to the wave leads to a net force that pulls a small segment of the string upward or downward.



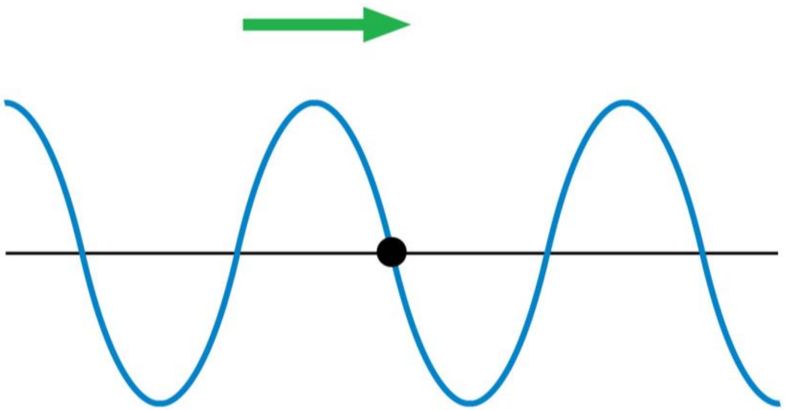
Waves on a String

- Each point on the string moves perpendicular to the motion of the wave, so **a wave on a string is a transverse wave.**
- An external force created the pulse, but **once started, the pulse continues to move because of the internal dynamics of the medium.**

QuickCheck 15.15

A wave on a string is traveling to the right. At this instant, the motion of the piece of string marked with a dot is

A. Up.
B. Down.
C. Right.
D. Left.
E. Zero, instantaneously at rest.



QuickCheck 15.15

A wave on a string is traveling to the right. At this instant, the motion of the piece of string marked with a dot is

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B. Down.
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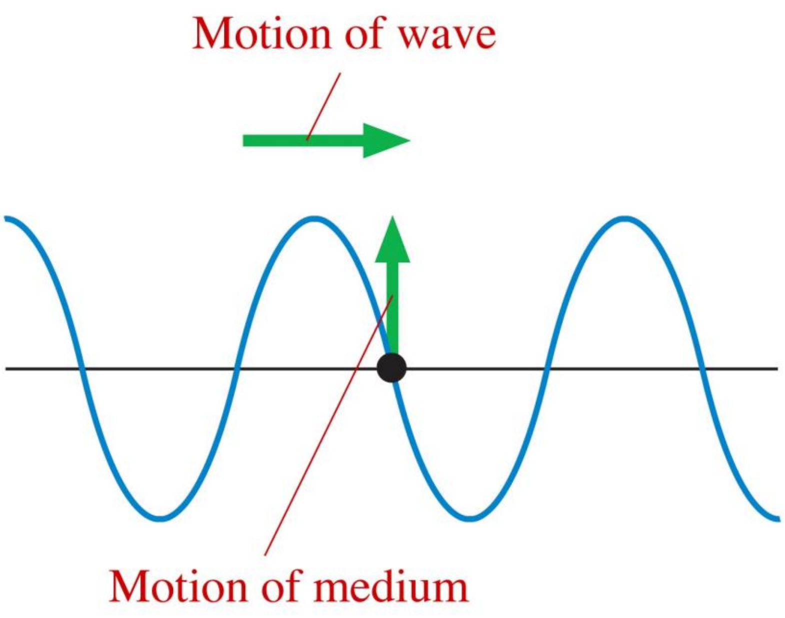
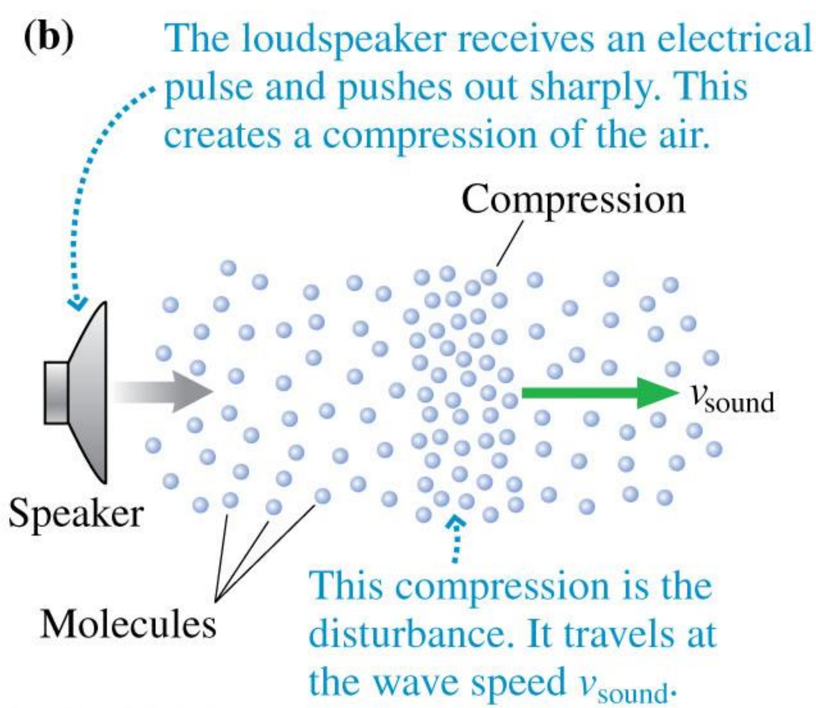


Sound Waves

- When a loudspeaker cone moves forward, it compresses the air in front of it.
- The *compression* is the disturbance that travels through the air.

Sound Waves

- A **sound wave is a longitudinal wave**.
- The motion of the sound wave is determined by the properties of the air.



Wave Speed Is a Property of the Medium

- **The wave speed does not depend on the size and shape of the pulse, how the pulse was generated or how far it has traveled**—only the medium that carries the wave.
- The speed depends on the mass-to-length ratio, the **linear density** of the string:

$$\mu = \frac{m}{L}$$

Wave Speed Is a Property of the Medium

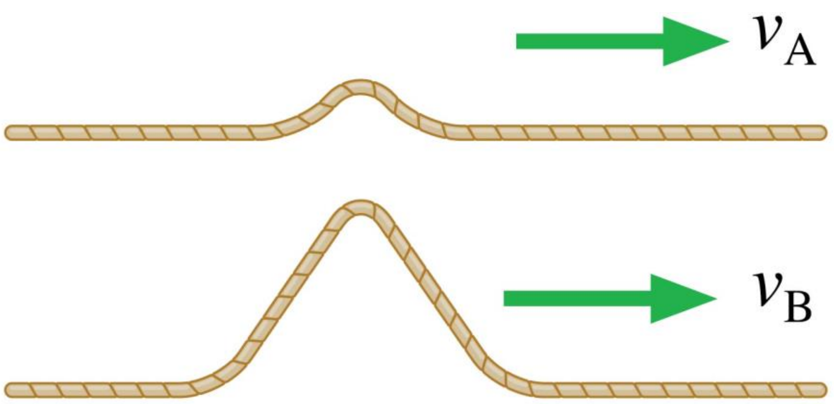
- A string with a greater tension responds more rapidly, so the wave will move at a higher speed. **Wave speed increases with increasing tension.**
- A string with a greater linear density has more inertia. It will respond less rapidly, so the wave will move at a lower speed. **Wave speed decreases with increasing linear density.**

$$v_{\text{string}} = \sqrt{\frac{T_s}{\mu}}$$

Wave speed on a stretched string with tension T_s and linear density μ

QuickCheck 15.1

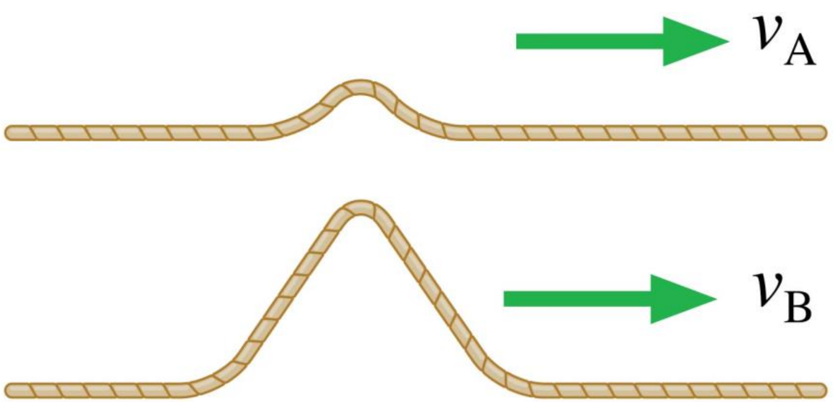
These two wave pulses travel along the same stretched string, one after the other. Which is true?



A. $v_A > v_B$
B. $v_B > v_A$
C. $v_A = v_B$
D. Not enough information to tell

QuickCheck 15.1

These two wave pulses travel along the same stretched string, one after the other. Which is true?



A. $v_A > v_B$
B. $v_B > v_A$
✔ C. $v_A = v_B$
D. Not enough information to tell

Wave speed depends on the properties of the medium, not on the amplitude of the wave.

QuickCheck 15.2

For a wave pulse on a string to travel twice as fast, the string tension must be

A. Increased by a factor of 4.
B. Increased by a factor of 2.
C. Decreased to one half its initial value.
D. Decreased to one fourth its initial value.
E. Not possible. The pulse speed is always the same.

QuickCheck 15.2

For a wave pulse on a string to travel twice as fast, the string tension must be

✔ A. Increased by a factor of 4.
B. Increased by a factor of 2.
C. Decreased to one half its initial value.
D. Decreased to one fourth its initial value.
E. Not possible. The pulse speed is always the same.

Example 15.1 When does the spider sense his lunch?

All spiders are very sensitive to vibrations. An orb spider will sit at the center of its large, circular web and monitor radial threads for vibrations created when an insect lands. Assume that these threads are made of silk with a linear density of 1.0×10^{-5} kg/m under a tension of 0.40 N, both typical numbers. If an insect lands in the web 30 cm from the spider, how long will it take for the spider to find out?

Example 15.1 When does the spider sense his lunch? (cont.)

PREPARE When the insect hits the web, a wave pulse will be transmitted along the silk fibers. The speed of the wave depends on the properties of the silk.

Example 15.1 When does the spider sense his lunch? (cont.)

SOLVE First, we determine the speed of the wave:

$$v = \sqrt{\frac{T_s}{\mu}} = \sqrt{\frac{0.40\text{ N}}{1.0 \times 10^{-5}\text{ kg/m}}} = 200\text{ m/s}$$

The time for the wave to travel a distance d = 30 cm to reach the spider is

$$\Delta t = \frac{d}{v} = \frac{0.30\text{ m}}{200\text{ m/s}} = 1.5\text{ ms}$$

Example 15.1 When does the spider sense his lunch? (cont.)

ASSESS Spider webs are made of very light strings under significant tension, so the wave speed is quite high and we expect a short travel time—important for the spider to quickly respond to prey caught in the web. Our answer makes sense.

Wave Speed Is a Property of the Medium

- Sound speed is slightly less than the rms speed of the molecules of the gas medium, though it does have the same dependence on temperature and molecular mass:

$$v_{\text{sound}} = \sqrt{\frac{\gamma k_B T}{m}} = \sqrt{\frac{\gamma R T}{M}}$$

Sound speed in a gas at temperature T

- M is the molar mass and γ is a constant that depends on the gas.

Wave Speed Is a Property of the Medium

- The speed of sound in air (and other gases) increases with temperature. **For calculations in this chapter, you can use the speed of sound in air at 20°C, 343 m/s, unless otherwise specified.**
- At a given temperature, the speed of sound increases as the molecular mass of the gas decreases. Thus the speed of sound in room-temperature helium is faster than that in room-temperature air.
- The speed of sound doesn't depend on the pressure or the density of the gas.

Wave Speed Is a Property of the Medium

TABLE 15.1 The speed of sound

Medium	Speed (m/s)
Air (0°C)	331
Air (20°C)	343
Helium (0°C)	970
Ethyl alcohol	1170
Water	1480
Human tissue (ultrasound)	1540
Lead	1200
Aluminum	5100
Granite	6000
Diamond	12,000

QuickCheck 15.13

A wave bounces back and forth on a guitar string; this is responsible for making the sound of the guitar. As the temperature of the string rises, the tension decreases. This _______ the speed of the wave on the string.

A. Increases
B. Does not change
C. Decreases

QuickCheck 15.13

A wave bounces back and forth on a guitar string; this is responsible for making the sound of the guitar. As the temperature of the string rises, the tension decreases. This _______ the speed of the wave on the string.

A. Increases
B. Does not change
✔ C. Decreases

Wave Speed Is a Property of the Medium

- The **speed of light** c is the speed that all electromagnetic waves travel in a vacuum.
- The value of the speed of light is

$$v_{\text{light}} = c = 3.00 \times 10^8 \text{ m/s}$$

- Although light travels more slowly in air than in a vacuum, this value is still a good approximation for the speed of electromagnetic waves through air.

Example 15.3 How far away was the lightning?

During a thunderstorm, you see a flash from a lightning strike. 8.0 seconds later, you hear the crack of the thunder. How far away did the lightning strike?

Example 15.3 How far away was the lightning? (cont.)

PREPARE Two different kinds of waves are involved, with very different wave speeds. The flash of the lightning generates light waves; these waves travel from the point of the strike to your position very quickly. The strike also generates the sound waves that you hear as thunder; these waves travel much more slowly.

Example 15.3 How far away was the lightning? (cont.)

The time for light to travel 1 mile (1610 m) is

$$\Delta t = \frac{d}{v} = \frac{1610\ \text{m}}{3.00 \times 10^8\ \text{s}} = 5.37 \times 10^{-6}\ \text{s} \approx 5\ \mu\text{s}$$

We are given the time to an accuracy of only 0.1 s, so it's clear that we can ignore the travel time for the light flash! The delay between the flash and the thunder is simply the time it takes for the sound wave to travel.

Example 15.3 How far away was the lightning? (cont.)

SOLVE We will assume that the speed of sound has its room temperature (20°C) value of 343 m/s. During the time between seeing the flash and hearing the thunder, the sound travels a distance

$$d = v\,\Delta t = (343\text{ m/s})(8.0\text{ s}) = 2.7 \times 10^{3}\text{ m} = 2.7\text{ km}$$

Example 15.3 How far away was the lightning? (cont.)

ASSESS This seems reasonable. As you know from casual observations of lightning storms, an 8-second delay between the flash of the lightning and the crack of the thunder means a strike that is close but not too close. A few km seems reasonable.

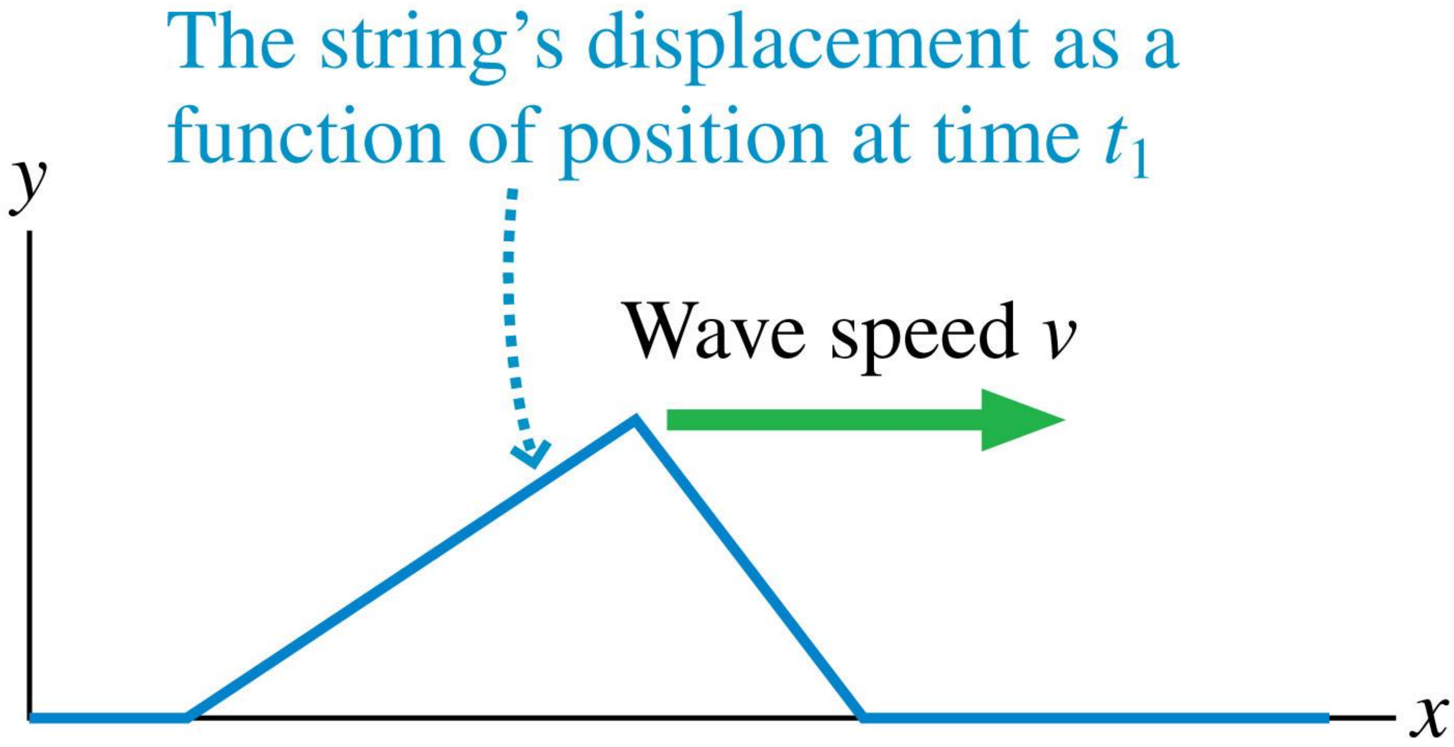
Try It Yourself: Distance to a Lightning Strike

Sound travels approximately 1 km in 3s, or 1 mi in 5 s. When you see a lightning flash, start counting seconds. When you hear the thunder, stop counting. Divide the result by 3, and you will have the approximate distance to the lightning strike in kilometers; divide by 5 and you have the approximate distance in miles.

Section 15.3 Graphical and Mathematical Descriptions of Waves

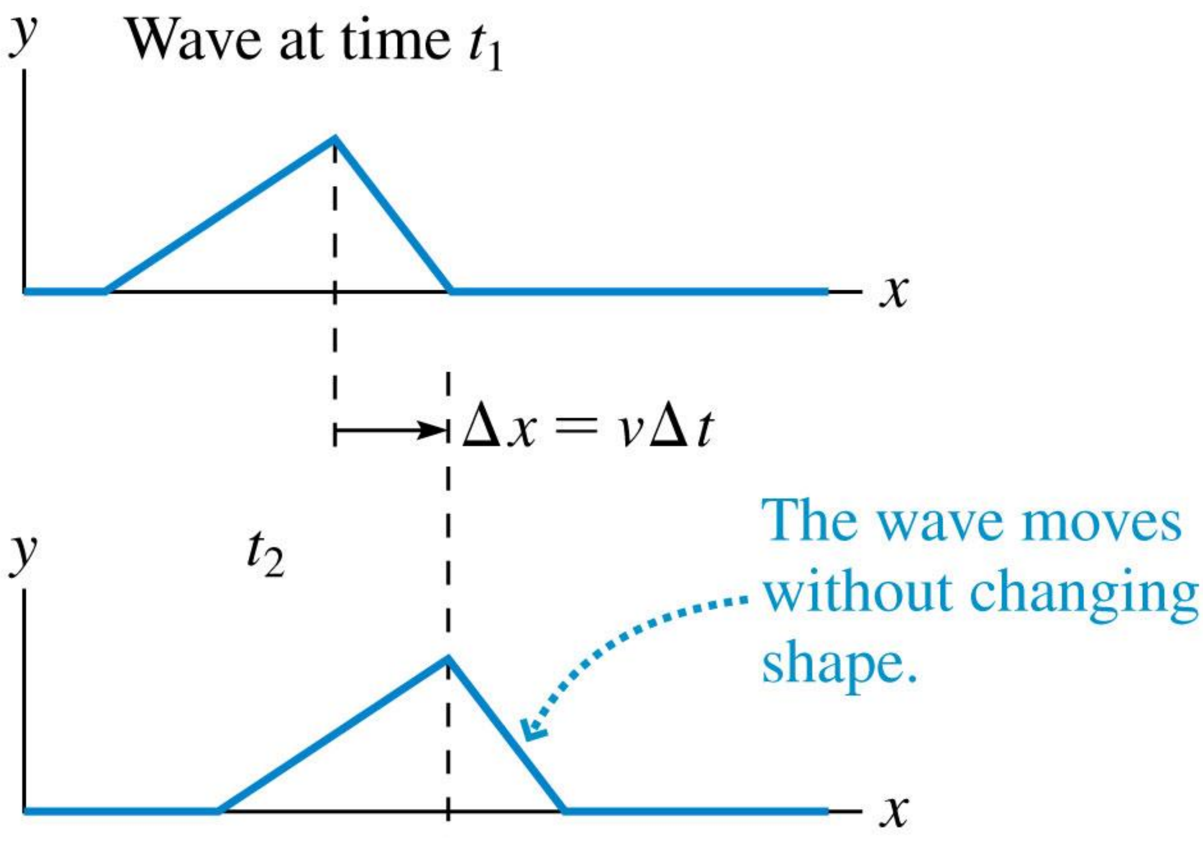
Snapshot and History Graphs

- A **snapshot graph** shows a wave's displacement as a function of position at a single instant of time.



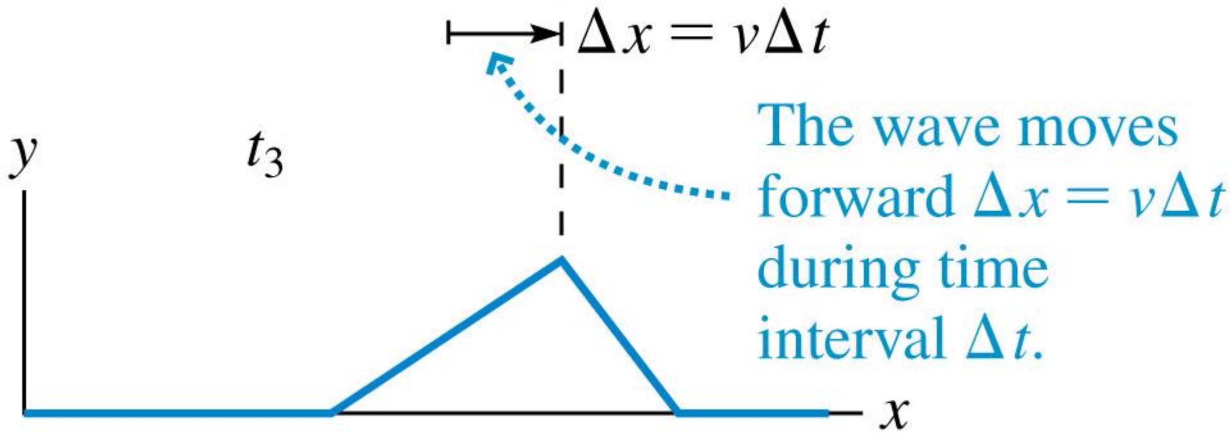
Snapshot and History Graphs

- As the wave moves, we can plot a sequence of snapshot graphs



Snapshot and History Graphs

- These graphs show the motion of the wave, but not the motion of the *medium*.

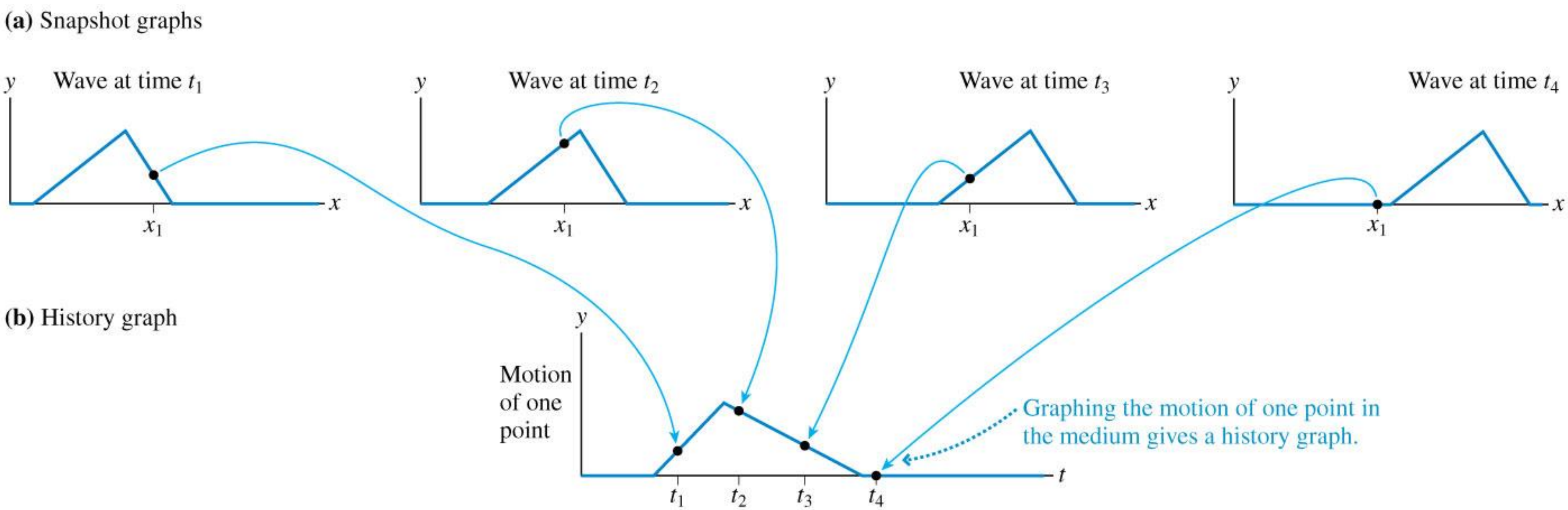


Snapshot and History Graphs

- If we study a dot on a string as a wave moves through it, we can plot a series of snapshot graphs.
- From them we can graph the motion of the single dot over time.

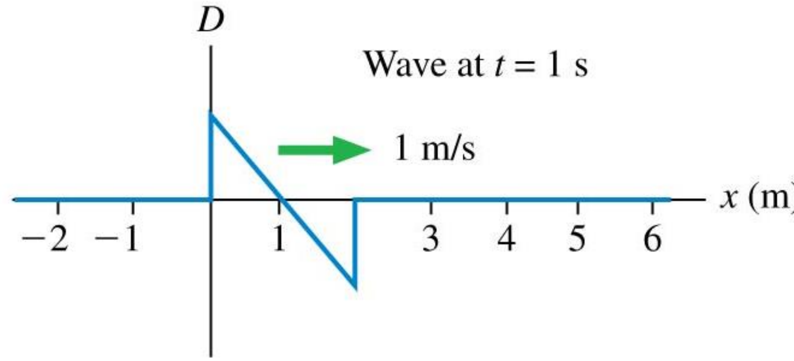
Snapshot and History Graphs

- This is called a history graph because it shows the time evolution a particular point of a medium.

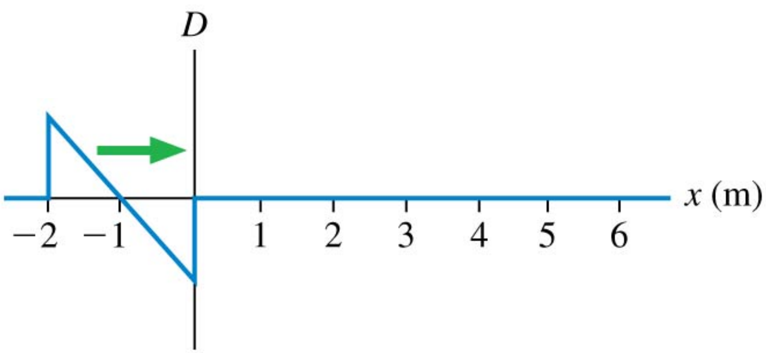


QuickCheck 15.3

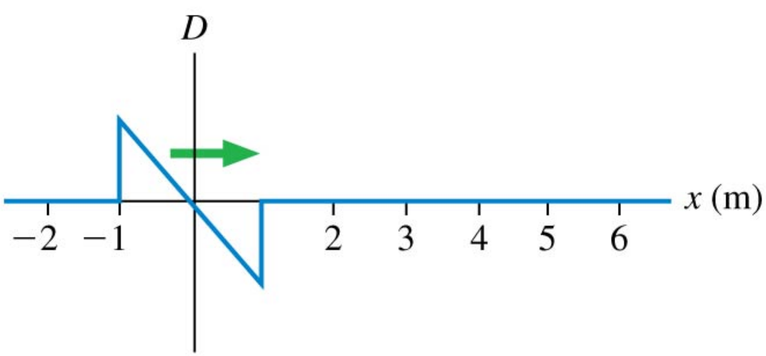
This is a snapshot graph at $t = 1$ s of a wave pulse traveling to the right at 1 m/s. Which graph below shows the wave pulse at $t = -1$ s?



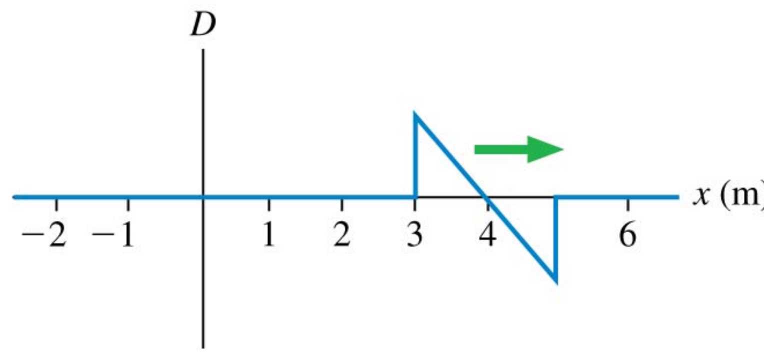
A.



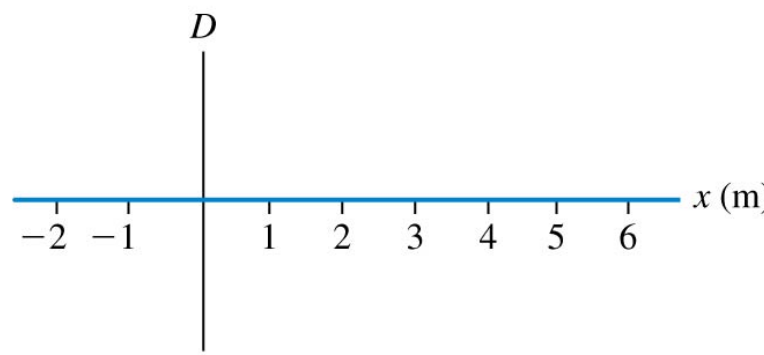
B.



C.



D.



QuickCheck 15.3

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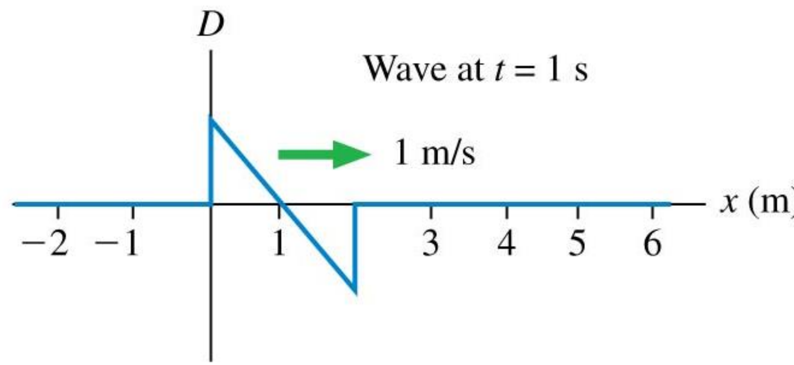
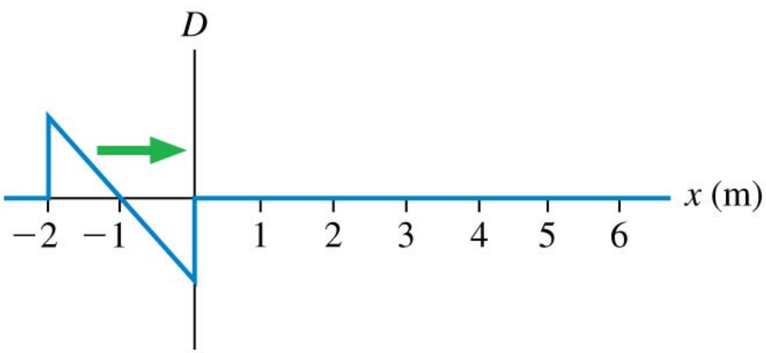
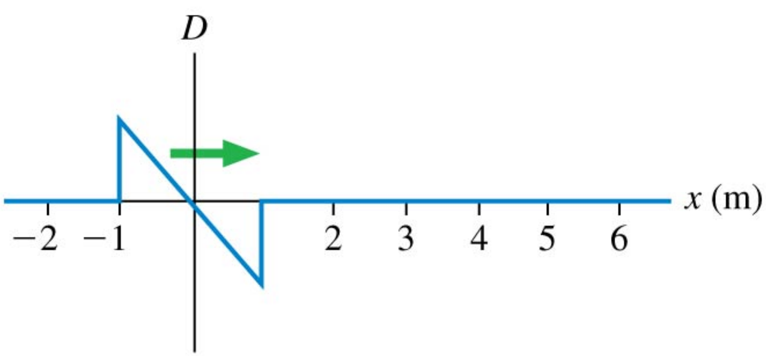


✔ A.



B.



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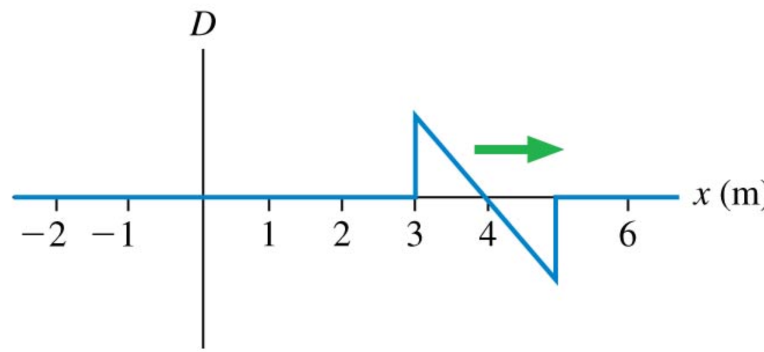

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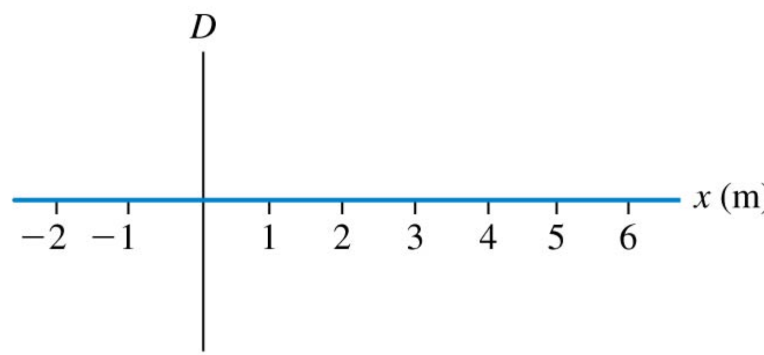
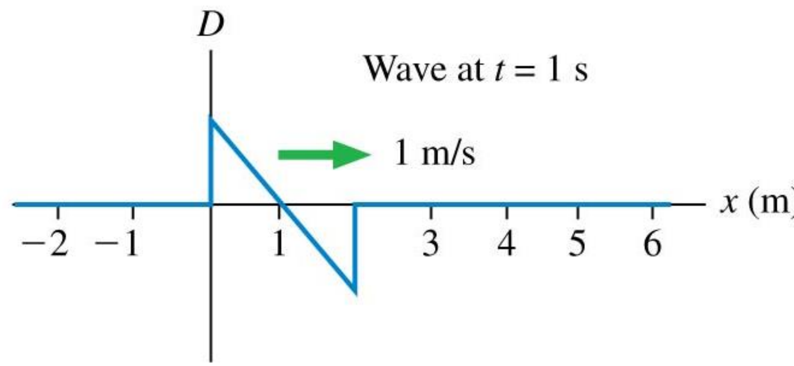
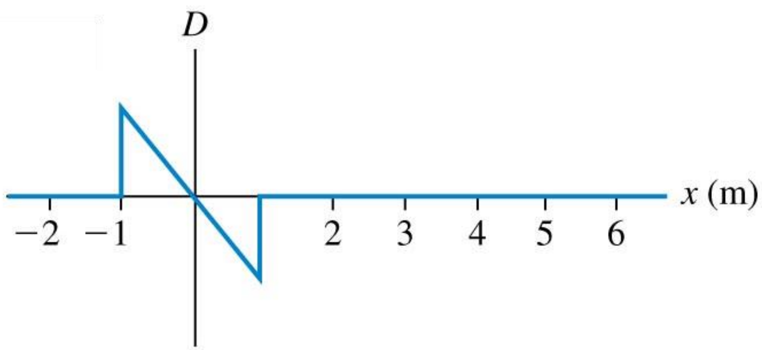


QuickCheck 15.4

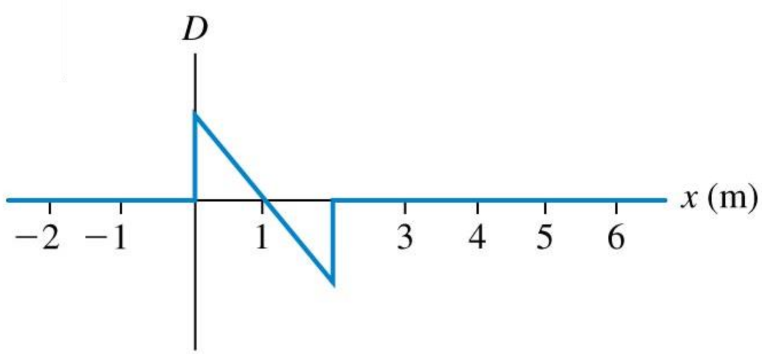
This is a snapshot graph at $t = 1$ s of a wave pulse traveling to the right at 1 m/s. Which graph below shows the history graph at $x = 1$ m?



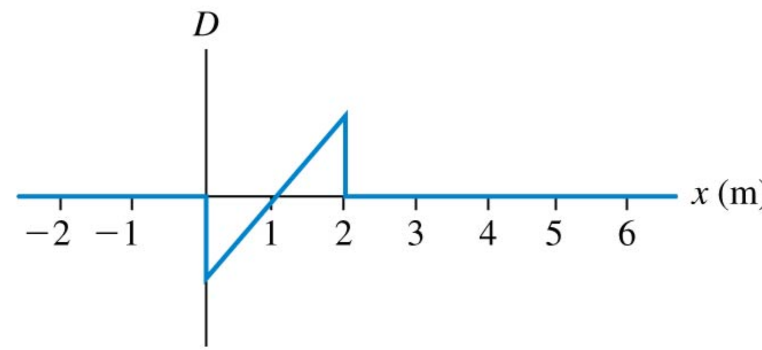
A.



B.



C.



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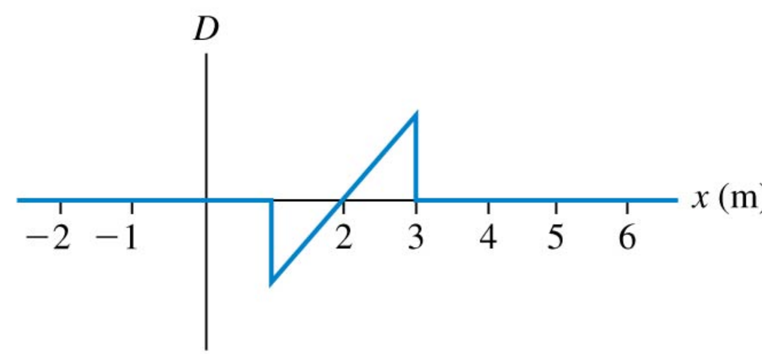
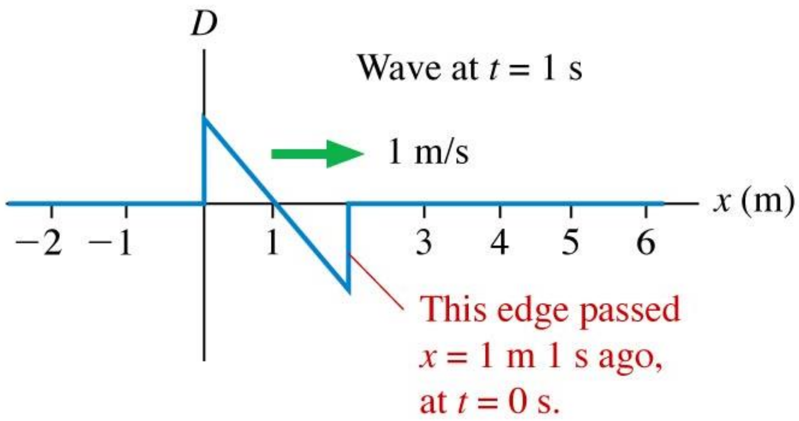
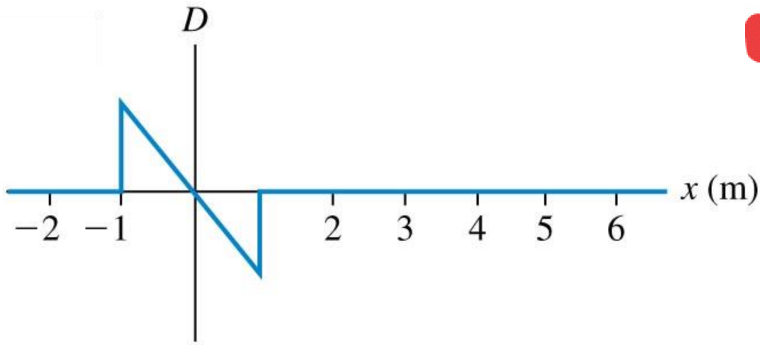


QuickCheck 15.4

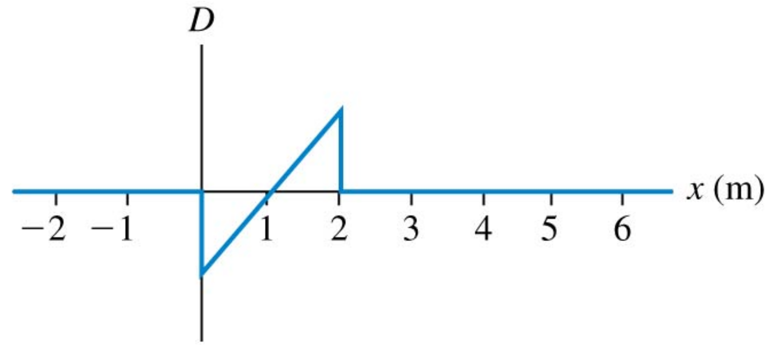
This is a snapshot graph at $t = 1$ s of a wave pulse traveling to the right at 1 m/s. Which graph below shows the history graph at $x = 1$ m?



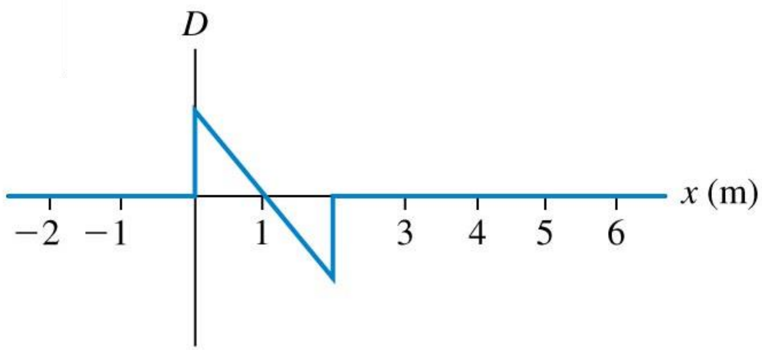
A.



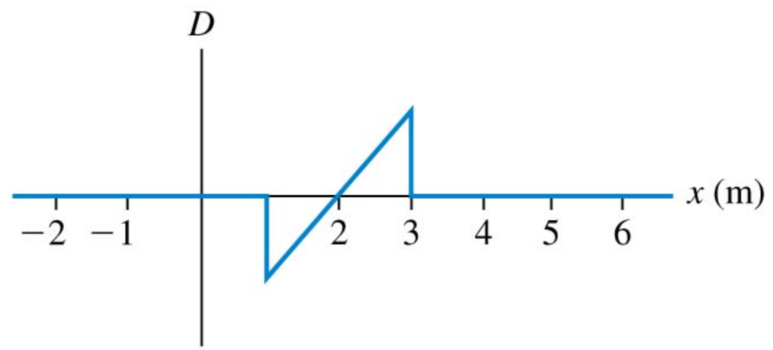
C.



B.

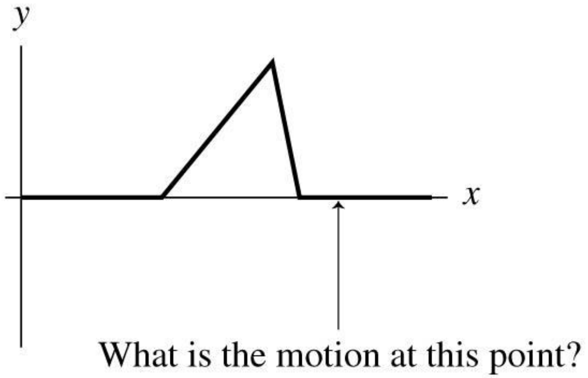


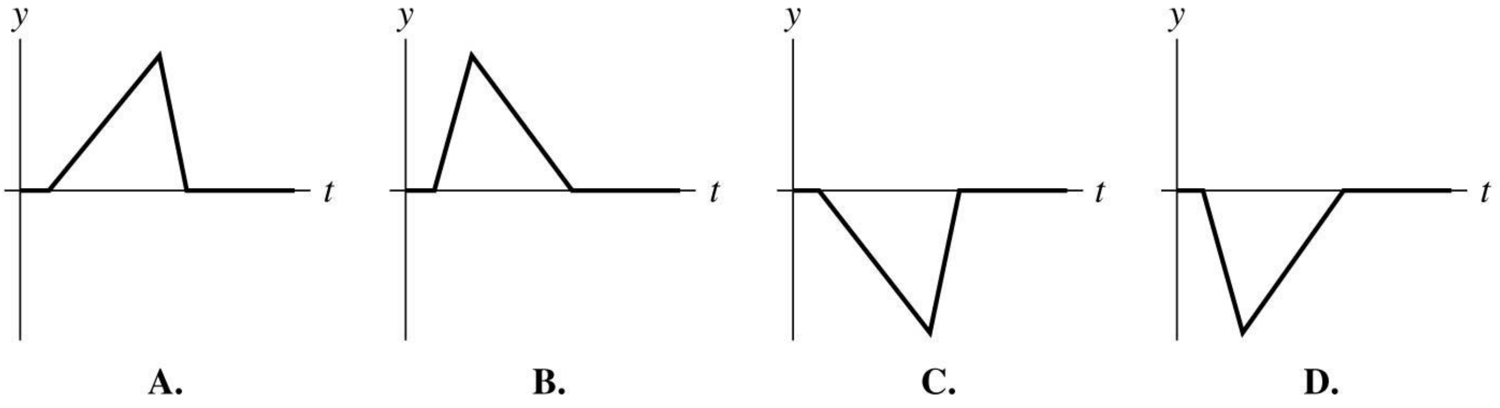
D.



QuickCheck 15.5

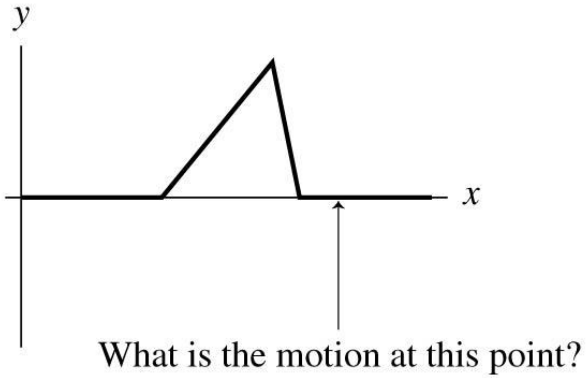
The graph below shows a snapshot graph of a wave on a string that is moving to the right. A point on the string is noted. Which of the choices is the correct history graph for the subsequent motion of this point?

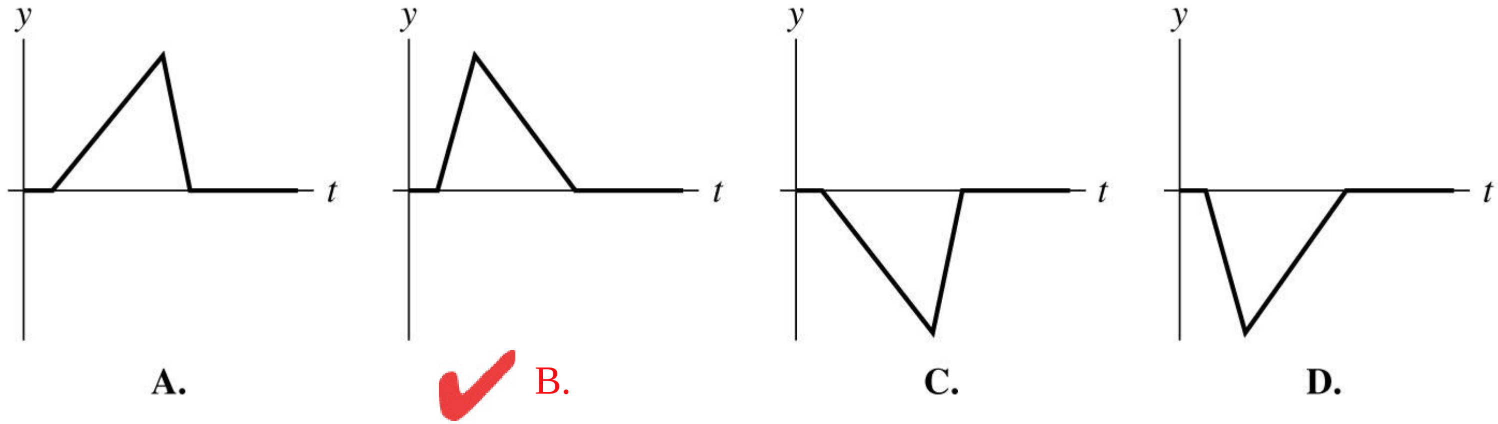




QuickCheck 15.5

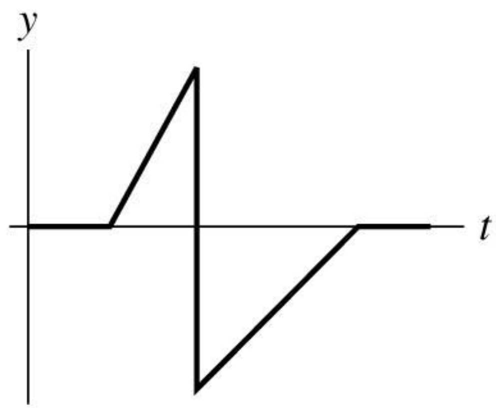
The graph below shows a snapshot graph of a wave on a string that is moving to the right. A point on the string is noted. Which of the choices is the correct history graph for the subsequent motion of this point?

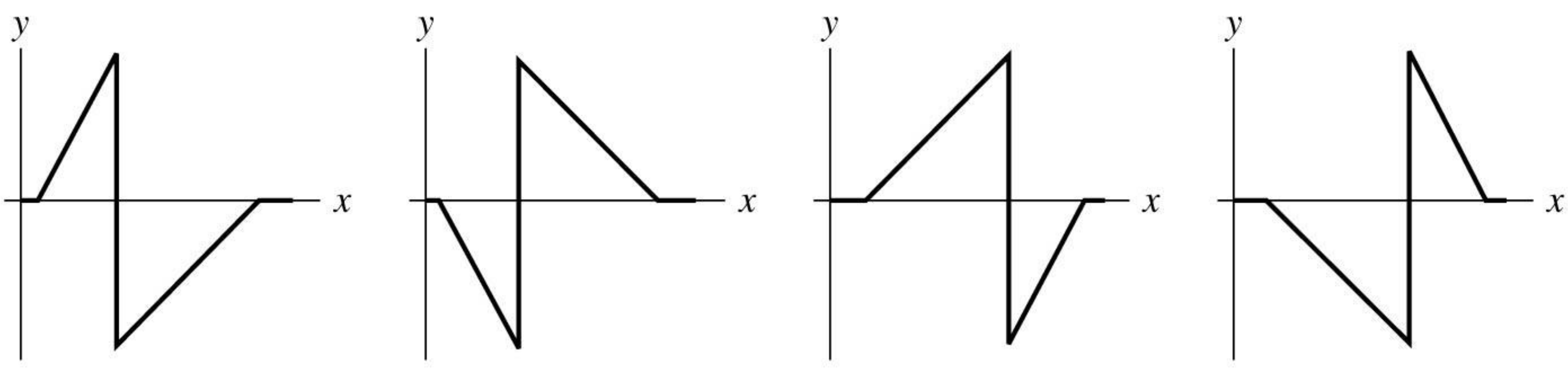




QuickCheck 15.6

The graph below shows a history graph of the motion of one point on a string as a wave moves by to the right. Which of the choices is the correct snapshot graph for the motion of the string?

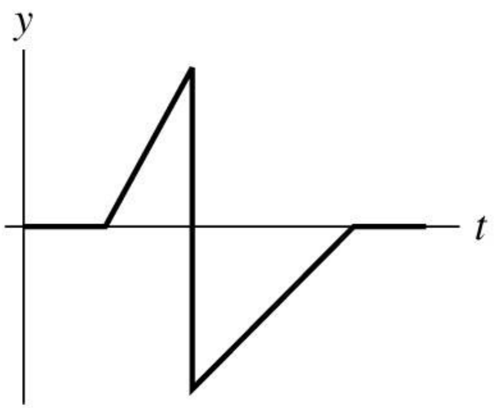


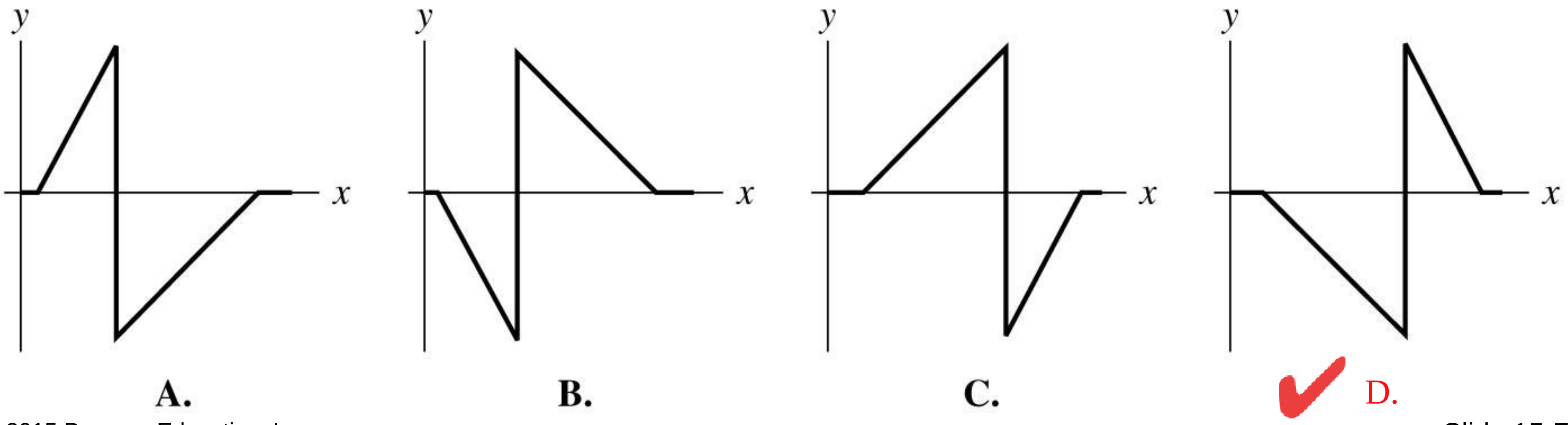


A. B. C. D.

QuickCheck 15.6

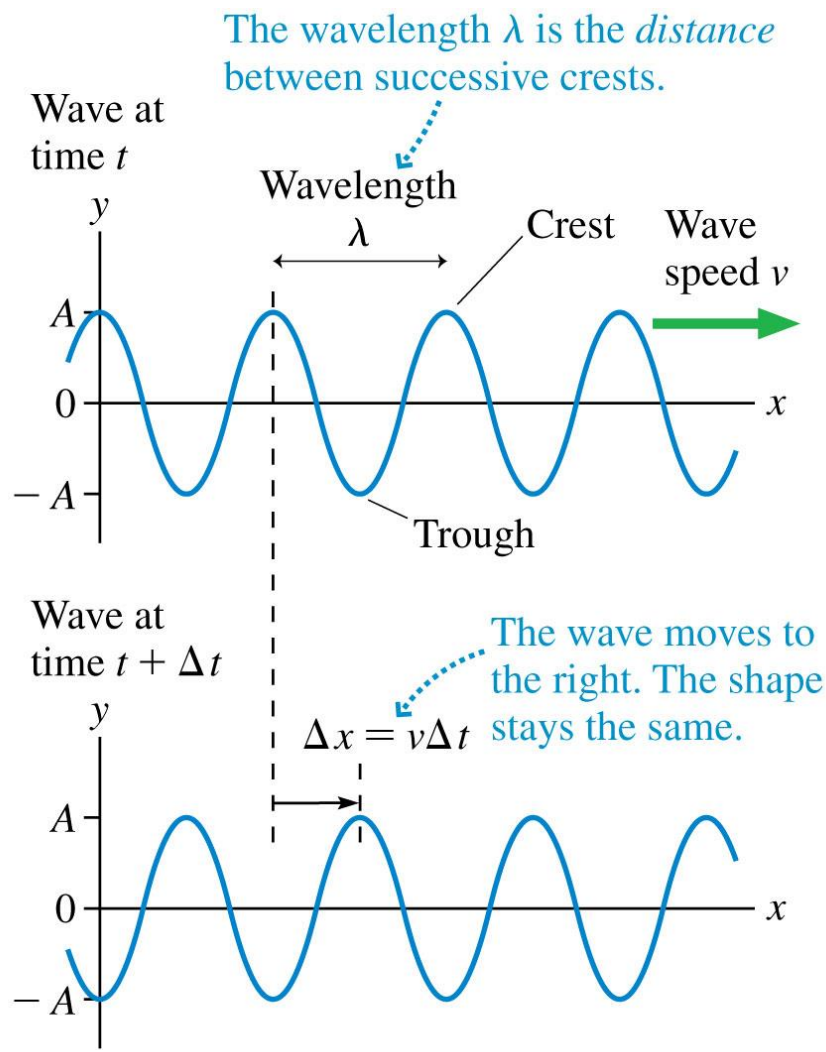
The graph below shows a history graph of the motion of one point on a string as a wave moves by to the right. Which of the choices is the correct snapshot graph for the motion of the string?





Sinusoidal Waves

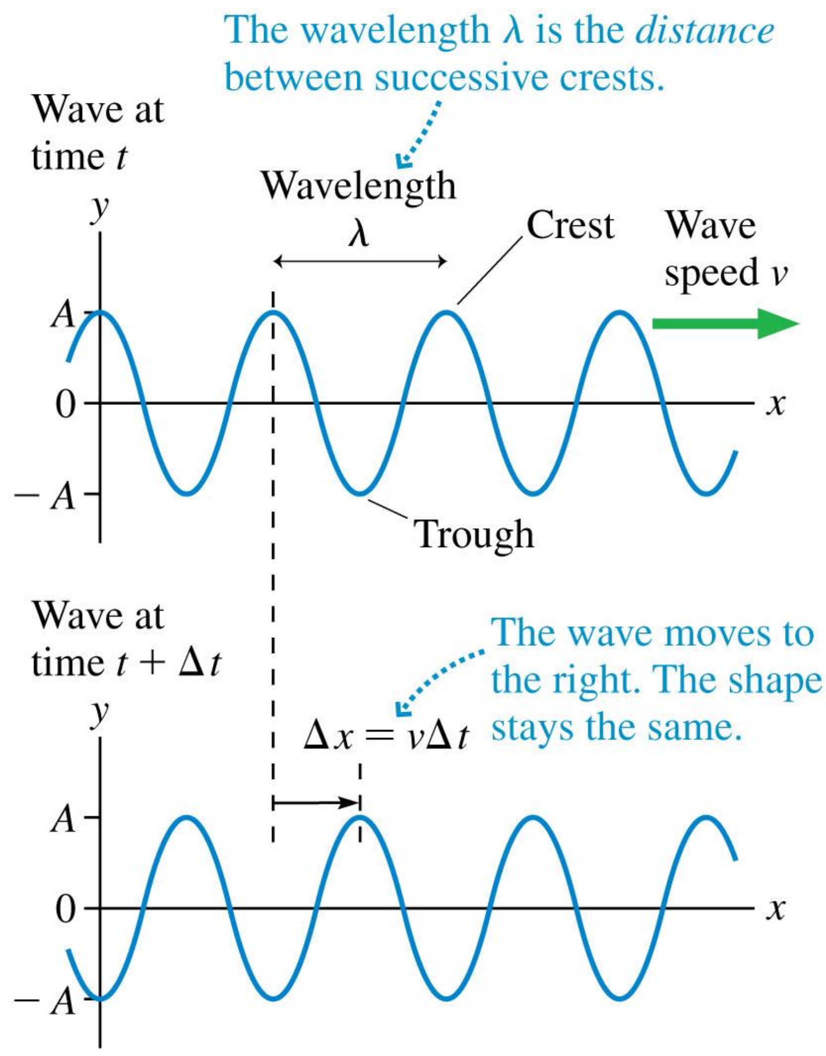
- A **sinusoidal wave** is the type of wave produced by a source that oscillates with simple harmonic motion (SHM).
- The **amplitude** *A* is the maximum value of displacement.
- The crests have displacement of *A* and the troughs have a displacement of –*A*.



Sinusoidal Waves

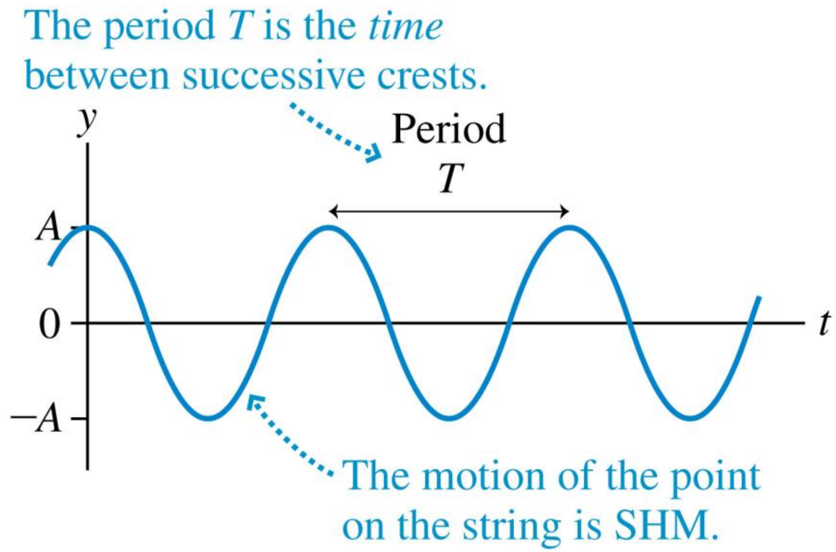
- The wave, like SHM, is repetitive.
- The **wavelength** λ is the distance spanned in one cycle of the motion.
- At time t, the displacement as a function of distance is

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



Sinusoidal Waves

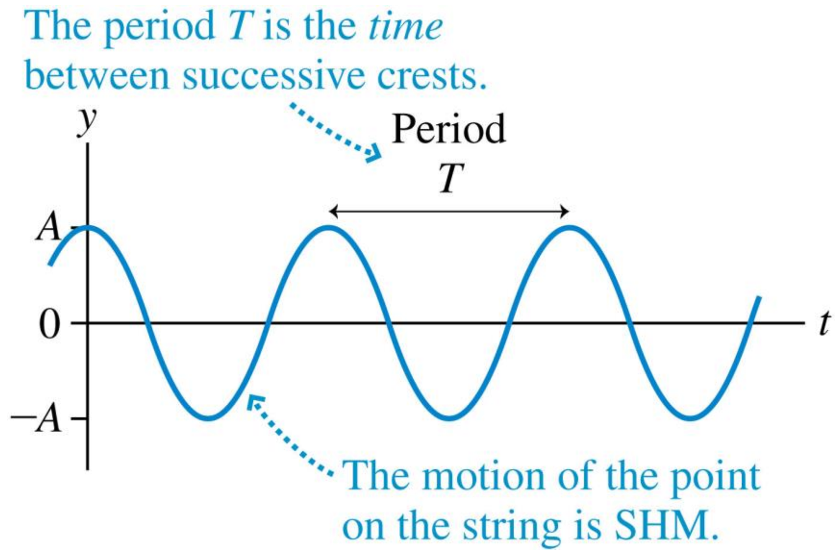
- A history graph of the motion of one point of the medium as a function of time is also sinusoidal. **Each point in the medium oscillates with simple harmonic motion as the wave passes.**



Sinusoidal Waves

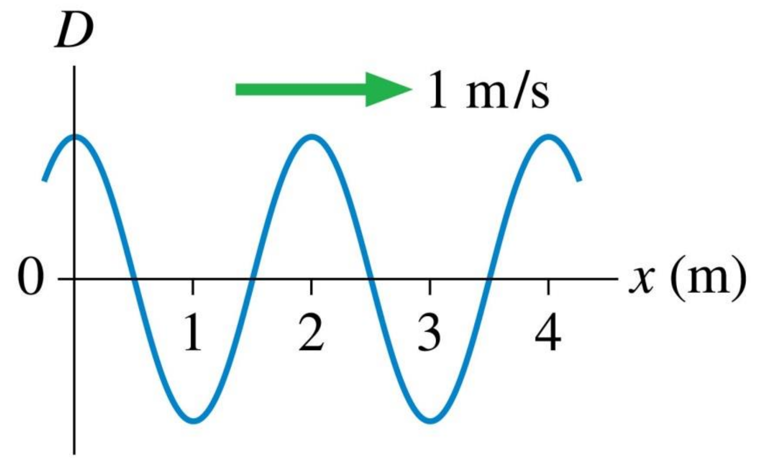
- The period T of the wave is the time interval to complete one cycle of motion.
- The wave *frequency* is related to the period $T = 1/f$, exactly the same as in SHM. Therefore the motion of the point is

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



QuickCheck 15.7

The period of this wave is



A. 1 s

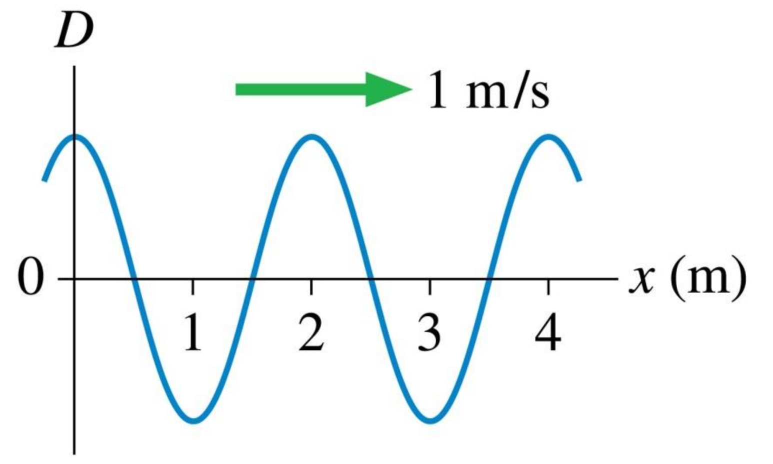
B. 2 s

C. 4 s

D. Not enough information to tell

QuickCheck 15.7

The period of this wave is



A. 1 s
B. 2 s
C. 4 s
D. Not enough information to tell

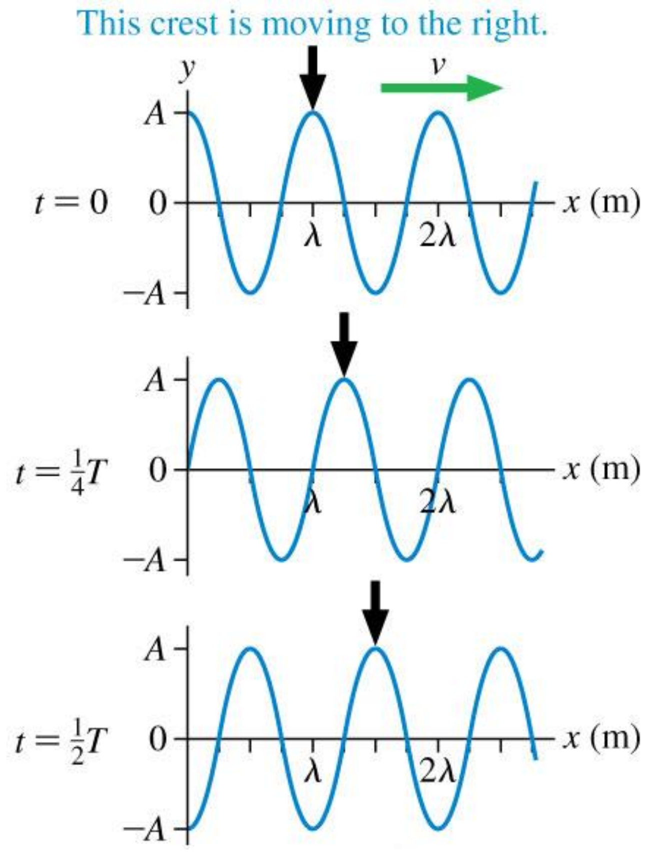
A sinusoidal wave moves forward one wavelength (2 m) in one period.

Sinusoidal Waves

- We combine the mathematical expressions for the displacement as a function of position at one time and the displacement as a function of time at one position:

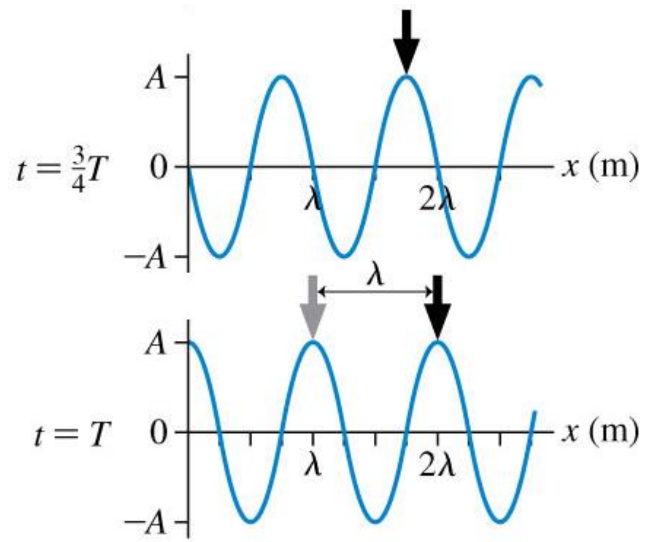
$$y(x, t) = A \cos\left(2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right)$$

Displacement of a traveling wave moving to the right with amplitude A, wavelength λ, and period T



Sinusoidal Waves

- In the snapshots the wave moves an entire wavelength to the right. At the same time, each point in the medium has undergone one complete oscillation as well.
- For a wave travelling to the left, the equation is



During a time interval of exactly one period, the crest has moved forward exactly one wavelength.

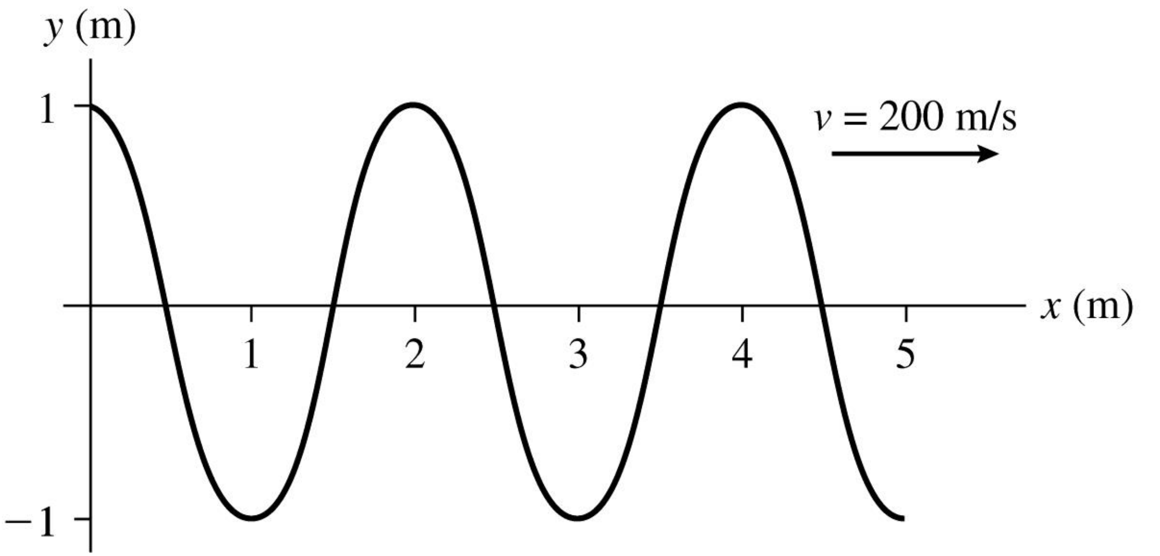
$$y(x,t) = A\cos\left(2\pi\left(\frac{x}{\lambda} + \frac{t}{T}\right)\right)$$

Displacement of a traveling wave moving to the left

QuickCheck 15.8

For this sinusoidal wave, what is the amplitude?

A. 0.5 m
B. 1 m
C. 2 m
D. 4 m



QuickCheck 15.8

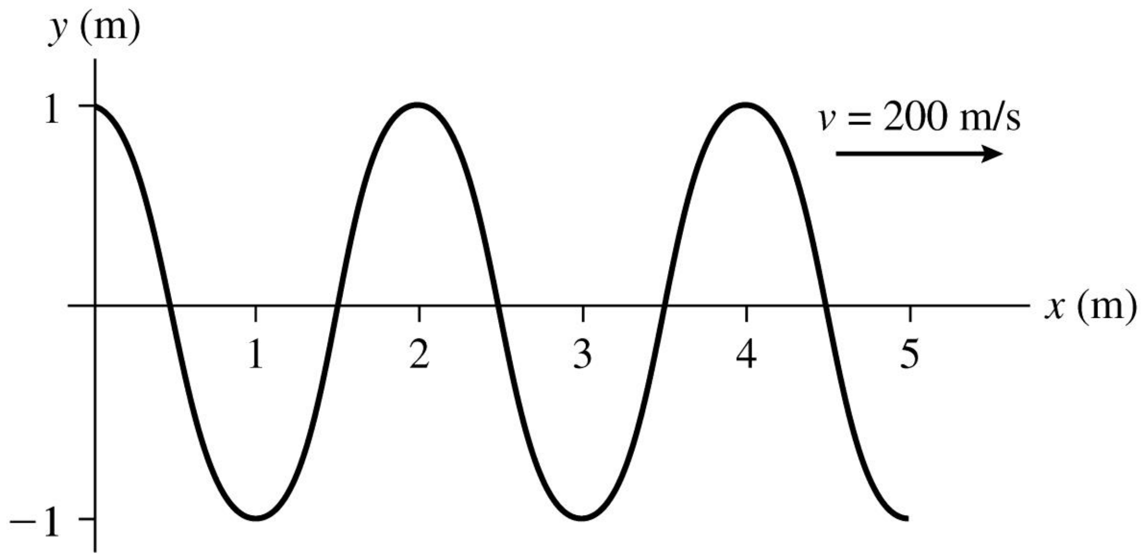
For this sinusoidal wave, what is the amplitude?

A. 0.5 m

B. 1 m

✔ C. 2 m

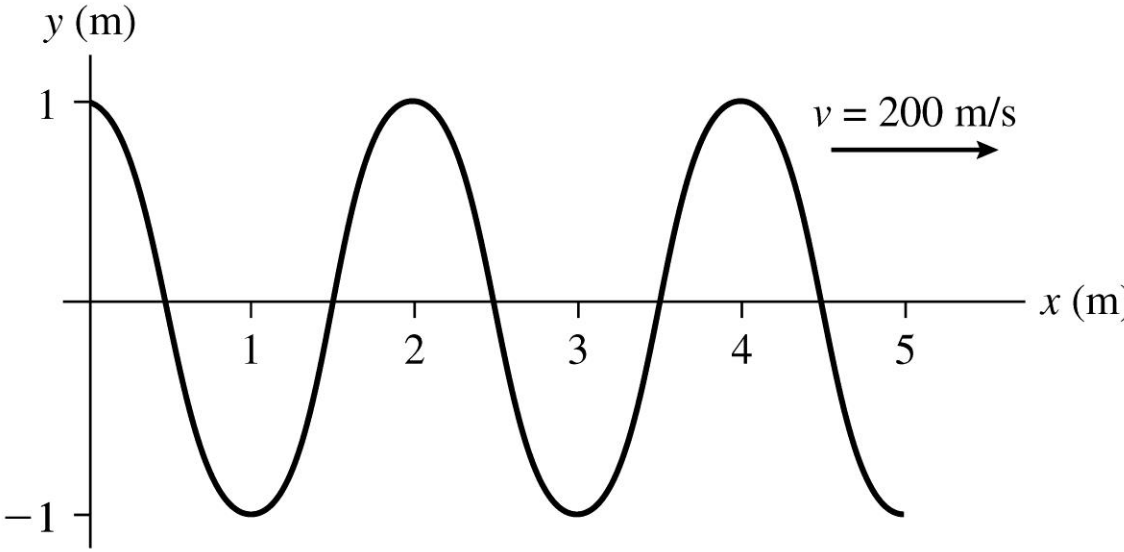
D. 4 m



QuickCheck 15.9

For this sinusoidal wave, what is the wavelength?

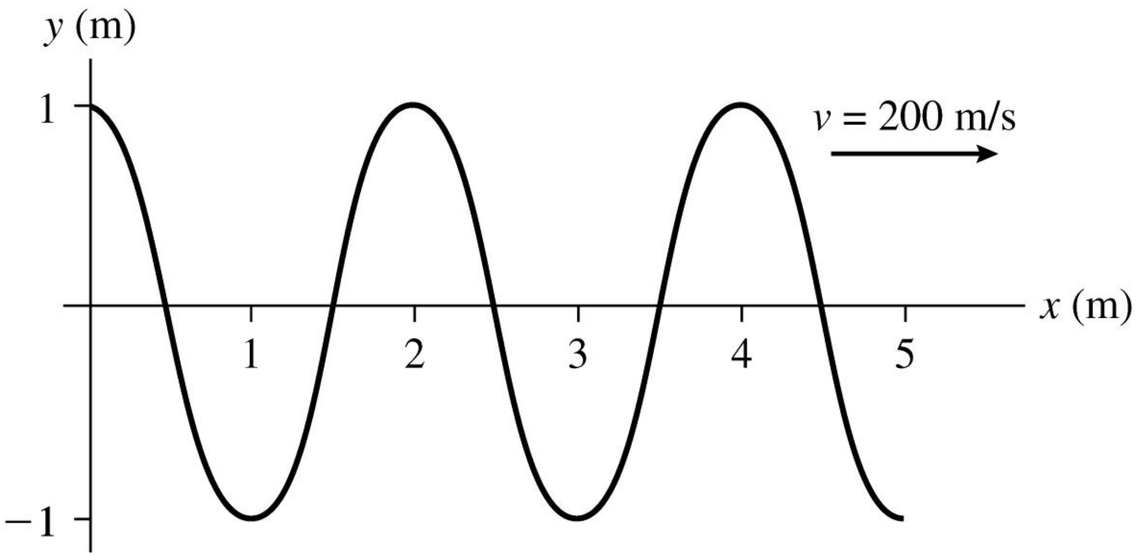
A. 0.5 m
B. 1 m
C. 2 m
D. 4 m



QuickCheck 15.9

For this sinusoidal wave, what is the wavelength?

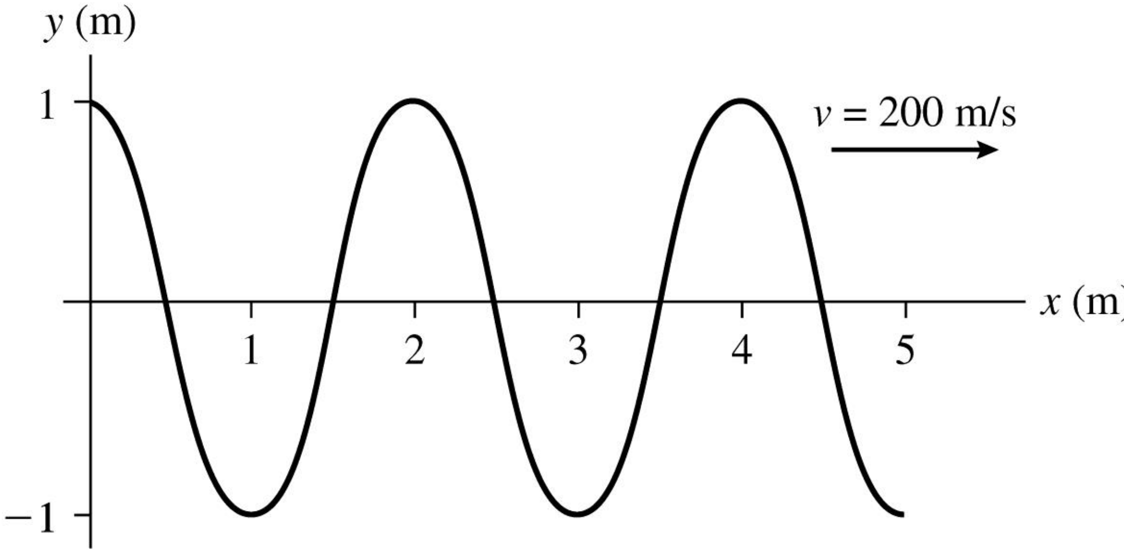
A. 0.5 m
B. 1 m
✔ C. 2 m
D. 4 m



QuickCheck 15.10

For this sinusoidal wave, what is the frequency?

A. 50 Hz
B. 100 Hz
C. 200 Hz
D. 400 Hz



QuickCheck 15.10

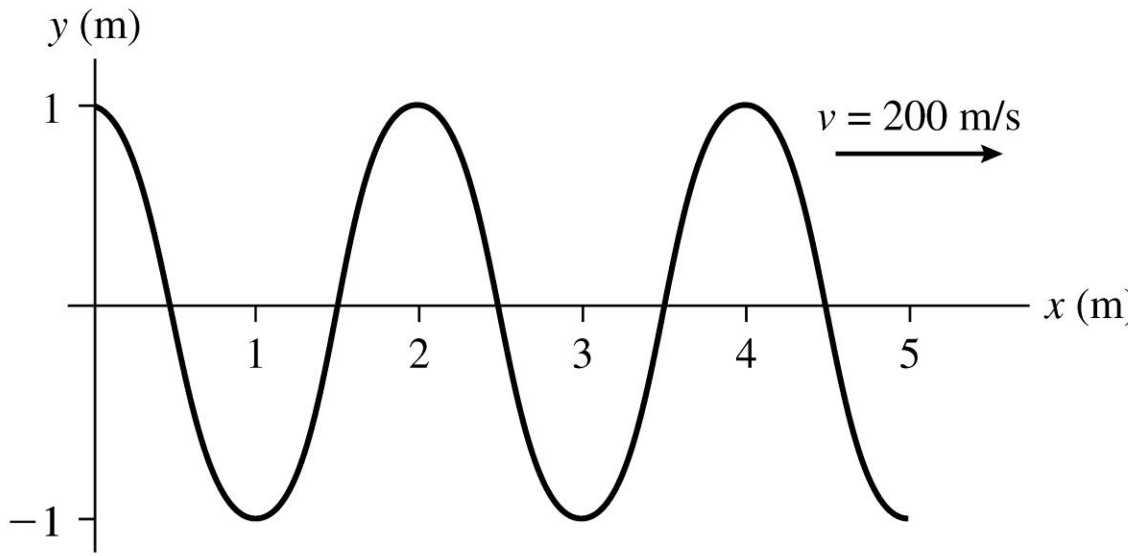
For this sinusoidal wave, what is the frequency?

A. 50 Hz

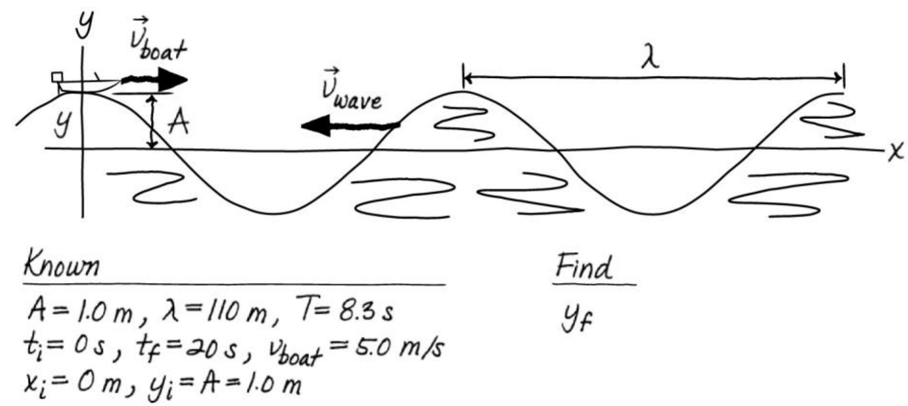
✔ B. 100 Hz

C. 200 Hz

D. 400 Hz

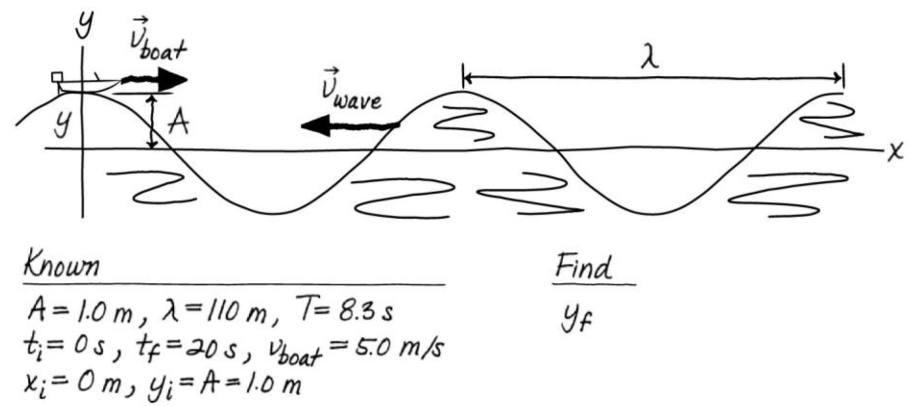


Example 15.4 Determining the rise and fall of a boat



A boat is moving to the right at 5.0 m/s with respect to the water. An ocean wave is moving to the left, opposite the motion of the boat. The waves have 2.0 m between the top of the crests and the bottom of the troughs. The period of the waves is 8.3 s, and their wavelength is 110 m. At one instant, the boat sits on a crest of the wave. 20 s later, what is the vertical displacement of the boat?

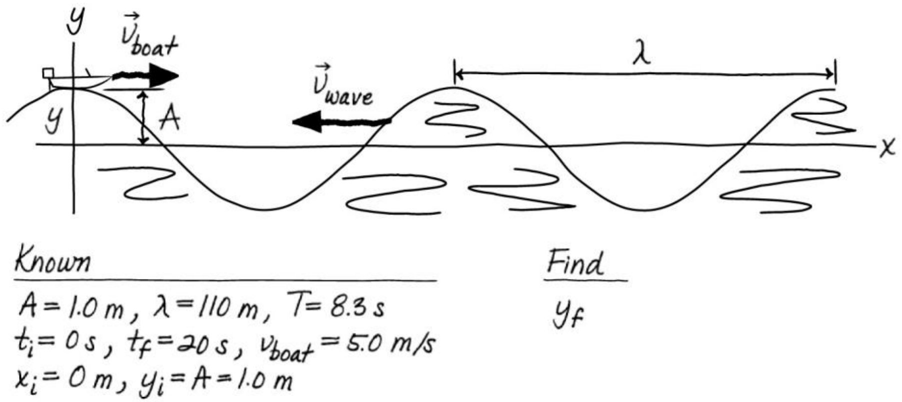
Example 15.4 Determining the rise and fall of a boat (cont.)



PREPARE We begin with the visual overview, as in FIGURE 15.11. Let $t = 0$ be the instant the boat is on the crest, and draw a snapshot graph of the traveling wave at that time. Because the wave is traveling to the left, we will use Equation 15.8 to represent the wave.

Example 15.4 Determining the rise and fall of a boat (cont.)

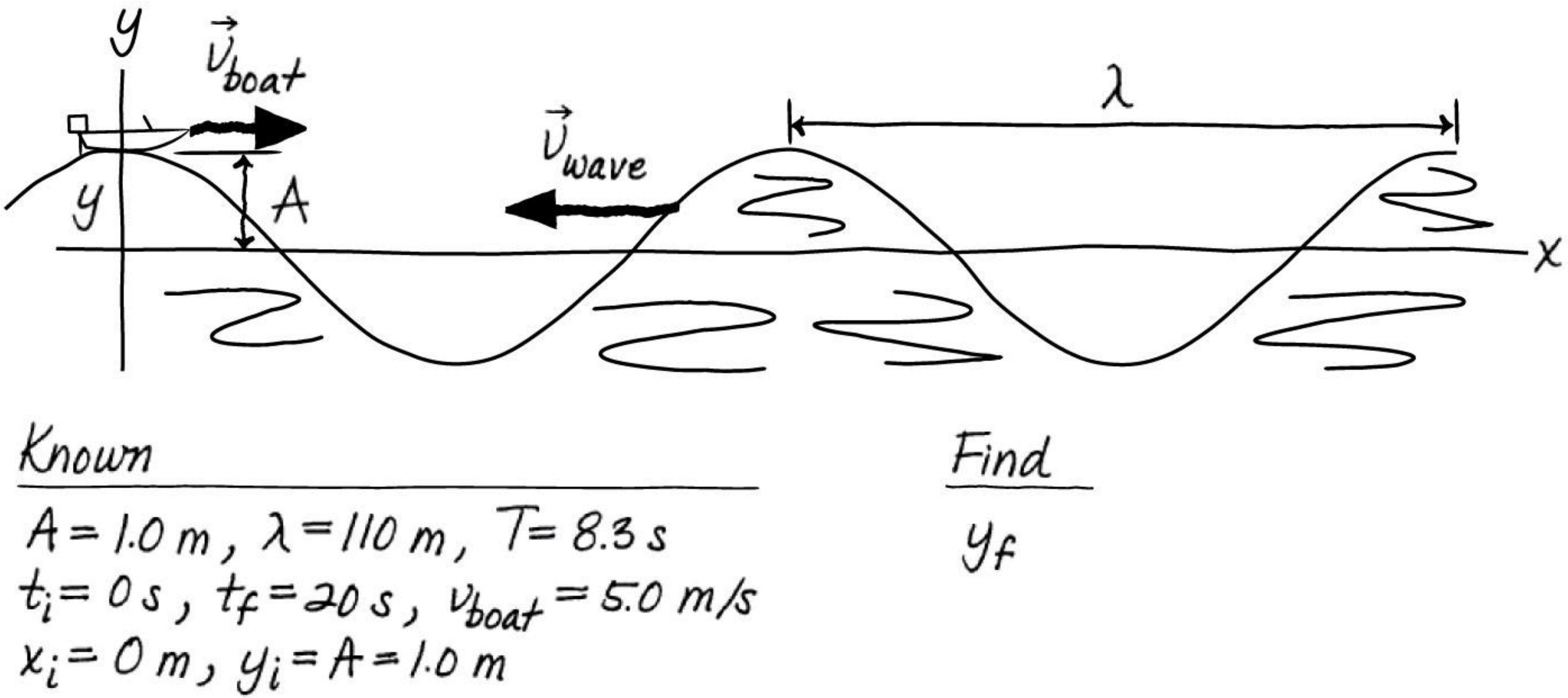
The boat begins at a crest of the wave, so we see that the boat can start the problem at $x = 0$.



The distance between the high and low points of the wave is 2.0 m; the amplitude is half this, so $A = 1.0$ m. The wavelength and period are given in the problem.

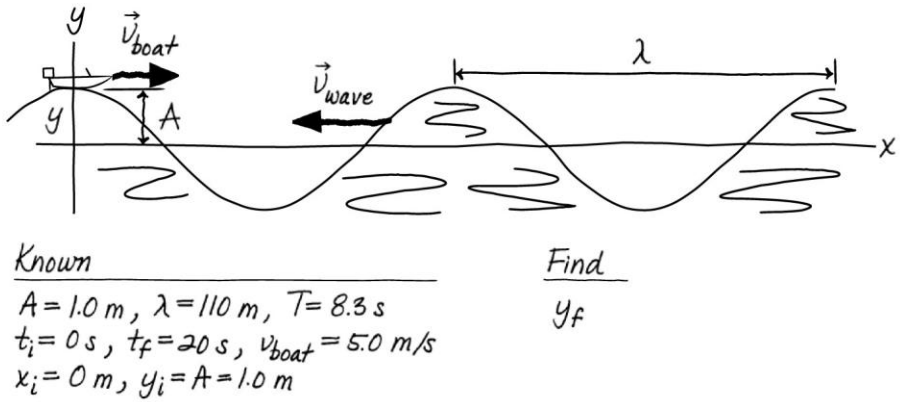
Example 15.4 Determining the rise and fall of a boat (cont.)

SOLVE The boat is moving to the right at 5.0 m/s. At t_f = 20 s the boat is at position x_f = (5.0 m/s)(20 s) = 100 m.



Example 15.4 Determining the rise and fall of a boat (cont.)

We need to find the wave's displacement at this position and time. Substituting known values for amplitude, wavelength, and period into Equation 15.8, for a wave traveling to the left, we obtain the following equation for the wave:



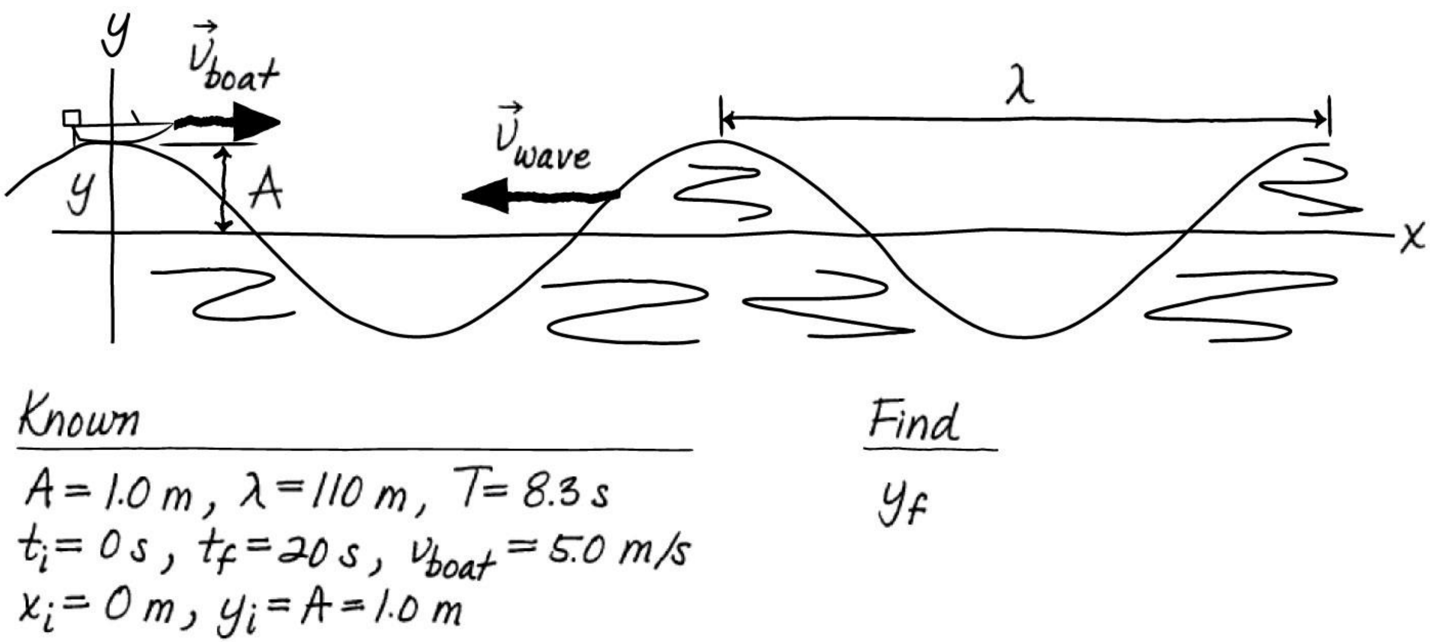
$$y(x, t) = (1.0\text{ m})\cos\left(2\pi\left(\frac{x}{110\text{ m}} + \frac{t}{8.3\text{ s}}\right)\right)$$

Example 15.4 Determining the rise and fall of a boat (cont.)

At t_f = 20 s and x_f = 100 m, the boat's displacement on the wave is

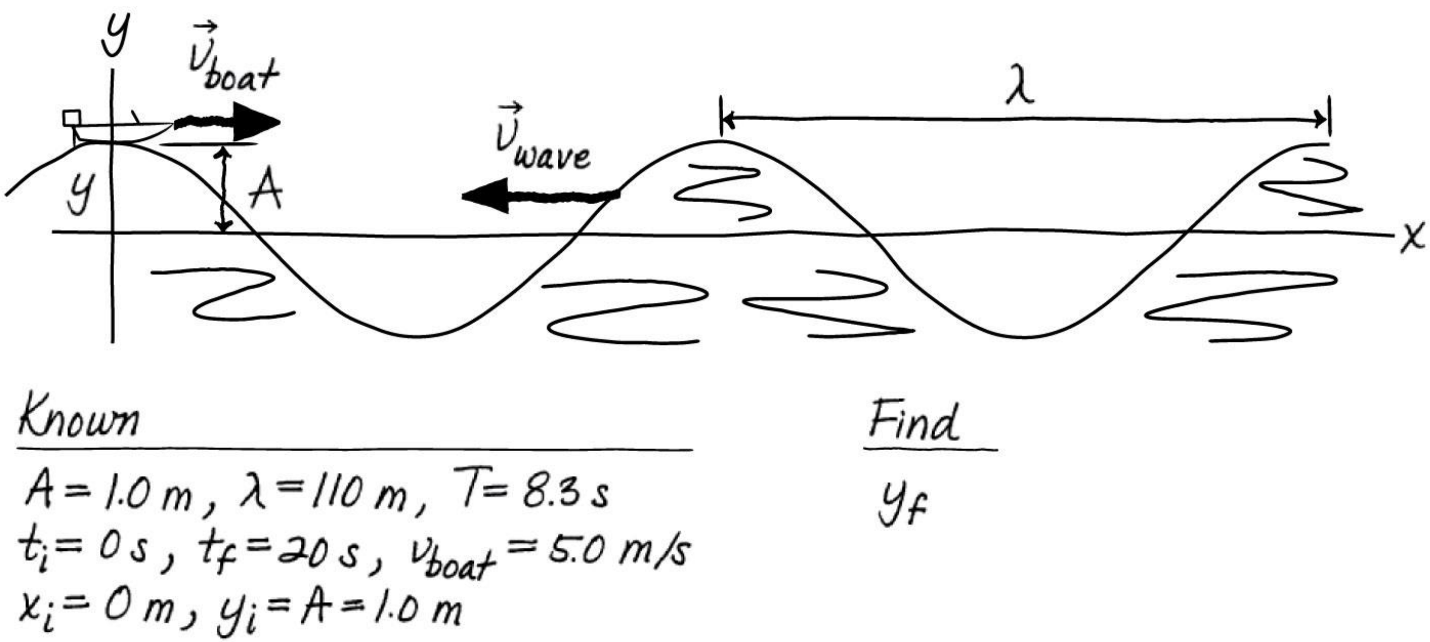
$$y_f = y(\text{at } 100\text{ m}, 20\text{ s}) = (1.0\text{ m})\cos\left(2\pi\left(\frac{100\text{ m}}{110\text{ m}} + \frac{20\text{ s}}{8.3\text{ s}}\right)\right)$$

$$= -0.42\text{ m}$$



Example 15.4 Determining the rise and fall of a boat (cont.)

ASSESS The final displacement is negative—meaning the boat is in a trough of a wave, not underwater. Don't forget that your calculator must be in radian mode when you make your final computation!



The Fundamental Relationship for Sinusoidal Waves

- During a time interval of exactly one period T, each crest of a sinusoidal wave travels forward a distance of exactly one wavelength λ:

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

- In terms of frequency, the velocity of the wave is

$$v = \lambda f$$

Relationship between velocity, wavelength, and frequency for sinusoidal waves

QuickCheck 15.14

A speaker emits a 400-Hz tone. The air temperature increases. This _______ the wavelength of the sound.

A. Increases
B. Does not change
C. Decreases

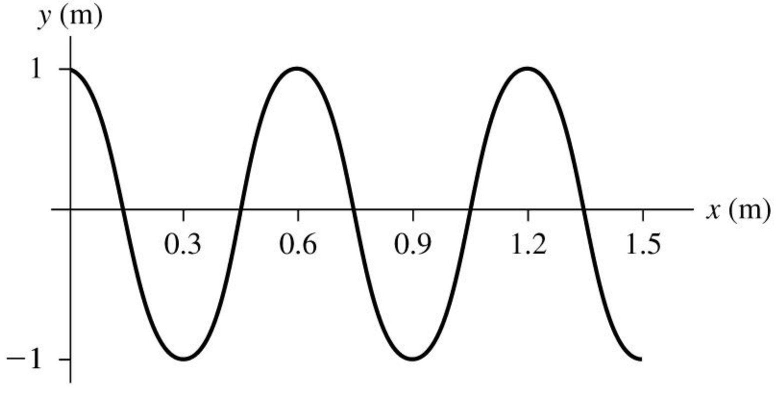
QuickCheck 15.14

A speaker emits a 400-Hz tone. The air temperature increases. This _______ the wavelength of the sound.

✔ A. Increases
B. Does not change
C. Decreases

QuickCheck 15.11

A snapshot and a history graph for a sinusoidal wave on a string appear as follows:



What is the speed of the wave?

A. 1.5 m/s

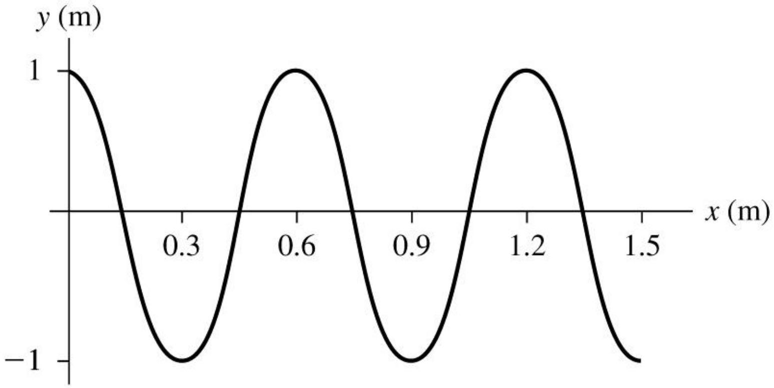
B. 3.0 m/s

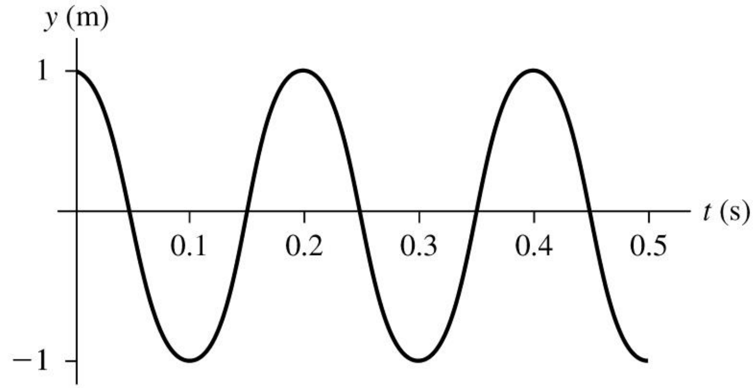
C. 5.0 m/s

D. 15 m/s

QuickCheck 15.11

A snapshot and a history graph for a sinusoidal wave on a string appear as follows:





What is the speed of the wave?

A. 1.5 m/s

B. 3.0 m/s

✔ C. 5.0 m/s

D. 15 m/s

QuickCheck 15.12

Which has a longer wavelength?

A. A 400-Hz sound wave in air
B. A 400-Hz sound wave in water

QuickCheck 15.12

Which has a longer wavelength?

A. A 400-Hz sound wave in air
✔ B. A 400-Hz sound wave in water

The Fundamental Relationship for Sinusoidal Waves

SYNTHESIS 15.1 Wave motion

Wave speed is determined by the medium.

For a wave on a stretched string:

$$v_{string} = \sqrt{\frac{T_s}{\mu}}$$

T_s: String tension (N)
μ: String mass divided by length (kg/m)

For a sound wave in a gas:

$$v_{sound} = \sqrt{\frac{\gamma k_B T}{m}}$$

T: Temperature (K)
m: Molecular mass (kg)

For example, at room temperature in air:

$$v_{sound}(20^\circ\ \text{C}) = 343\ \text{m/s}$$

In a vacuum or air, the speed of light is

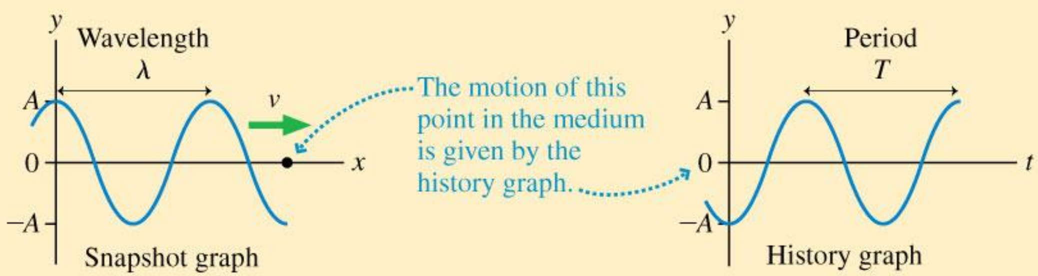
$$v_{light} = 3.00 \times 10^8\ \text{m/s}$$

A sinusoidal wave moves one wavelength in one period, giving the fundamental relationship:

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

v: Speed of the wave (m/s)
λ: Wavelength (m)
f: Frequency of the wave (Hz)
T: Period of the wave (s)

As a sinusoidal wave travels, each point in the medium moves with simple harmonic motion.



Text: p. 480

Example Problem

Suppose a boat is at rest in the open ocean. The wind has created a steady wave with wavelength 190 m traveling at 14 m/s. (The ocean supports a mix of waves, but for steady winds of 30–40 knots, this is the most prevalent wavelength, and this is the correct speed for a wave of this wavelength in deep water.) The top of the crests of the waves is 2.0 m above the bottom of the troughs. (This wave height is quite typical for windy days in the Atlantic Ocean.) What is the maximum vertical speed of the boat as it bobs up and down on the passing wave? What is the maximum vertical acceleration?

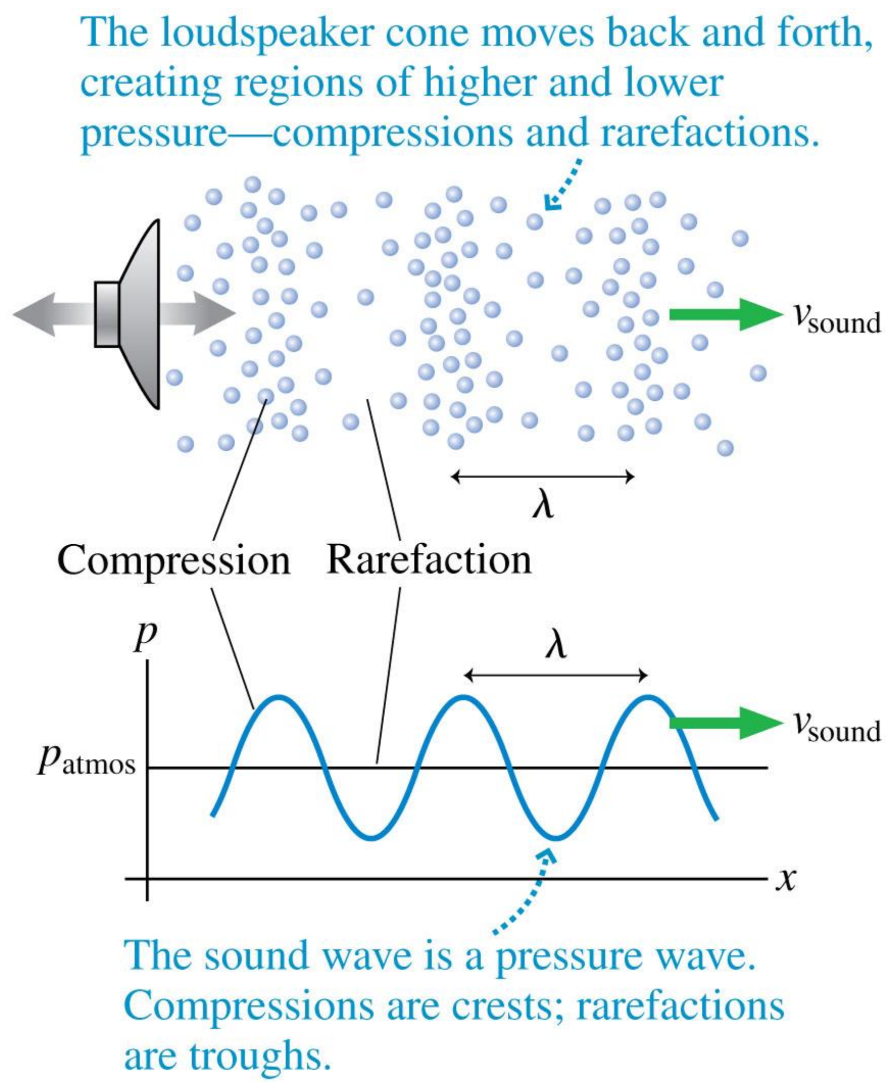
Example Problem

A particular species of spider spins a web with silk threads of density 1300 kg/m^3 and diameter 3.0 μm. A typical tension in the radial threads of such a web is 7.0 mN. If a fly lands in this web, which will reach the spider first, the sound or the wave on the web silk?

Section 15.4 Sound and Light Waves

Sound Waves

- As the cone of a loudspeaker moves forward, it moves air molecules closer together, creating a region of higher pressure. A half cycle later, the cone moves backward, and pressure decreases.
- The regions of higher and lower pressures are called **compressions** and **rarefactions**, respectively.



Example 15.6 Range of wavelengths of sound

What are the wavelengths of sound waves at the limits of human hearing and at the midrange frequency of 500 Hz? Notes sung by human voices are near 500 Hz, as are notes played by striking keys near the center of a piano keyboard.

PREPARE We will do our calculation at room temperature, 20°C, so we will use v = 343 m/s for the speed of sound.

Example 15.6 Range of wavelengths of sound (cont.)

SOLVE We can solve for the wavelengths given the fundamental relationship $v = \lambda f$:

$$f = 20 \text{ Hz:} \qquad \lambda = \frac{v}{f} = \frac{343 \text{ m/s}}{20 \text{ Hz}} = 17 \text{ m}$$

$$f = 500 \text{ Hz:} \qquad \lambda = \frac{v}{f} = \frac{343 \text{ m/s}}{500 \text{ Hz}} = 0.69 \text{ m}$$

$$f = 20 \text{ kHz:} \qquad \lambda = \frac{v}{f} = \frac{343 \text{ m/s}}{20 \times 10^3 \text{ Hz}} = 0.017 \text{ m} = 1.7 \text{ cm}$$

Example 15.6 Range of wavelengths of sound (cont.)

ASSESS The wavelength of a 20 kHz note is a small 1.7 cm. At the other extreme, a 20 Hz note has a huge wavelength of 17 m! A wave moves forward one wavelength during a time interval of one period, and a wave traveling at 343 m/s can move 17 m during the $\frac{1}{20}$ s period of a 20 Hz note.

Sound Waves

- **Ultrasound waves** are high-frequency sounds above our range of hearing that are used by some animals for *echolocation.*
- The resolution that can be detected by an optical instrument or your eyes is limited by the wavelength of the light. Acoustic imaging is the same; the higher the frequency (thus the shorter the wavelength), the finer the detail.

Example 15.7 Ultrasonic frequencies in medicine

To make a sufficiently detailed ultrasound image of a fetus in its mother's uterus, a physician has decided that a wavelength of 0.50 mm is needed. What frequency is required?

PREPARE The speed of ultrasound in the body is given in Table 15.1 as 1540 m/s.

Example 15.7 Ultrasonic frequencies in medicine (cont.)

SOLVE We can use the fundamental relationship for sinusoidal waves to calculate

$$f = \frac{v}{\lambda} = \frac{1540 \text{ m/s}}{0.50 \times 10^{-3} \text{ m}} = 3.1 \times 10^6 \text{ Hz} = 3.1 \text{ MHz}$$

Example 15.7 Ultrasonic frequencies in medicine (cont.)

ASSESS This is a reasonable result. Clinical ultrasound uses frequencies in the range of 1–20 MHz. Lower frequencies have greater penetration; higher frequencies (and thus shorter wavelengths) show finer detail.

Light and Other Electromagnetic Waves

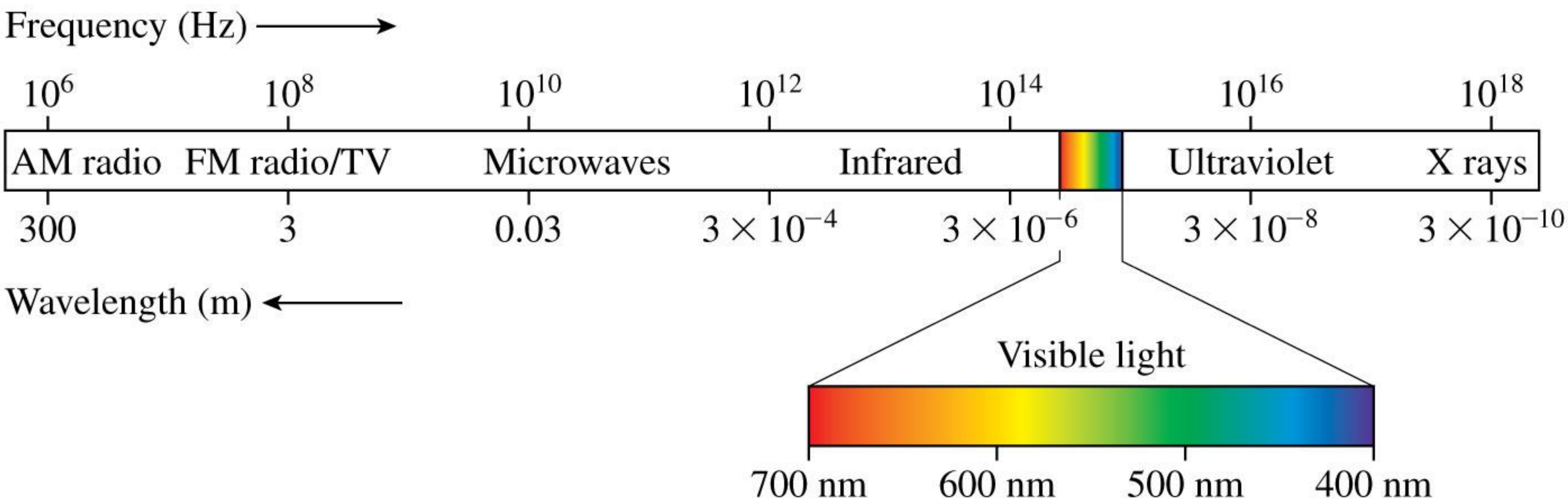
- An electromagnetic wave is the oscillation of the electromagnetic field.
- Electromagnetic waves include visible light, radio waves, microwaves, and ultraviolet light.
- All electromagnetic waves travel through a vacuum at the same speed $c = 3.00 \times 10^8$ m/s.

Light and Other Electromagnetic Waves

- Electromagnetic waves have extremely short wavelengths. In air, visible light has a wavelength of roughly 400–700 nm.
- Each wavelength is perceived as a different color. Longer wavelengths (600–700 nm) are seen as orange and red light while shorter wavelengths (400–500 nm) are seen as violet and blue light.

Light and Other Electromagnetic Waves

- The visible spectrum is a small slice out of the much broader **electromagnetic spectrum.**



Example 15.8 Finding the frequency of microwaves

The wavelength of microwaves in a microwave oven is 12 cm. What is the frequency of the waves?

PREPARE Microwaves are electromagnetic waves, so their speed is the speed of light, $c = 3.00 \times 10^8$ m/s.

Example 15.8 Finding the frequency of microwaves (cont.)

SOLVE Using the fundamental relationship for sinusoidal waves, we find

$$f = \frac{v}{\lambda} = \frac{3.00 \times 10^8 \text{ m/s}}{0.12 \text{ m}} = 2.5 \times 10^9 \text{ Hz} = 2.5 \text{ GHz}$$

ASSESS This is a high frequency, but the speed of the waves is also very high, so our result seems reasonable.

Example Problem

The new generation of cordless phones use radio waves at a frequency of 5.8 GHz. What is the wavelength of these radio waves?

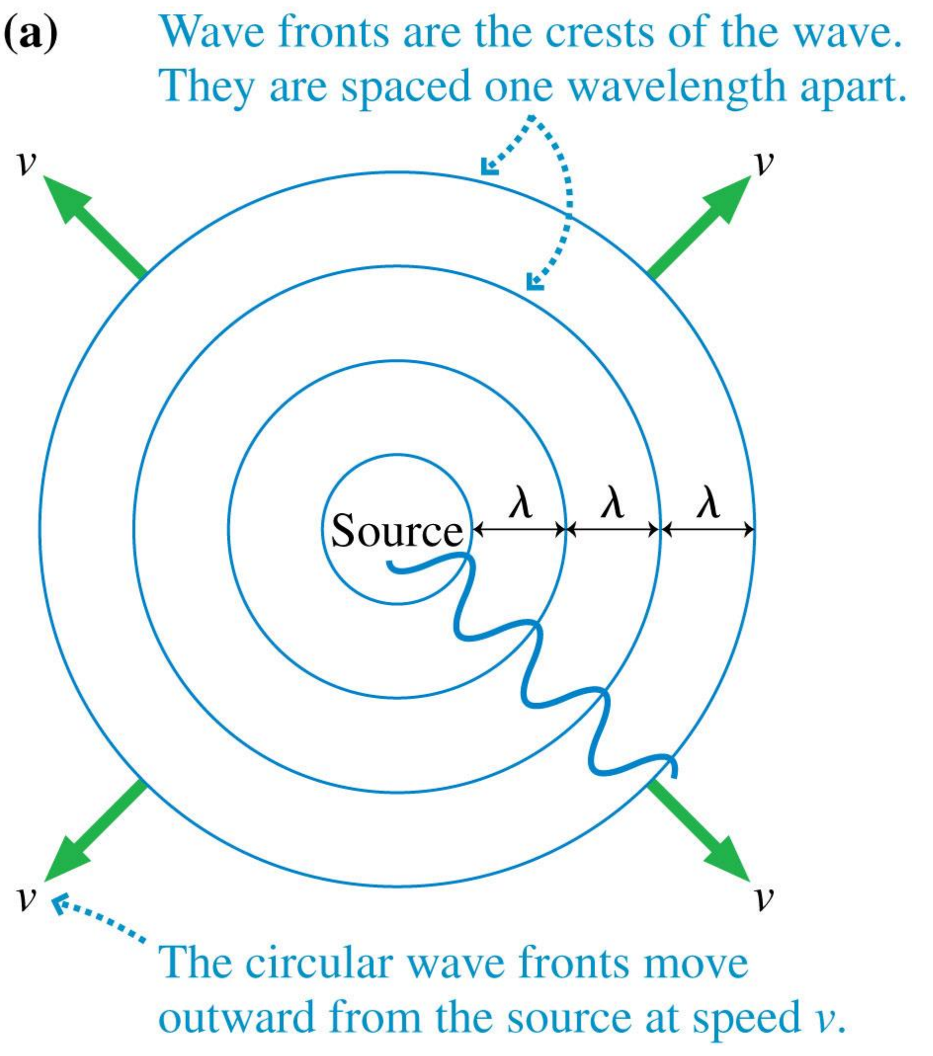
Section 15.5 Energy and Intensity

Energy and Intensity

- A traveling wave transfers energy from one point to another.
- The *power* of the wave is the rate at which the wave transfers energy.

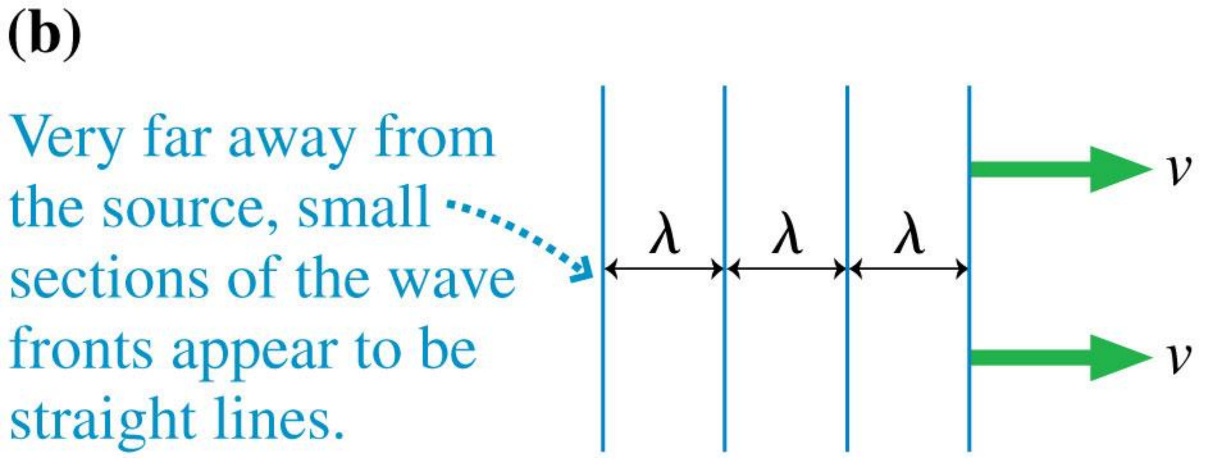
Circular, Spherical, and Plane Waves

- A **circular wave** is a two-dimensional wave that spreads across a surface.
- In a photograph of ripples in a pond, the locations of the *crests* would be the **wave fronts**. They are spaced one wavelength apart.



Circular, Spherical, and Plane Waves

- Although the wave fronts are circles, the curvature isn't noticeable if you observed a small section of the wave front very far away from the source.



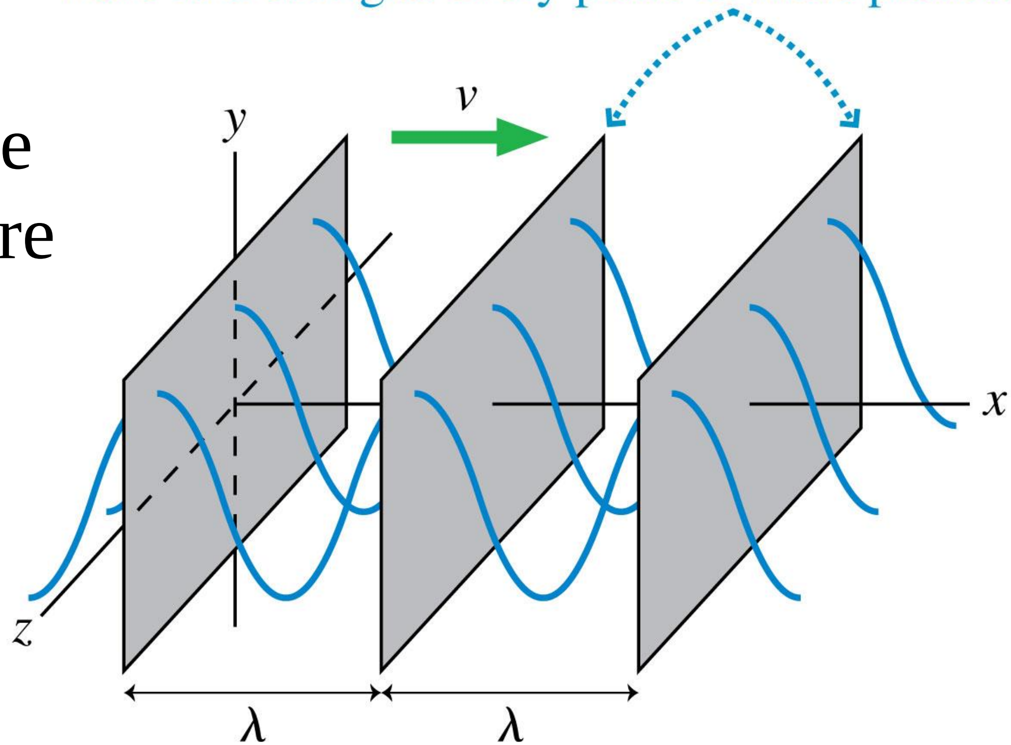
Circular, Spherical, and Plane Waves

- **Spherical waves** move in three dimensions. Light and sound waves are spherical waves.
- The waves are three-dimensional ripples; the crests are spherical shells still spaced one wavelength apart.
- The wave-front diagrams are now circles that represent slices through the spherical shells locating the wave crests.

Circular, Spherical, and Plane Waves

- When you observe a wave far from its source, the small piece of the wave front is a little patch of the large sphere. The curvature of the sphere will be unnoticed, and the wave front will appear to be a plane.
- A **plane wave** describes observations of waves far from their source. The planes represent the crests of the spherical waves.

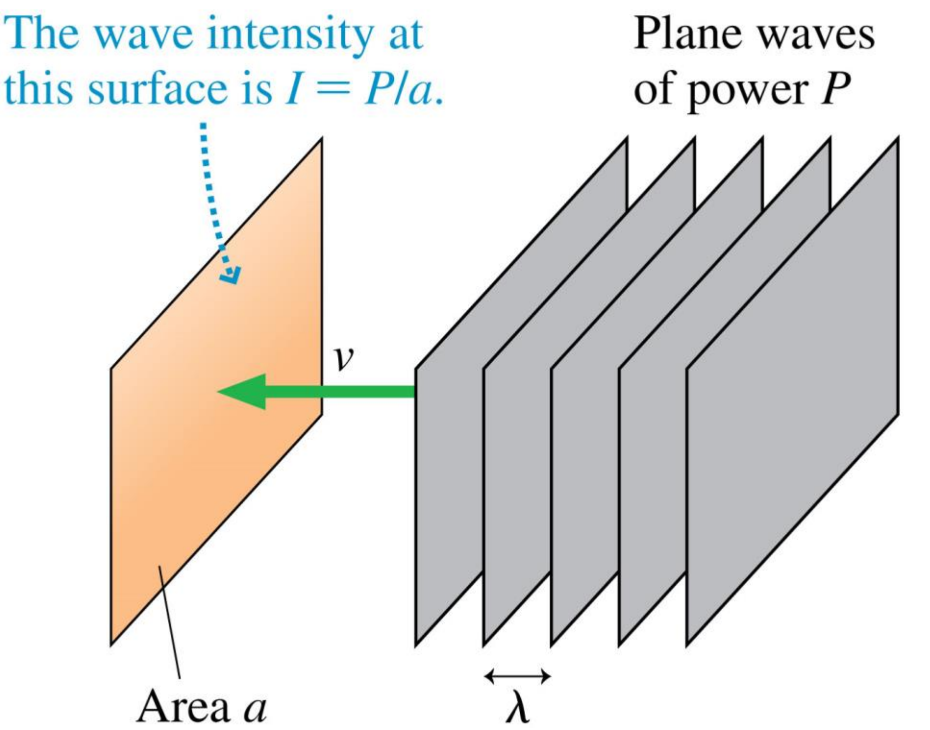
Very far from the source, small segments of spherical wave fronts appear to be planes. The wave is cresting at every point in these planes.



Power, Energy, and Intensity

- The **intensity** of light or sound (brightness or loudness) depends on the power of the source and the *area* that receives the power:

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



- The SI units are W/m^2.
- A wave focused on a small area has higher intensity than if it were spread out.

Example 15.9 The intensity of a laser beam

A bright, tightly focused laser pointer emits 1.0 mW of light power into a beam that is 1.0 mm in diameter. What is the intensity of the laser beam?

SOLVE The light waves of the laser beam pass through a circle of diameter 1.0 mm. The intensity of the laser beam is

$$I = \frac{P}{a} = \frac{P}{\pi r^2} = \frac{0.0010\ \text{W}}{\pi(0.00050\ \text{m})^2} = 1300\ \text{W/m}^2$$

Example 15.9 The intensity of a laser beam (cont.)

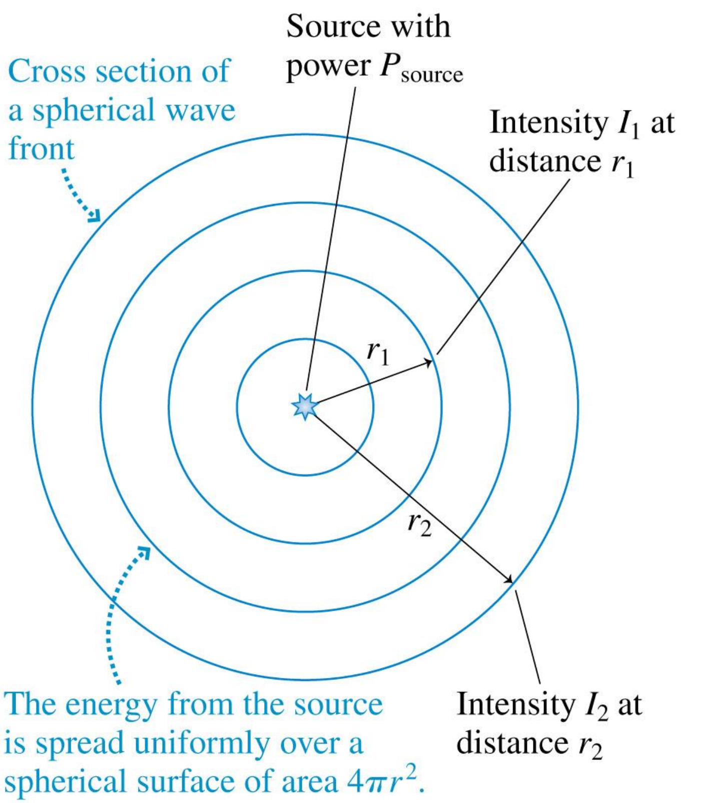
ASSESS This intensity is roughly equal to the intensity of sunlight at noon on a summer day. Such a high intensity for a low-power source may seem surprising, but the area is very small, so the energy is packed into a tiny spot. You know that the light from a laser pointer won't burn you but you don't want the beam to shine into your eye, so an intensity similar to that of sunlight seems reasonable.

Power, Energy, and Intensity

- If a source of spherical waves radiates uniformly in all directions, then the surface area of the sphere is $4\pi r^2$ and the intensity is

$$I = \frac{P_{\text{source}}}{4\pi r^2}$$

Intensity at distance r of a spherical wave from a source of power P_{source}



- The intensity ratio at two points is

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2}$$

Example Problem

Suppose you are powering a spacecraft with a 1.0 m^2 array of solar cells with an efficiency of 12%. Above the earth's atmosphere, where the intensity of sunlight is approximately 1300 W/m^2, what is the maximum power you could get from the solar cells? How much power could you get if your spacecraft was nearing Neptune, which is 30 times as far from the sun as the earth?

Section 15.6 Loudness of Sound

Loudness of Sound

- Generally, **increasing the sound intensity by a factor of 10 results in an increase in perceived loudness by a factor of approximately 2.**
- The loudness of sound is measured by a quantity called the **sound intensity level.**
- The sound intensity level is measured on a *logarithmic scale* because the perceived loudness is much less than the actual increase in intensity.

The Decibel Scale

- The *threshold of hearing* is the lowest intensity sound that can be heard. It is where we place the 0 for our loudness scale. For the average human, it is

$$I_0 = 1.0 \times 10^{-12}\ \mathrm{W/m^2}$$

- The *sound intensity level* is expressed in **decibels** (dB) as

$$\beta = (10\ \mathrm{dB})\log_{10}\left(\frac{I}{I_0}\right)$$

Sound intensity level in decibels for a sound of intensity I

The Decibel Scale

- As a reminder, logarithms work like this:

If you express a number as a power of 10 . . . . . . the logarithm is the exponent.

$$\log_{10}(1000) = \log_{10}(10^3) = 3$$

The Decibel Scale

- Right at the threshold of hearing, where $I = I_0$, the sound intensity level is

$$\beta = (10\text{ dB})\log_{10}\left(\frac{I_0}{I_0}\right) = (10\text{ dB})\log_{10}(1) = (10\text{ dB})\log_{10}(10^0) = 0\text{ dB}$$

- The threshold of hearing corresponds to 0 dB.

The Decibel Scale

- We can find the intensity from the sound intensity level by taking the inverse of the $\log_{10}$ function
- Recall, from the definition of the base-10 logarithm, that $10^{\log(x)} = x$.
- Applying this to Equation 15.14, we find

$$I = (I_0)10^{(\beta/10\ \text{dB})}$$

The Decibel Scale

TABLE 15.3 Intensity and sound intensity levels of common environmental sounds

Sound	β (dB)	I (W/m^2)
Threshold of hearing	0	1.0×10^{-12}
Person breathing, at 3 m	10	1.0×10^{-11}
A whisper, at 1 m	20	1.0×10^{-10}
Classroom during test, no talking	30	1.0×10^{-9}
Residential street, no traffic	40	1.0×10^{-8}
Quiet restaurant	50	1.0×10^{-7}
Normal conversation, at 1 m	60	1.0×10^{-6}
Busy traffic	70	1.0×10^{-5}
Vacuum cleaner, for user	80	1.0×10^{-4}
Niagara Falls, at viewpoint	90	1.0×10^{-3}
Pneumatic hammer, at 2 m	100	0.010
Home stereo at max volume	110	0.10
Rock concert	120	1.0
Threshold of pain	130	10

Text: p. 486

The Decibel Scale

SYNTHESIS 15.2 Wave power and intensity

We have different measures of the energy carried by waves.

The **intensity** of a wave is the power per square meter of area:

Intensity (W/m^2) · Power (W)

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

Area (m^2)

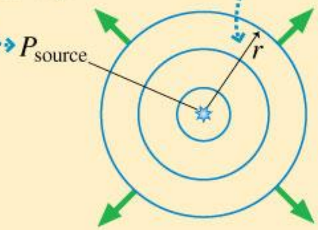
When a wave hits a surface, the power absorbed in area a is

$$P = Ia$$

Spherical waves spread over the surface of a sphere of increasing size.

The **power** of the source is the rate at which it emits energy (J/s, or W).

Distance from the source (m)



As distance increases, intensity decreases.

Surface area of sphere of radius r

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

We compute **sound intensity level** from relative intensity:

Sound intensity level (dB) · Intensity (W/m^2)

$$\beta = (10\text{ dB})\log_{10}\left(\frac{I}{I_0}\right)$$

The smallest intensity humans can sense

$$I_0 = 1.0 \times 10^{-12}\text{ W/m}^2$$

We can also compute intensity from sound intensity level:

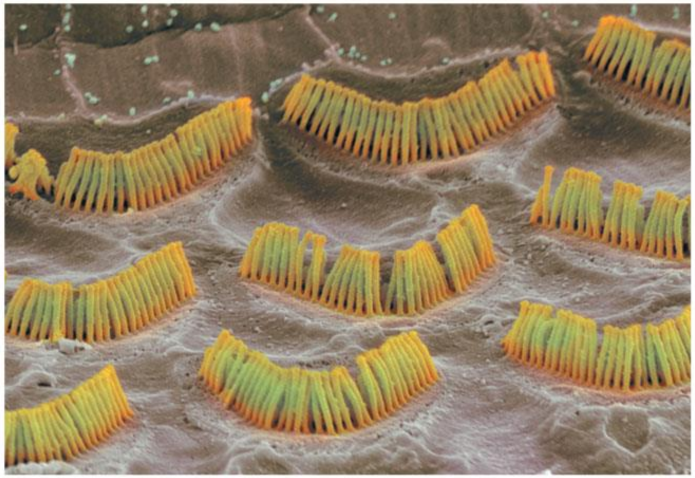
$$I = (I_0)10^{(\beta/10\text{ dB})}$$

Text: p. 487

Example 15.11 Finding the loudness of a shout

A person shouting at the top of his lungs emits about 1.0 W of energy as sound waves. What is the sound intensity level 1.0 m from such a person?

PREPARE We will assume that the shouting person emits a spherical sound wave. Synthesis 15.2 gives the details for the decrease in intensity with distance and the calculation of the resulting sound intensity level.



Example 15.11 Finding the loudness of a shout

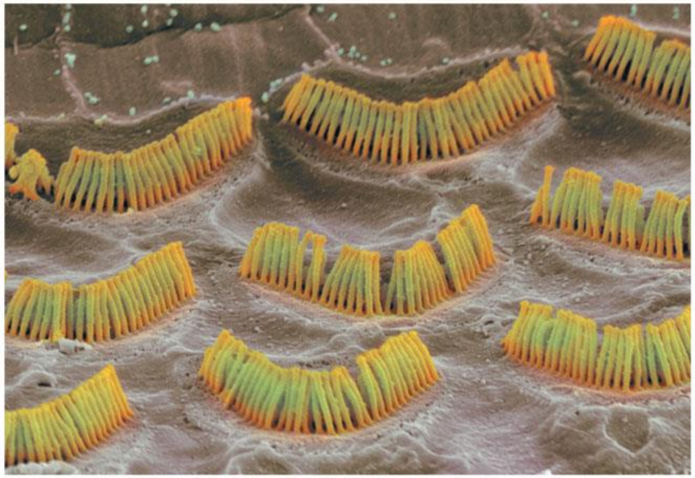
SOLVE At a distance of 1.0 m, the sound intensity is

$$I = \frac{P}{4\pi r^2} = \frac{1.0\text{ W}}{4\pi(1.0\text{ m})^2} = 0.080\text{ W/m}^2$$

Thus the sound intensity level is

$$\beta = (10\text{ dB})\log_{10}\left(\frac{0.080\text{ W/m}^2}{1.0 \times 10^{-12}\text{ W/m}^2}\right) = 110\text{ dB}$$

ASSESS This is quite loud (compare with values in Table 15.3), as you might expect.



Example Problem

You are working in a shop where the noise level is a constant 90 dB.

A. Your eardrum has a diameter of approximately 8.4 mm. How much power is being received by one of your eardrums?

B. This level of noise is damaging over a long time, so you use earplugs that are rated to reduce the sound intensity level by 26 dB, a typical rating. What is the power received by one eardrum now?

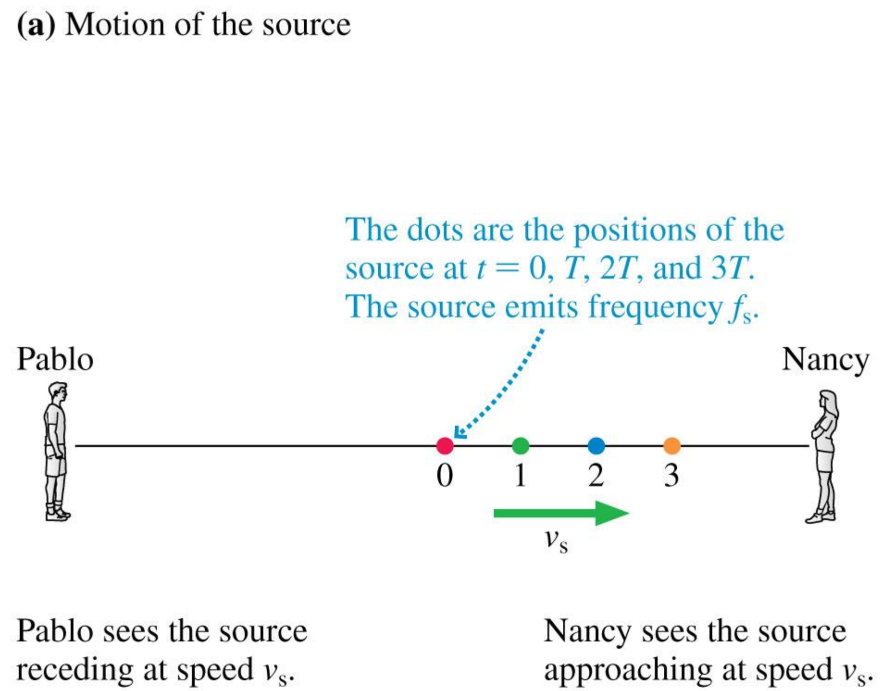
Section 15.7 The Doppler Effect and Shock Waves

The Doppler Effect and Shock Waves

- The *Doppler effect* is a change in frequency due to the motion of the source. This effect is heard as the pitch of an ambulance siren changes from its approach to after it has passed you by.
- A *shock wave* is produced when an object moves faster than the speed of sound.
- When you hear the crack of the whip, the tip of a whip is moving at *supersonic* speeds.

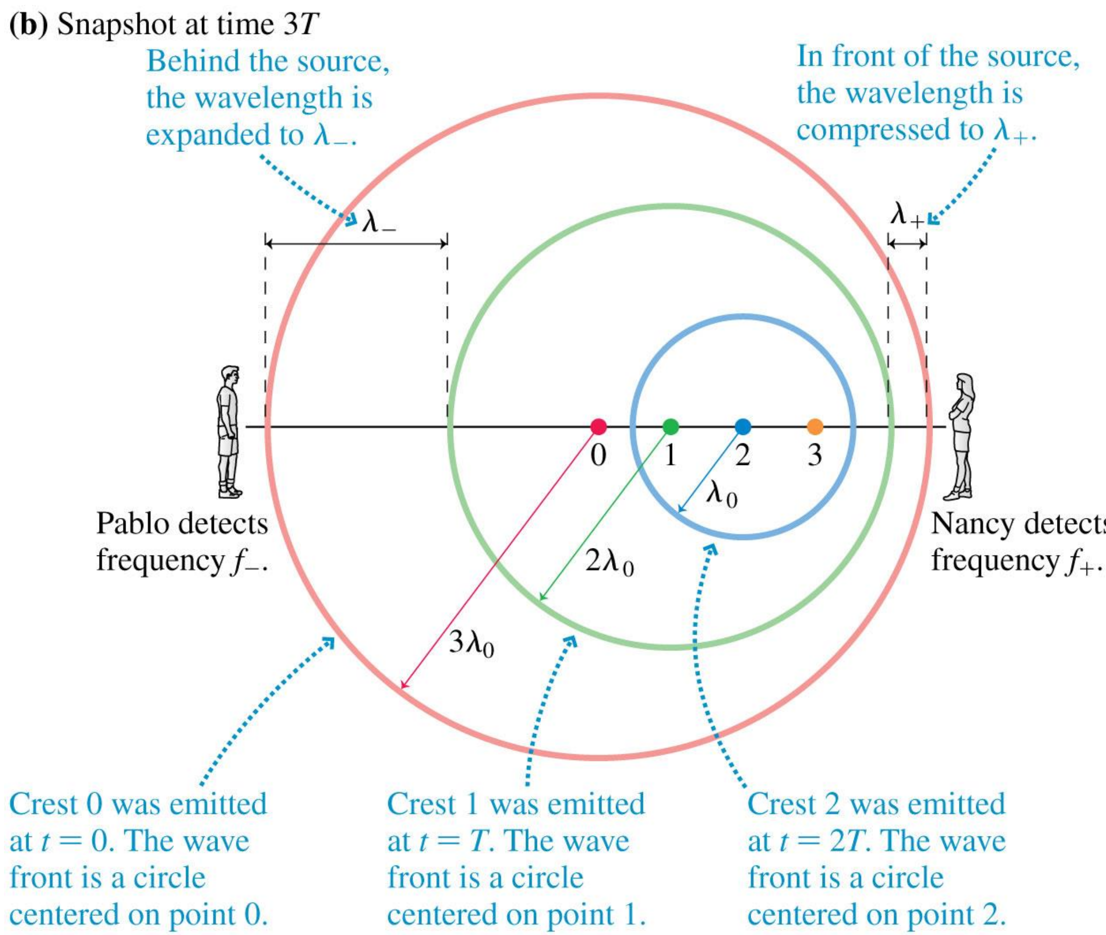
Sound Waves from a Moving Source

- A source of sound waves is moving away from Pablo and towards Nancy with a speed v_s.
- After a wave crest leaves the source, its motion is governed by the properties of the medium. The motion of the source has no affect on each crest once emitted.



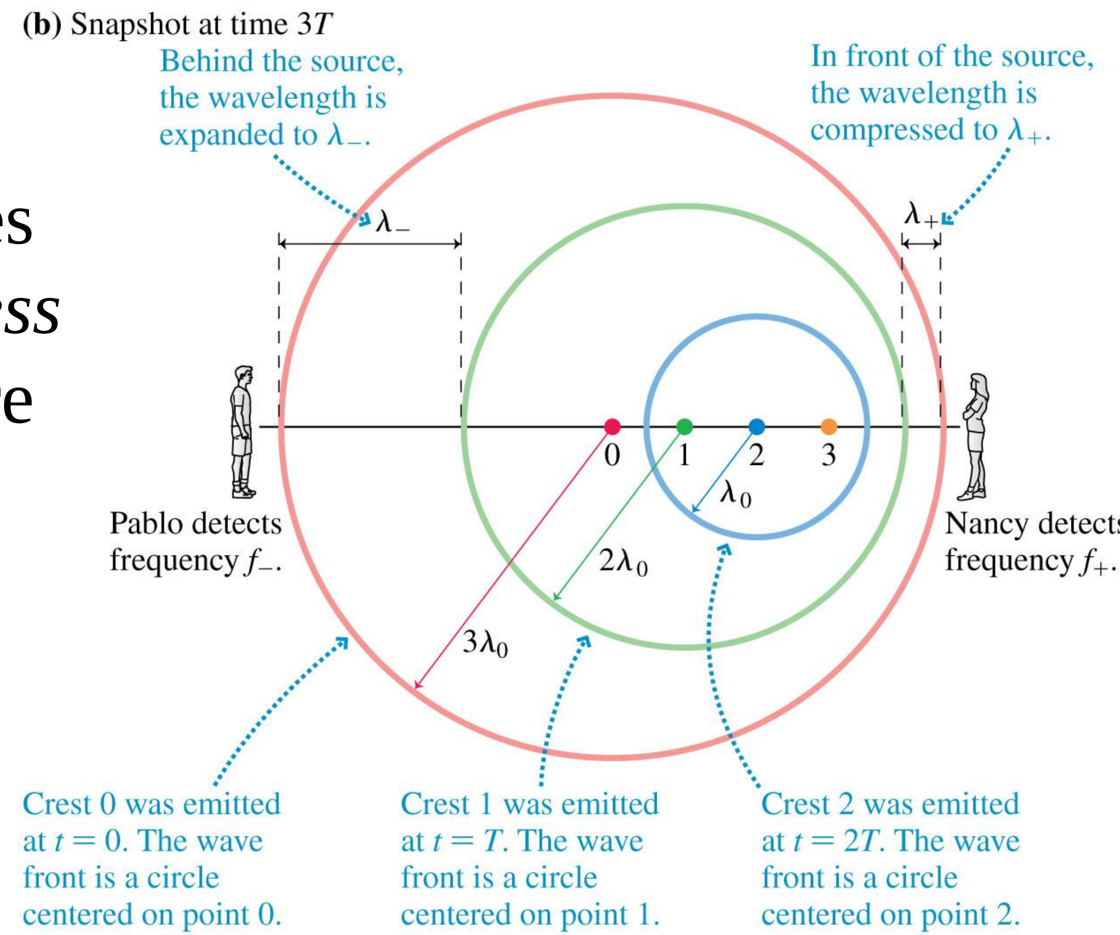
Sound Waves from a Moving Source

- Each circular wave front is centered on where it was emitted.
- Due to the motion of the source, the wave crests bunch up in the direction of motion of the source, and are stretched behind it.



Sound Waves from a Moving Source

- The wavelength is the distance between crests. Nancy measures a wavelength that is *less* than if the source were stationary $\lambda_0 = v/f_s$. Similarly, the wavelength is larger behind the source.



Sound Waves from a Moving Source

- The frequency $f_+ = v/\lambda_+$ detected by the observer whom the source is approaching is higher than the frequency emitted by the source. The observer behind the source detects a lower frequency than the source emits.
- The **Doppler effect** is the change in frequency when a source moves relative to an observer.

Approaching source

$$f_+ = \frac{f_s}{1 - v_s/v}$$

Frequency of the source (Hz): f_s

Speed of the *waves* (m/s): v

Speed of the *source* of the waves (m/s): v_s

The observed frequency is *increased*.

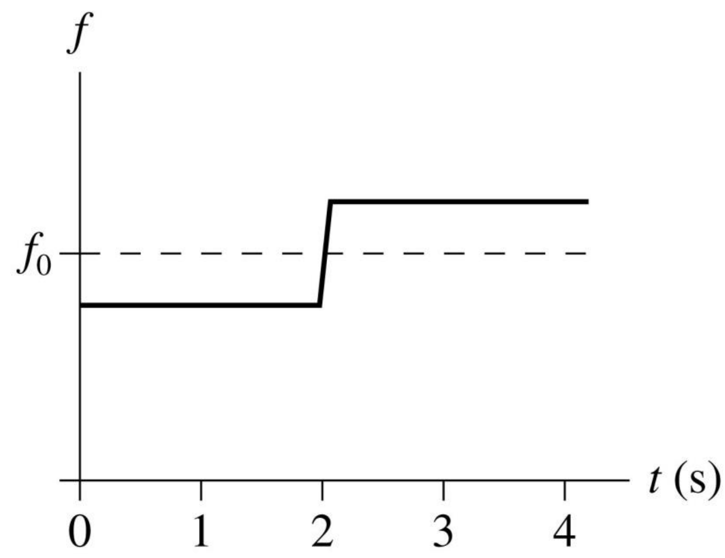
Receding source

$$f_- = \frac{f_s}{1 + v_s/v}$$

The observed frequency is *decreased*.

QuickCheck 15.16

A siren emits a sound wave with frequency f_0. The graph shows the frequency you hear as you stand at rest at $x = 0$ on the x-axis. Which is the correct description of the siren's motion?



A. It moves from left to right and passes you at $t = 2$ s.

B. It moves from right to left and passes you at $t = 2$ s.

C. It moves toward you for 2 s but doesn't reach you, then reverses direction at $t = 2$ s and moves away.

D. It moves away from you for 2 s, then reverses direction at $t = 2$ s and moves toward you but doesn't reach you.

QuickCheck 15.16

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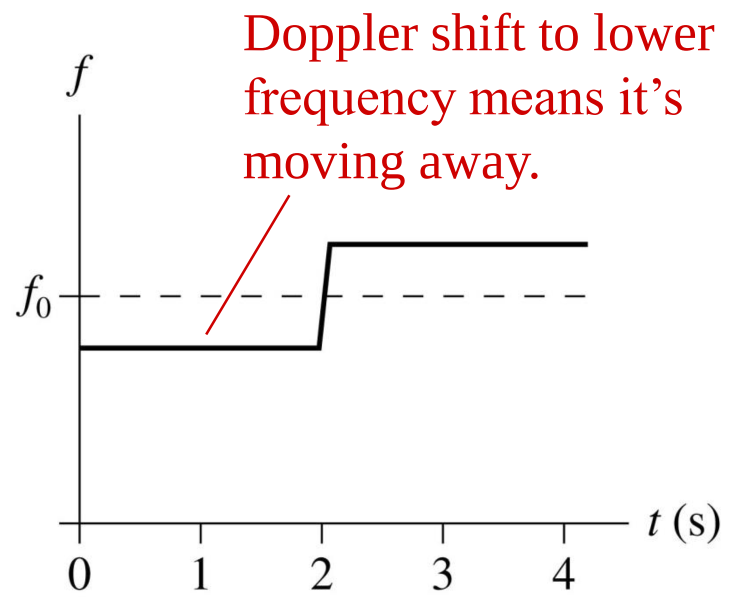


A. It moves from left to right and passes you at $t = 2$ s.

B. It moves from right to left and passes you at $t = 2$ s.

C. It moves toward you for 2 s but doesn't reach you, then reverses direction at $t = 2$ s and moves away.

✔ D. It moves away from you for 2 s, then reverses direction at $t = 2$ s and moves toward you but doesn't reach you.

Example 15.13 How fast are the police driving? (cont.)

A police siren has a frequency of 550 Hz as the police car approaches you, 450 Hz after it has passed you and is moving away. How fast are the police traveling?

PREPARE The siren's frequency is altered by the Doppler effect. The frequency is f_+ as the car approaches and f_- as it moves away. We can write two equations for these frequencies and solve for the speed of the police car, v_s.

Example 15.13 How fast are the police driving? (cont.)

SOLVE Because our goal is to find v_s, we rewrite Equations 15.16 as

$$f_s = \left(1 + \frac{v_s}{v}\right) f_- \quad \text{and} \quad f_s = \left(1 - \frac{v_s}{v}\right) f_+$$

Subtracting the second equation from the first, we get

$$0 = f_- - f_+ + \frac{v_s}{v}(f_- + f_+)$$

Example 15.13 How fast are the police driving? (cont.)

Now we can solve for the speed v_s:

$$v_s = \frac{f_+ - f_-}{f_+ + f_-} v = \frac{100\ \text{Hz}}{1000\ \text{Hz}} 343\ \text{m/s} = 34\ \text{m/s}$$

ASSESS This is pretty fast (about 75 mph) but reasonable for a police car speeding with the siren on.

A Stationary Source and a Moving Observer

- The frequency heard by a moving observer depends on whether the observer is approaching or receding from the source:

Approaching observer

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

Speed of the *observer* (m/s): v_o

Frequency of the source (Hz): f_s

Speed of the *waves* (m/s): v

The observed frequency is *increased*.

Receding observer

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

The observed frequency is *decreased*.

The Doppler Effect for Light Waves

- If the source of light is receding from you, the wavelength you detect is longer than that emitted by the source. The light is shifted toward the red end of the visible spectrum; this effect is called the **red shift.**
- The light you detect from a source moving toward you is **blue shifted** to shorter wavelengths.

The Doppler Effect for Light Waves

- All distant galaxies are redshifted, so *all* galaxies are moving away from us. Extrapolating backward brings us to a time where all matter in the universe began rushing out of a primordial fireball in an event known as the *Big Bang*.

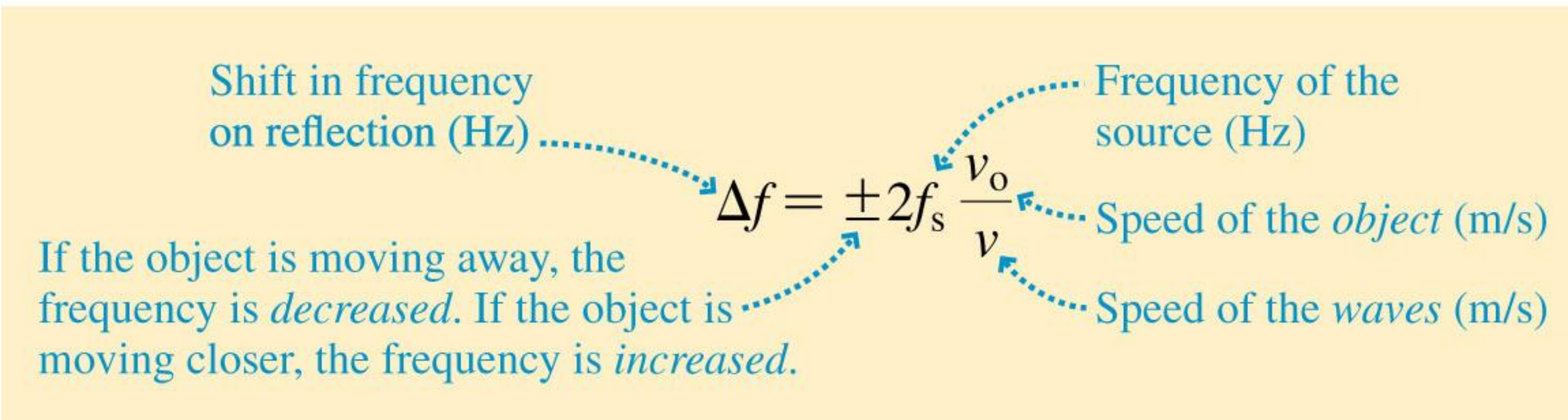
- Measurements show the universe began 14 billion years ago.

Frequency Shift on Reflection from a Moving Object

- A wave striking a barrier or obstacle can *reflect* and travel back to the source. For sound, this is an echo.
- For an object moving toward a source, it will detect a frequency Doppler shifted to a higher frequency.
- The wave reflected back will again be Doppler shifted since the object (where reflection occurred) is approaching the source.

Frequency Shift on Reflection from a Moving Object

- Thus, the echo from a moving object is "double Doppler shifted." The frequency *shift* of reflected waves is



- A *Doppler ultrasound* can detect not only structure but also motion.

Example 15.14 The Doppler blood flowmeter

If an ultrasound source is pressed against the skin, the sound waves reflect off tissues in the body. Some of the sound waves reflect from blood cells moving through arteries toward or away from the source, producing a frequency shift in the reflected wave. A biomedical engineer is designing a *Doppler blood flowmeter* to measure blood flow in an artery where a typical flow speed is known to be 0.60 m/s. What ultrasound frequency should she use to produce a frequency shift of 1500 Hz when this flow is detected?

Example 15.14 The Doppler blood flowmeter (cont.)

SOLVE We can rewrite Equation 15.18 to calculate the frequency of the emitter:

$$f_s = \left(\frac{\Delta f}{2}\right)\left(\frac{v}{v_{\text{blood}}}\right)$$

The values on the right side are all known. Thus the required ultrasound frequency is

$$f_s = \left(\frac{1500 \text{ Hz}}{2}\right)\left(\frac{1540 \text{ m/s}}{0.60 \text{ m/s}}\right) = 1.9 \text{ MHz}$$

Example 15.14 The Doppler blood flowmeter (cont.)

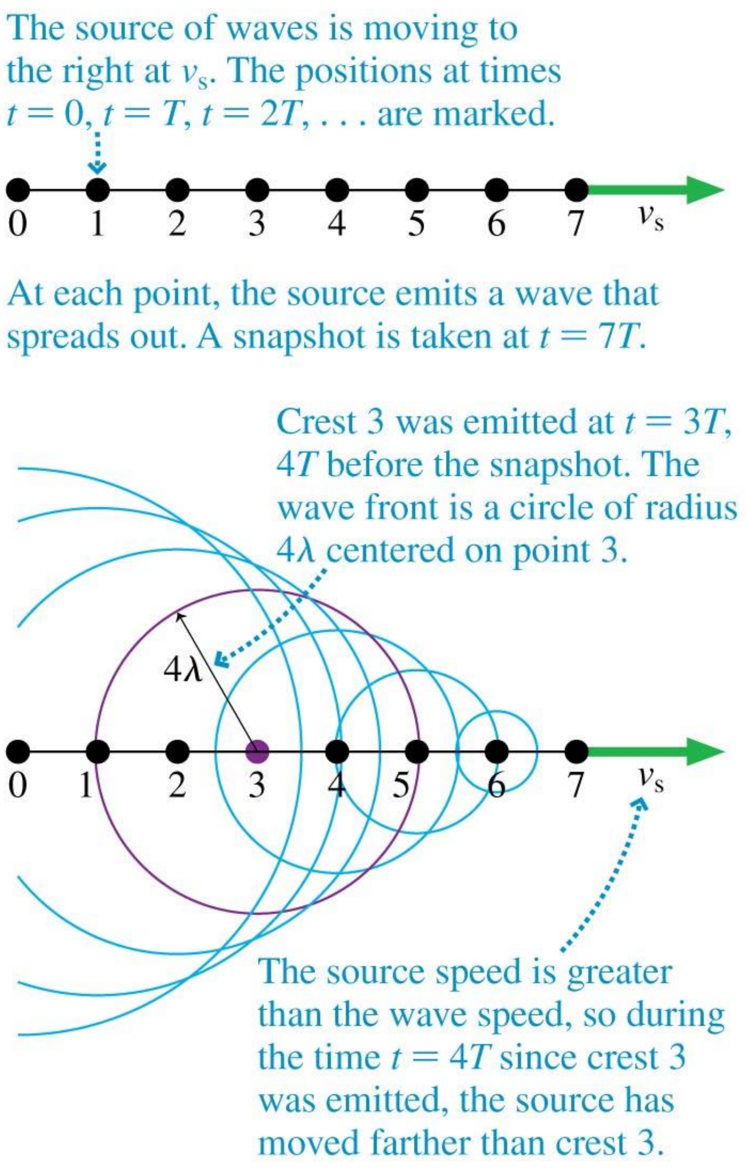
ASSESS Doppler units to measure blood flow in deep tissues actually work at about 2.0 MHz, so our answer is reasonable.

Example Problem

A Doppler ultrasound is used to measure the motion of blood in a patient's artery. The probe has a frequency of 5.0 MHz, and the maximum frequency shift on reflection is 400 Hz. What is the maximum speed of the blood in the artery?

Shock Waves

- A **shock wave** is produced when a source moves faster than the waves, which causes waves to overlap. The overlapping waves add up to a large amplitude wave, which is the shock wave.



Shock Waves

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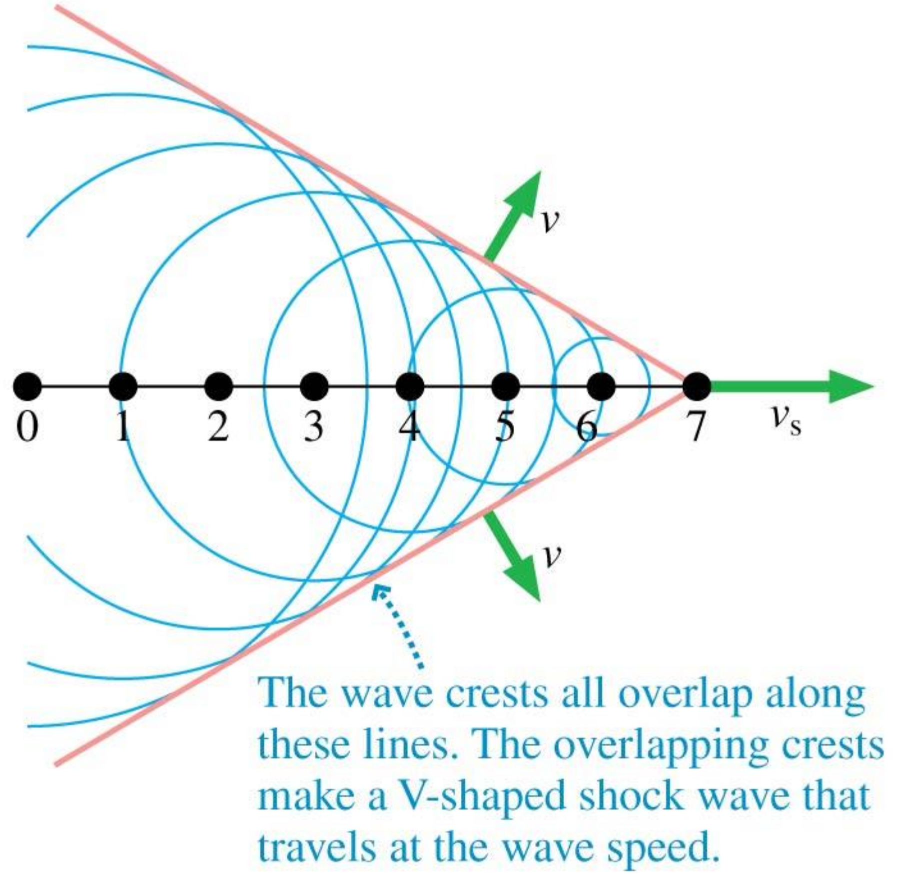
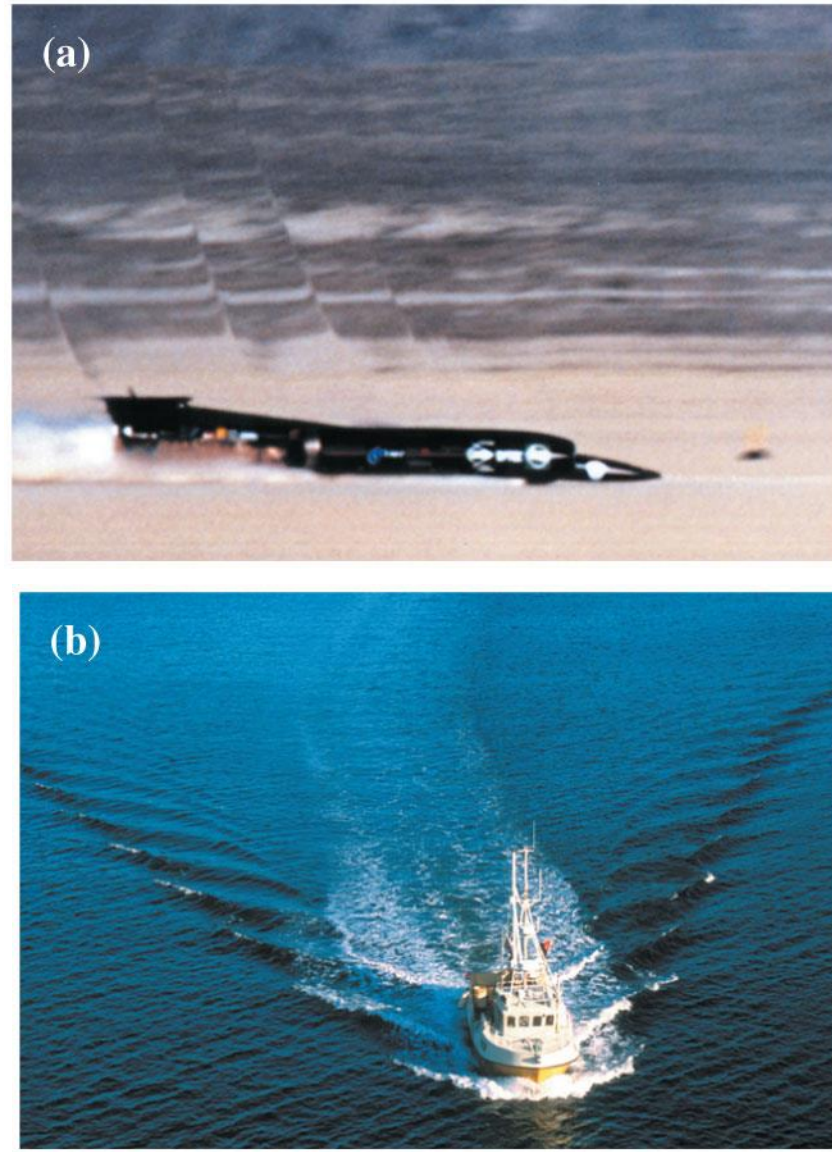


Shock Waves

- A source is **supersonic** if it travels faster than the speed of sound.
- A shock wave travels with the source. If a supersonic source passes an observer, the shock wave produces a **sonic boom**.
- Less extreme examples of shock waves include the wake of a boat and the crack of a whip.

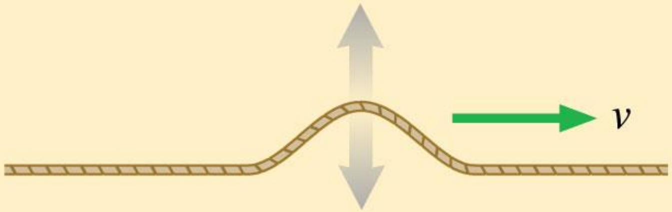


Summary: General Principles

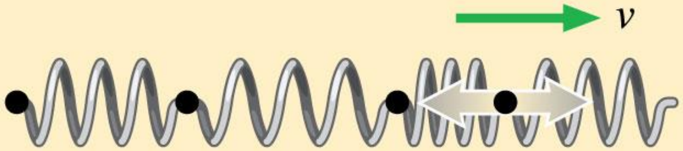
The Wave Model

This model is based on the idea of a **traveling wave,** which is an organized disturbance traveling at a well-defined **wave speed** v.

- In **transverse waves** the particles of the medium move *perpendicular* to the direction in which the wave travels.



- In **longitudinal waves** the particles of the medium move *parallel* to the direction in which the wave travels.



A wave transfers energy, but there is no material or substance transferred.

Text: p. 493

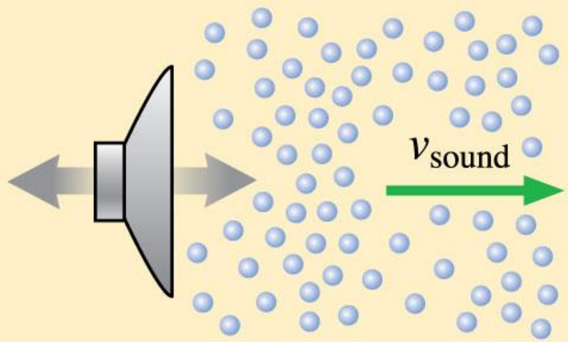
Summary: General Principles

Mechanical waves require a material **medium.** The speed of the wave is a property of the medium, not the wave. The speed does not depend on the size or shape of the wave.

- For a **wave on a string,** the string is the medium.

$$v_{string} = \sqrt{\frac{T_s}{\mu}}$$

- A **sound wave** is a wave of compressions and rarefactions of a medium such as air.



In a gas:

$$v_{sound} = \sqrt{\frac{\gamma RT}{M}}$$

Electromagnetic waves are waves of the electromagnetic field. They do not require a medium. All electromagnetic waves travel at the same speed in a vacuum, $c = 3.00 \times 10^8$ m/s.

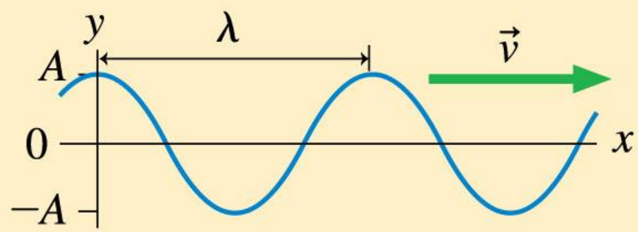
Text: p. 493

Summary: Important Concepts

Graphical representation of waves

A **snapshot graph** is a picture of a wave at one instant in time. For a periodic wave, the **wavelength** λ is the distance between crests.

Fixed t:



A **history graph** is a graph of the displacement of one point in a medium versus time. For a periodic wave, the **period** T is the time between crests.

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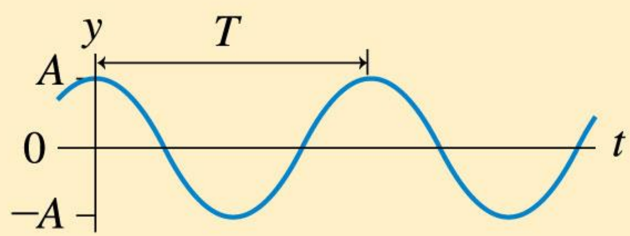

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Summary: Important Concepts

Mathematical representation of waves

Sinusoidal waves are produced by a source moving with simple harmonic motion. The equation for a sinusoidal wave is a function of position and time:

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

$+$: wave travels to left
$-$: wave travels to right

For sinusoidal waves:

$$T = \frac{1}{f} \qquad v = \lambda f$$

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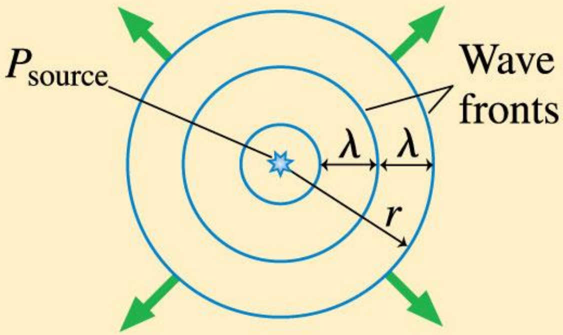
Summary: Important Concepts

The **intensity** of a wave is the ratio of the power to the area:

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

For a **spherical wave** the power decreases with the surface area of the spherical **wave fronts:**



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

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Summary: Applications

The loudness of a sound is given by the **sound intensity level.** This is a logarithmic function of intensity and is in units of **decibels.**

- The usual **reference level** is the quietest sound that can be heard:

$$I_0 = 1.0 \times 10^{-12}\ \mathrm{W/m^2}$$

- The sound intensity level in dB is computed relative to this value:

$$\beta = (10\ \mathrm{dB})\log_{10}\left(\frac{I}{I_0}\right)$$

- A sound at the reference level corresponds to 0 dB.

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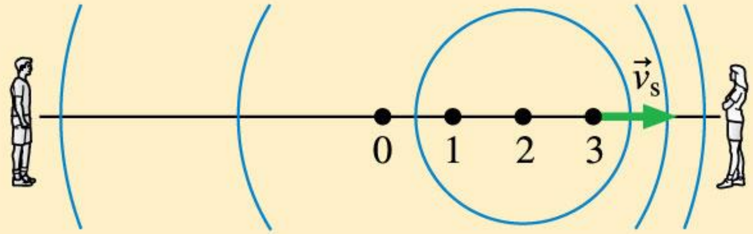
Summary: Applications

The **Doppler effect** is a shift in frequency when there is relative motion of a wave source (frequency f_s, wave speed v) and an observer.

Moving source, stationary observer:

Receding source:

$$f_- = \frac{f_s}{1 + v_s/v}$$



Approaching source:

$$f_+ = \frac{f_s}{1 - v_s/v}$$

Moving observer, stationary source:

Approaching the source:

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

Moving away from the source:

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Reflection from a moving object:

For $v_o \ll v$, $\Delta f = \pm 2 f_s \frac{v_o}{v}$

When an object moves faster than the wave speed in a medium, a **shock wave** is formed.

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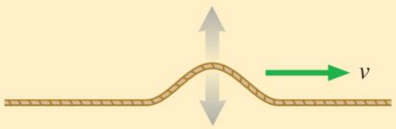
Summary

GENERAL PRINCIPLES

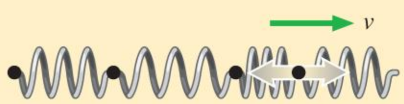
The Wave Model

This model is based on the idea of a **traveling wave,** which is an organized disturbance traveling at a well-defined **wave speed** v.

- In **transverse waves** the particles of the medium move *perpendicular* to the direction in which the wave travels.



- In **longitudinal waves** the particles of the medium move *parallel* to the direction in which the wave travels.



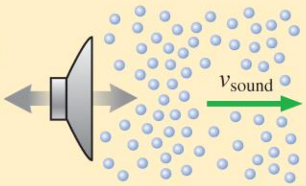
A wave transfers energy, but there is no material or substance transferred.

Mechanical waves require a material **medium.** The speed of the wave is a property of the medium, not the wave. The speed does not depend on the size or shape of the wave.

- For a **wave on a string,** the string is the medium.

$$v_{string} = \sqrt{\frac{T_s}{\mu}}$$

- A **sound wave** is a wave of compressions and rarefactions of a medium such as air.



In a gas:

$$v_{sound} = \sqrt{\frac{\gamma RT}{M}}$$

Electromagnetic waves are waves of the electromagnetic field. They do not require a medium. All electromagnetic waves travel at the same speed in a vacuum, $c = 3.00 \times 10^8$ m/s.

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Summary

IMPORTANT CONCEPTS

Graphical representation of waves

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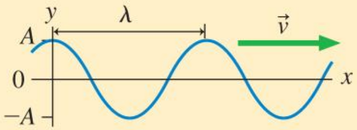

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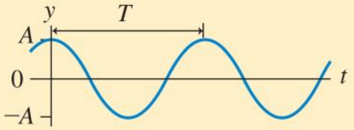

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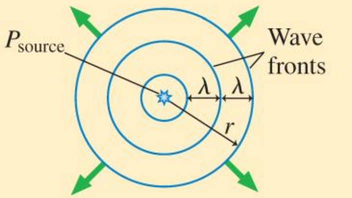

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Text: p. 493

Summary

APPLICATIONS

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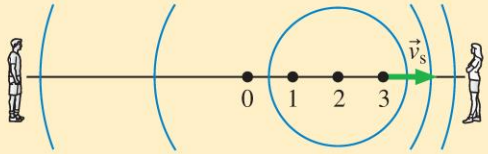

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