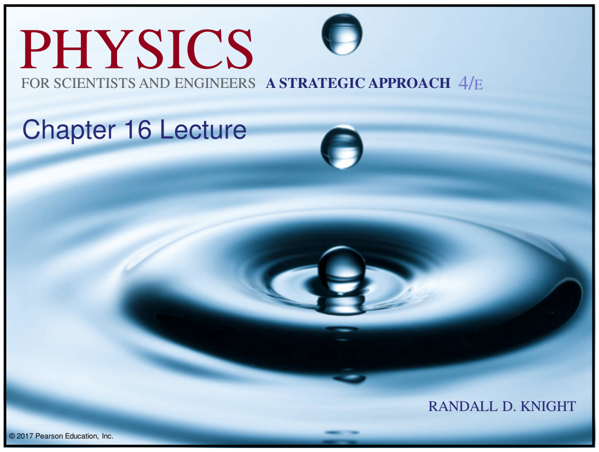


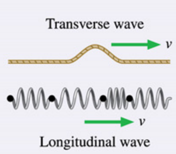
Chapter 16 Traveling Waves

IN THIS CHAPTER, you will learn the basic properties of traveling waves.

Chapter 16 Preview

What is a wave?

A wave is a disturbance traveling through a medium. In a transverse wave, the displacement is perpendicular to the direction of travel. In a longitudinal wave, the displacement is parallel to the direction of travel.

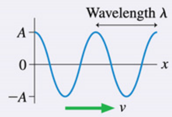


Chapter 16 Preview

What are some wave properties?

A wave is characterized by:

- Wave speed: How fast it travels through the medium.
- Wavelength: The distance between two neighboring crests.
- Frequency: The number of oscillations per second.
- Amplitude: The maximum displacement.



« LOOKING BACK Sections 15.1–15.2 Properties of simple harmonic motion

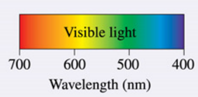
 Slide 16-4

Chapter 16 Preview

Are sound and light waves?

Yes! Very important waves.

- Sound waves are longitudinal waves.
- Light waves are transverse waves.



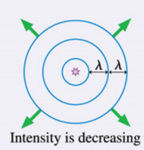
The colors of visible light correspond to different wavelengths.

 Slide 16-5

Chapter 16 Preview

Do waves carry energy?

They do. The rate at which a wave delivers energy to a surface is the intensity of the wave. For sound waves, we'll use a logarithmic decibel scale to characterize the loudness of a sound.

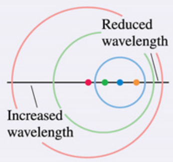


 Slide 16-6

Chapter 16 Preview

What is the Doppler effect?

The frequency and wavelength of a wave are shifted if there is relative motion between the source and the observer of the waves. This is called the Doppler effect. It explains why the pitch of an ambulance siren drops as it races past you.



Slide 16-7

Chapter 16 Preview

How will I use waves?

Waves are literally everywhere. Communications systems from radios to cell phones to fiber optics use waves. Sonar and radar and medical ultrasound use waves. Music and musical instruments are all about waves. Waves are present in the oceans, the atmosphere, and the earth. This chapter and the next will allow you to understand and work with a wide variety of waves that you may meet in your career.

Slide 16-8

Chapter 16 Reading Questions

Slide 16-9

Reading Question 16.1

A graph showing wave displacement versus position at a specific instant of time is called a

A. Snapshot graph.
B. History graph.
C. Bar graph.
D. Line graph.
E. Composite graph.

Reading Question 16.1

A graph showing wave displacement versus position at a specific instant of time is called a

✔**A. Snapshot graph.**
B. History graph.
C. Bar graph.
D. Line graph.
E. Composite graph.

Reading Question 16.2

A graph showing wave displacement versus time at a specific point in space is called a

A. Snapshot graph.
B. History graph.
C. Bar graph.
D. Line graph.
E. Composite graph.

Reading Question 16.2

A graph showing wave displacement versus time at a specific point in space is called a

A. Snapshot graph.
✔**B. History graph.**
C. Bar graph.
D. Line graph.
E. Composite graph.

Slide 16-13

Reading Question 16.3

A *wave front diagram* shows

A. The wavelengths of a wave.
B. The crests of a wave.
C. How the wave looks as it moves toward you.
D. The forces acting on a string that's under tension.
E. Wave front diagrams were not discussed in this chapter.

Slide 16-14

Reading Question 16.3

A *wave front diagram* shows

A. The wavelengths of a wave.
✔**B. The crests of a wave.**
C. How the wave looks as it moves toward you.
D. The forces acting on a string that's under tension.
E. Wave front diagrams were not discussed in this chapter.

Slide 16-15

Reading Question 16.4

The constant, k, introduced in Section 16.3 on Sinusoidal Waves, is

A. The Boltzman's constant, with units: J/K
B. The Coulomb constant, with units: N m^2/c^2
C. The force constant, with units: n/m
D. The wave number, with units: rad/m
E. The wavelength, with units: m

Slide 16-16

Reading Question 16.4

The constant, k, introduced in Section 16.3 on Sinusoidal Waves, is

A. The Boltzman's constant, with units: J/K
B. The Coulomb constant, with units: N m^2/c^2
C. The force constant, with units: n/m
✔**D. The wave number, with units: rad/m**
E. The wavelength, with units: m

Slide 16-17

Reading Question 16.5

The waves analyzed in this chapter are

A. String waves.
B. Sound and light waves.
C. Sound and water waves.
D. String, sound, and light waves.
E. String, water, sound, and light waves.

Slide 16-18

Reading Question 16.5

The waves analyzed in this chapter are

A. String waves.
B. Sound and light waves.
C. Sound and water waves.
✔**D. String, sound, and light waves.**
E. String, water, sound, and light waves.

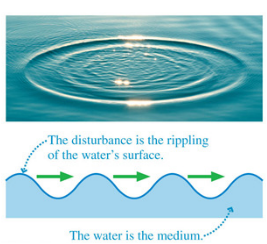
Slide 16-19

Chapter 16 Content, Examples, and QuickCheck Questions

Slide 16-20

The Wave Model

- The wave model is built around the idea of a **traveling wave**, which is an organized disturbance traveling with a well-defined wave speed.
- The **medium** of a mechanical wave is the substance through or along which the wave moves.

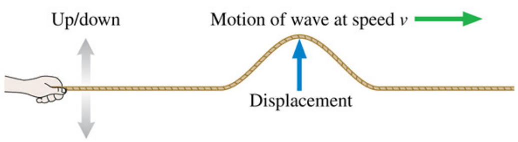


Slide 16-21

A Transverse Wave

- A **transverse wave** is a wave in which the displacement is *perpendicular* to the direction in which the wave travels.
- For example, a wave travels along a string in a horizontal direction while the particles that make up the string oscillate vertically.

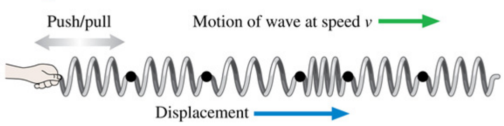
A transverse wave



A Longitudinal Wave

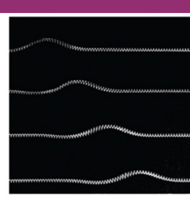
- In a **longitudinal wave**, the particles in the medium move *parallel* to the direction in which the wave travels.
- Here we see a chain of masses connected by springs.
- If you give the first mass in the chain a sharp push, a disturbance travels down the chain by compressing and expanding the springs.

A longitudinal wave



Wave Speed

- The speed of transverse waves on a string stretched with tension T_s is



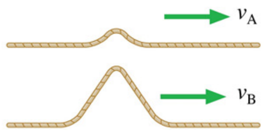
$$v_{\text{string}} = \sqrt{\frac{T_s}{\mu}} \quad \text{(wave speed on a stretched string)}$$

where μ is the string's mass-to-length ratio, also called the **linear density**:

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

QuickCheck 16.1

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



A. $v_A > v_B$

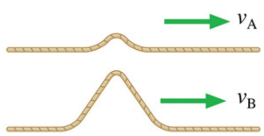
B. $v_B > v_A$

C. $v_A = v_B$

D. Not enough information to tell.

QuickCheck 16.1

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.** $\mathbf{v_A = v_B}$ Wave speed depends on the properties of the medium, not on the amplitude of the wave.

D. Not enough information to tell.

QuickCheck 16.2

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 16.2

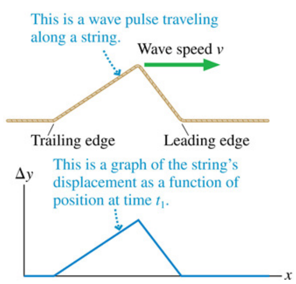
For a wave pulse on a string to travel twice as fast, the string tension must be

✔**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.

Slide 16-28

Snapshot Graph

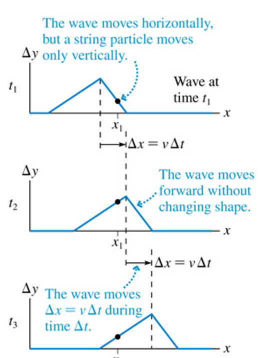
- A graph that shows the wave's displacement as a function of position at a single instant of time is called a **snapshot graph**.
- For a wave on a string, a snapshot graph is literally a picture of the wave at this instant.



Slide 16-29

One-Dimensional Waves

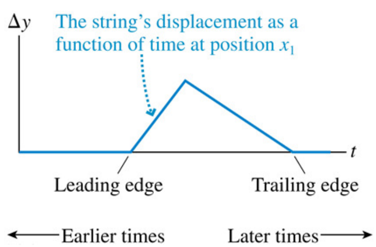
- The figure shows a sequence of snapshot graphs as a wave pulse moves.
- These are like successive frames from a movie.
- Notice that the wave pulse moves forward distance $\Delta x = v\Delta t$ during the time interval Δt.
- That is, the wave moves with *constant speed.*



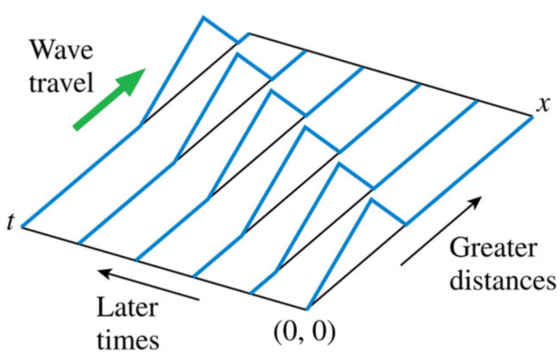
Slide 16-30

History Graph

- A graph that shows the wave's displacement as a function of time at a single position in space is called a **history graph**.
- This graph tells the history of that particular point in the medium.
- Note that for a wave moving from left to right, the shape of the history graph is *reversed* compared to the snapshot graph.



An Alternative Look at a Traveling Wave

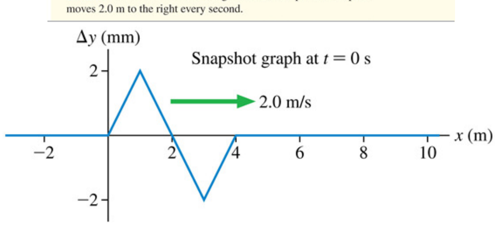


Example 16.2 Finding a History Graph From a Snapshot Graph

EXAMPLE 16.2 | **Finding a history graph from a snapshot graph**

FIGURE 16.7 is a snapshot graph at $t = 0$ s of a wave moving to the right at a speed of 2.0 m/s. Draw a history graph for the position $x = 8.0$ m.

MODEL This is a wave traveling at constant speed. The pulse moves 2.0 m to the right every second.



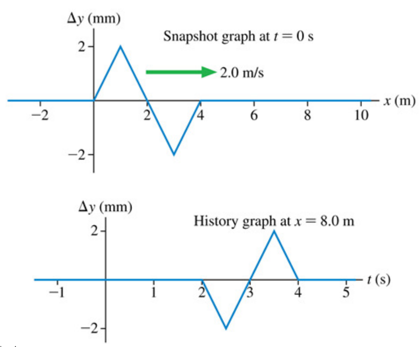
Example 16.2 Finding a History Graph From a Snapshot Graph

EXAMPLE 16.2 | **Finding a history graph from a snapshot graph**

VISUALIZE The snapshot graph of Figure 16.7 shows the wave at all points on the x-axis at $t = 0$ s. You can see that nothing is happening at $x = 8.0$ m at this instant of time because the wave has not yet reached $x = 8.0$ m. In fact, at $t = 0$ s the leading edge of the wave is still 4.0 m away from $x = 8.0$ m. Because the wave is traveling at 2.0 m/s, it will take 2.0 s for the leading edge to reach $x = 8.0$ m. Thus the history graph for $x = 8.0$ m will be zero until $t = 2.0$ s. The first part of the wave causes a *downward* displacement of the medium, so immediately after $t = 2.0$ s the displacement at $x = 8.0$ m will be negative.

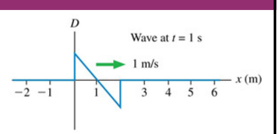
The negative portion of the wave pulse is 2.0 m wide and takes 1.0 s to pass $x = 8.0$ m, so the midpoint of the pulse reaches $x = 8.0$ m at $t = 3.0$ s. The positive portion takes another 1.0 s to go past, so the trailing edge of the pulse arrives at $t = 4.0$ s. You could also note that the trailing edge was initially 8.0 m away from $x = 8.0$ m and needed 4.0 s to travel that distance at 2.0 m/s. The displacement at $x = 8.0$ m returns to zero at $t = 4.0$ s and remains zero for all later times. This information is all portrayed on the history graph of FIGURE 16.8.

Example 16.2 Finding a History Graph From a Snapshot Graph

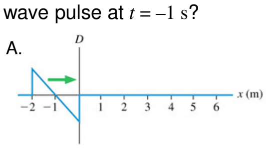


QuickCheck 16.3

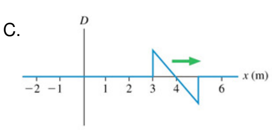
This is a snapshot graph at $t = 1$ s of a wave pulse traveling to the right at 1 m/s. Which graph below shows the wave pulse at $t = -1$ s?



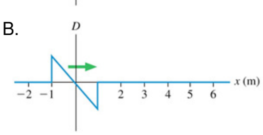
A.



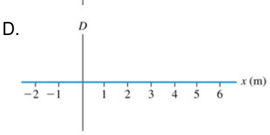
C.



B.



D.



QuickCheck 16.3

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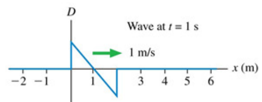
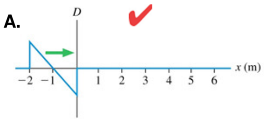
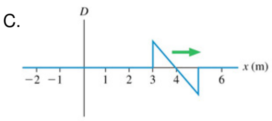


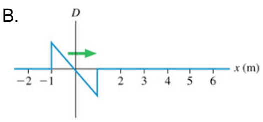
A. ✔



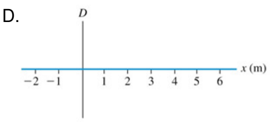
C.



B.

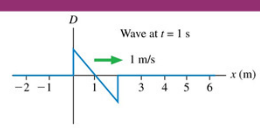


D.

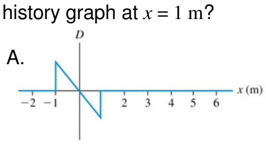


QuickCheck 16.4

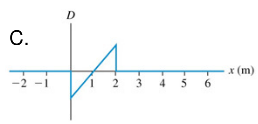
This is a snapshot graph at $t = 1$ s of a wave pulse traveling to the right at 1 m/s. Which graph below shows the history graph at $x = 1$ m?



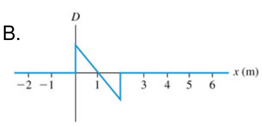
A.



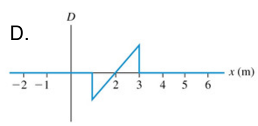
C.



B.

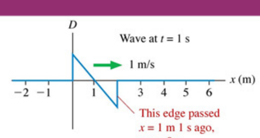


D.

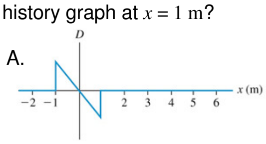


QuickCheck 16.4

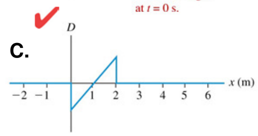
This is a snapshot graph at $t = 1$ s of a wave pulse traveling to the right at 1 m/s. Which graph below shows the history graph at $x = 1$ m?



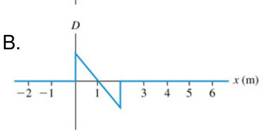
A.



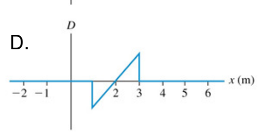
✔ **C.**



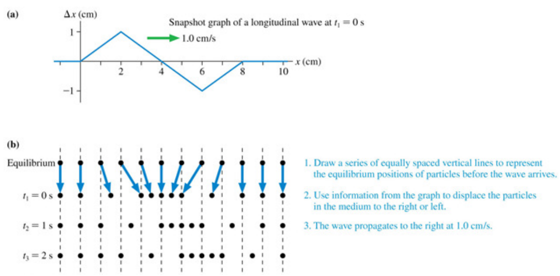
B.



D.



Visualizing a Longitudinal Wave



 Slide 16-40

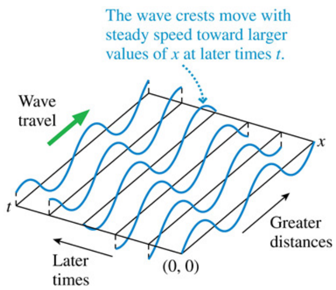
The Displacement

- In "the wave" at a sporting event, the wave moves around the stadium, but the particles (people) undergo small displacements from their equilibrium positions.
- When describing a wave mathematically, we'll use the generic symbol D to stand for the *displacement* of a wave of any type.
- $D(x, t)$ = the displacement at time t of a particle at position x.

 Slide 16-41

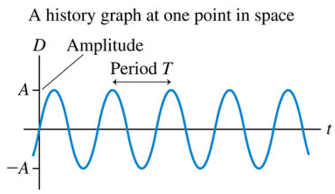
Sinusoidal Waves

- A wave source at $x = 0$ that oscillates with simple harmonic motion (SHM) generates a **sinusoidal wave**.



 Slide 16-42

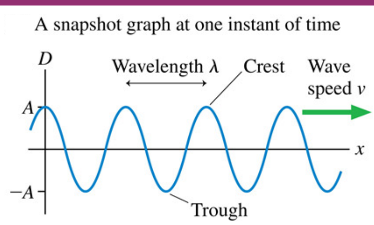
Sinusoidal Waves



- Above is a history graph for a sinusoidal wave, showing the displacement of the medium at one point in space.
- Each particle in the medium undergoes simple harmonic motion with frequency f, where $f = 1/T$.
- The **amplitude** A of the wave is the maximum value of the displacement.

Slide 16-43

Sinusoidal Waves

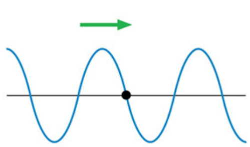


- Above is a snapshot graph for a sinusoidal wave, showing the wave stretched out in space, moving to the right with speed v.
- The distance spanned by one cycle of the motion is called the wavelength λ of the wave.

Slide 16-44

QuickCheck 16.5

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

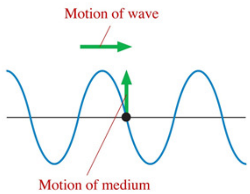


A. Up.
B. Down.
C. Right.
D. Left.
E. Zero. Instantaneously at rest.

Slide 16-45

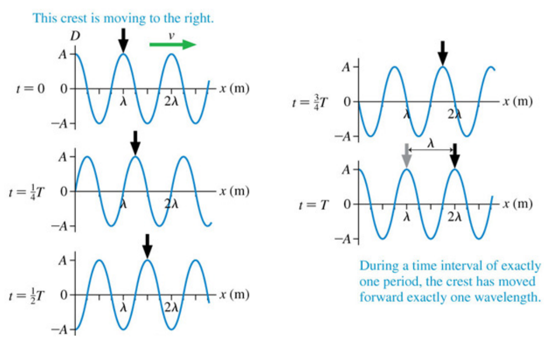
QuickCheck 16.5

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.

Sinusoidal Waves



Sinusoidal Waves

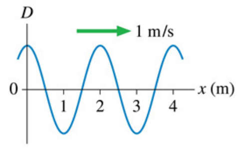
- The distance spanned by one cycle of the motion is called the **wavelength** λ of the wave. Wavelength is measured in units of meters.
- During a time interval of exactly one period T, each crest of a sinusoidal wave travels forward a distance of exactly one wavelength λ.
- Because speed is distance divided by time, the **wave speed** must be

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

or, in terms of frequency: $v = \lambda f$

QuickCheck 16.6

The period of this wave is



A. 1 s

B. 2 s

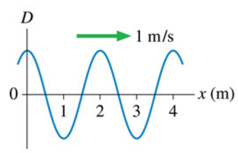
C. 4 s

D. Not enough information to tell.

Slide 16-49

QuickCheck 16.6

The period of this wave is



A. 1 s

✔ **B. 2 s** A sinusoidal wave moves forward one wavelength (2 m) in one period.

C. 4 s

D. Not enough information to tell.

Slide 16-50

The Mathematics of Sinusoidal Waves

- Define the *angular frequency* of a wave:

$$\omega = 2\pi f = \frac{2\pi}{T}$$

- Define the *wave number* of a wave:

$$k = \frac{2\pi}{\lambda}$$

- The displacement caused by a traveling sinusoidal wave is

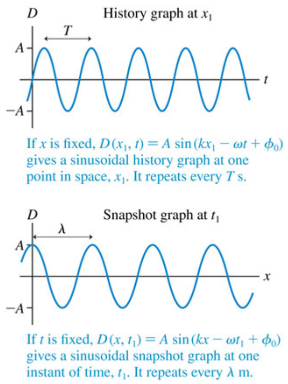
$$D(x, t) = A\sin(kx - \omega t + \phi_0)$$

(sinusoidal wave traveling in the positive x-direction)

- This wave travels at a speed $v = \omega/k$.

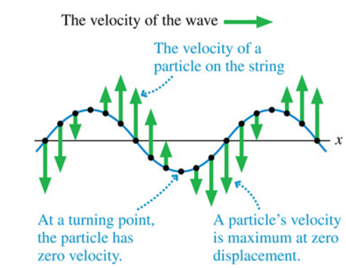
Slide 16-51

Equation of a Sinusoidal Traveling Wave



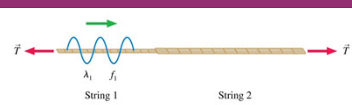
Wave Motion on a String

- Shown is a snapshot graph of a wave on a string with vectors showing the velocity of the string at various points.
- The velocity of the medium—**which is not the same as the velocity of the wave along the string**—is the time derivative of $D(x, t)$:



$$v = \frac{dD}{dt} = -\omega A\cos(kx - \omega t + \phi_0)$$

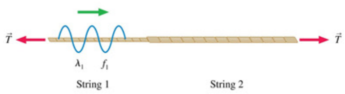
QuickCheck 16.7



A sinusoidal wave travels along a lightweight string with wavelength λ_1 and frequency f_1. It reaches a heavier string, with a slower wave speed, and continues on with wavelength λ_2 and frequency f_2. Which is true?

A. $\lambda_2 = \lambda_1$ and $f_2 < f_1$
B. $\lambda_2 = \lambda_1$ and $f_2 > f_1$
C. $\lambda_2 > \lambda_1$ and $f_2 = f_1$
D. $\lambda_2 < \lambda_1$ and $f_2 = f_1$
E. $\lambda_2 < \lambda_1$ and $f_2 < f_1$

QuickCheck 16.7

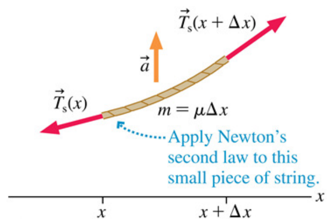


A sinusoidal wave travels along a lightweight string with wavelength λ_1 and frequency f_1. It reaches a heavier string, with a slower wave speed, and continues on with wavelength λ_2 and frequency f_2. Which is true?

A. $\lambda_2 = \lambda_1$ and $f_2 < f_1$
B. $\lambda_2 = \lambda_1$ and $f_2 > f_1$
C. $\lambda_2 > \lambda_1$ and $f_2 = f_1$
✔ **D. $\lambda_2 < \lambda_1$ and $f_2 = f_1$**
E. $\lambda_2 < \lambda_1$ and $f_2 < f_1$

Advanced Topic: The Wave Equation on a String

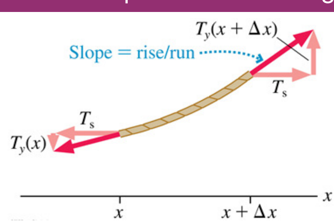
- The figure shows a small piece of string that is displaced from its equilibrium position.
- This piece is at position x and has a small horizontal width Δx.



- We're can apply Newton's second law, the familiar $F_{net} = ma$, to this little piece of string.
- Notice that it's curved, so the tension forces at the ends are *not* opposite each other.
- This is essential in order for there to be a net force.

Advanced Topic: The Wave Equation on a String

- The figure shows our little piece of the string with the tension forces resolved into x- and y-components.
- We identify the two horizontal components as T_s.



- Because they are equal but opposite, the net horizontal force is zero.
- The net force on this little piece of string in the transverse direction (the y-direction) is

$$F_{net\,y} = T_y(x + \Delta x) + T_y(x)$$

Advanced Topic: The Wave Equation on a String

- We can apply Newton's second law to a string segment of mass $\mu\Delta x$, where μ is the linear density of the string in kg/m.
- We make use of the partial derivatives of $D(x,t)$ with respect to time and distance:

$$\frac{\partial^2 D}{\partial t^2} = \frac{T_s}{\mu}\frac{\partial^2 D}{\partial x^2} \quad \text{(wave equation for a string)}$$

- This is the **wave equation** for a string.
- Just like Newton's second law for a particle, it governs the dynamics of motion on a string.

Slide 16-58

Traveling Wave Solutions

- Now that we have a wave equation for a string, we can apply it to a well known solution, sinusoidal waves:

$$D(x, t) = A\sin(kx - \omega t + \phi_0)$$

- Applying the wave equation, we can solve for the speed of this wave, which we know is ω/k:

$$v = \frac{\omega}{k} = \sqrt{\frac{T_s}{\mu}}$$

- We derived this specifically for a string, but any physical system that obeys the wave equation will support sinusoidal waves traveling with speed v:

$$\frac{\partial^2 D}{\partial t^2} = v^2\frac{\partial^2 D}{\partial x^2} \quad \text{(the general wave equation)}$$

Slide 16-59

Example 16.4 Generating a Sinusoidal Wave

EXAMPLE 16.4 **Generating a sinusoidal wave**

A very long string with $\mu = 2.0$ g/m is stretched along the x-axis with a tension of 5.0 N. At $x = 0$ m it is tied to a 100 Hz simple harmonic oscillator that vibrates perpendicular to the string with an amplitude of 2.0 mm. The oscillator is at its maximum positive displacement at $t = 0$ s.

a. Write the displacement equation for the traveling wave on the string.

b. At $t = 5.0$ ms, what is the string's displacement at a point 2.7 m from the oscillator?

MODEL The oscillator generates a sinusoidal traveling wave on a string. The displacement of the wave has to match the displacement of the oscillator at $x = 0$ m.

Slide 16-60

Example 16.4 Generating a Sinusoidal Wave

EXAMPLE 16.4 Generating a sinusoidal wave

SOLVE a. The equation for the displacement is

$$D(x, t) = A\sin(kx - \omega t + \phi_0)$$

with A, k, ω, and ϕ_0 to be determined. The wave amplitude is the same as the amplitude of the oscillator that generates the wave, so $A = 2.0$ mm. The oscillator has its maximum displacement $y_{osc} = A = 2.0$ mm at $t = 0$ s, thus

$$D(0\text{ m}, 0\text{ s}) = A\sin(\phi_0) = A$$

This requires the phase constant to be $\phi_0 = \pi/2$ rad. The wave's frequency is $f = 100$ Hz, the frequency of the source; therefore the angular frequency is $\omega = 2\pi f = 200\pi$ rad/s.

Example 16.4 Generating a Sinusoidal Wave

EXAMPLE 16.4 Generating a sinusoidal wave

SOLVE a. We still need $k = 2\pi/\lambda$ but we do not know the wavelength. However, we have enough information to determine the wave speed, and we can then use either $\lambda = v/f$ or $k = w/v$. The speed is

$$v = \sqrt{\frac{T_s}{\mu}} = \sqrt{\frac{5.0\text{ N}}{0.0020\text{ kg/m}}} = 50\text{ m/s}$$

Using v, we find $\lambda = 0.50$ m and $k = 2\pi/\lambda = 4\pi$ rad/m. Thus the wave's displacement equation is

$$D(x, t) = (2.0\text{ mm}) \times \sin\left[2\pi\left((2.0\text{ m}^{-1})x - (100\text{ s}^{-1})t\right) + \pi/2\text{ rad}\right]$$

Notice that we have separated out the 2π. This step is not essential, but for some problems it makes subsequent steps easier.

Example 16.4 Generating a Sinusoidal Wave

EXAMPLE 16.4 Generating a sinusoidal wave

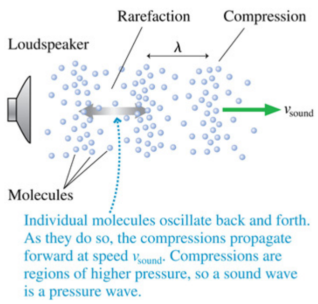
SOLVE b. The wave's displacement at $t = 5.0$ ms $= 0.0050$ s is

$$D(x, t = 5.0\text{ ms}) = (2.0\text{ mm})\sin(4\pi x - \pi\text{ rad} + \pi/2\text{ rad}) = (2.0\text{ mm})\sin(4\pi x - \pi/2\text{ rad})$$

At $x = 2.7$ m (calculator set to radians!), the displacement is

$$D(2.7\text{ m}, 5.0\text{ ms}) = 1.6\text{ mm}$$

Sound Waves



- A sound wave in a fluid is a sequence of compressions and rarefactions.
- The variation in density and the amount of motion have been greatly exaggerated in this figure.

Slide 16-64

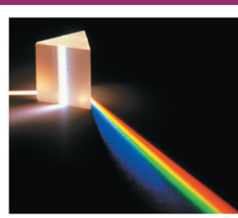
Sound Waves

- For air at room temperature (20°C), the speed of sound is v_{sound} = 343 m/s.
- Your ears are able to detect sinusoidal sound waves with frequencies between about 20 Hz and 20 kHz.
- Low frequencies are perceived as "low pitch" bass notes, while high frequencies are heard as "high pitch" treble notes.
- Sound waves with frequencies above 20 kHz are called *ultrasonic* frequencies.
- Oscillators vibrating at frequencies of many MHz generate the ultrasonic waves used in ultrasound medical imaging.

Slide 16-65

Electromagnetic Waves

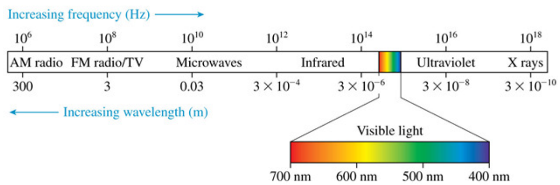
- A light wave is an *electromagnetic wave*, an oscillation of the electromagnetic field.
- Other electromagnetic waves, such as radio waves, microwaves, and ultraviolet light, have the same physical characteristics as light waves, even though we cannot sense them with our eyes.



- All electromagnetic waves travel through vacuum with the same speed, called the *speed of light*.
- The value of the speed of light is c = 299,792,458 m/s.
- At this speed, light could circle the earth 7.5 times in a mere second—if there were a way to make it go in circles!

Slide 16-66

The Electromagnetic Spectrum



 Slide 16-67

Example 16.5 Traveling at the Speed of Light

EXAMPLE 16.5 Traveling at the speed of light

A satellite exploring Jupiter transmits data to the earth as a radio wave with a frequency of 200 MHz. What is the wavelength of the electromagnetic wave, and how long does it take the signal to travel 800 million kilometers from Jupiter to the earth?

SOLVE Radio waves are sinusoidal electromagnetic waves traveling with speed c. Thus

$$\lambda = \frac{c}{f} = \frac{3.00 \times 10^8 \text{ m/s}}{2.00 \times 10^8 \text{ Hz}} = 1.5 \text{ m}$$

The time needed to travel 800×10^6 km $= 8.0 \times 10^{11}$ m is

$$\Delta t = \frac{\Delta x}{c} = \frac{8.0 \times 10^{11} \text{ m}}{3.00 \times 10^8 \text{ m/s}} = 2700 \text{ s} = 45 \text{ min}$$

 Slide 16-68

The Index of Refraction

- Light waves travel with speed c in a vacuum, but they slow down as they pass through transparent materials such as water or glass or even, to a very slight extent, air.
- The speed of light in a material is characterized by the material's **index of refraction** n, defined as

$$n = \frac{\text{speed of light in a vacuum}}{\text{speed of light in the material}} = \frac{c}{v}$$

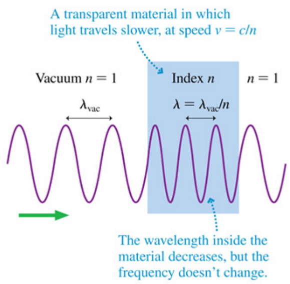
TABLE 16.2 Typical indices of refraction

Material	Index of refraction
Vacuum	1 exactly
Air	1.0003
Water	1.33
Glass	1.50
Diamond	2.42

 Slide 16-69

The Index of Refraction

- As a light wave travels through vacuum it has wavelength λ_{vac} and frequency f_{vac}.
- When it enters a transparent material, the frequency does not change, so the wavelength must:

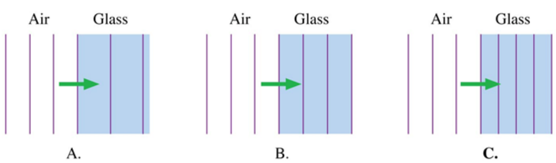


$$\lambda_{mat} = \frac{v}{f_{mat}} = \frac{c}{nf_{mat}} = \frac{c}{nf_{vac}} = \frac{\lambda_{vac}}{n}$$

Slide 16-70

QuickCheck 16.8

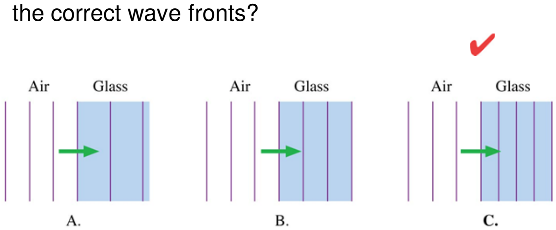
A light wave travels, as a plane wave, from air ($n = 1.0$) into glass ($n = 1.5$). Which diagram shows the correct wave fronts?



Slide 16-71

QuickCheck 16.8

A light wave travels, as a plane wave, from air ($n = 1.0$) into glass ($n = 1.5$). Which diagram shows the correct wave fronts?



Slide 16-72

Example 16.6 Light Traveling Through Glass

EXAMPLE 16.6 **Light traveling through glass**

Orange light with a wavelength of 600 nm is incident upon a 1.00-mm-thick glass microscope slide.

a. What is the light speed in the glass?

b. How many wavelengths of the light are inside the slide?

SOLVE a. From Table 16.2 we see that the index of refraction of glass is $n_{glass} = 1.50$. Thus the speed of light in glass is

$$v_{glass} = \frac{c}{n_{glass}} = \frac{3.00 \times 10^8 \text{ m/s}}{1.50} = 2.00 \times 10^8 \text{ m/s}$$

b. The wavelength inside the glass is

$$\lambda_{glass} = \frac{\lambda_{vac}}{n_{glass}} = \frac{600 \text{ nm}}{1.50} = 400 \text{ nm} = 4.00 \times 10^{-7} \text{ m}$$

N wavelengths span a distance $d = N\lambda$, so the number of wavelengths in $d = 1.00$ mm is

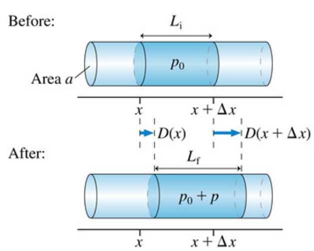
$$N = \frac{d}{\lambda} = \frac{1.00 \times 10^{-3} \text{ m}}{4.00 \times 10^{-7} \text{ m}} = 2500$$

ASSESS The fact that 2500 wavelengths fit within 1 mm shows how small the wavelengths of light are.

Advanced Topic: The Wave Equation in a Fluid

- Recall from Chapter 14 that if excess pressure p is applied to an object of volume V, then the fractional change in volume is

$$\frac{\Delta V}{V} = -\frac{p}{B}$$



- This excess fluid pressure at position x can be related to the displacement of the medium by

$$p(x, t) = -B\frac{\partial D}{\partial x}$$

Advanced Topic: The Wave Equation in a Fluid

- A displacement wave of amplitude A

$$D(x, t) = A\sin(kx - \omega t + \phi_0)$$

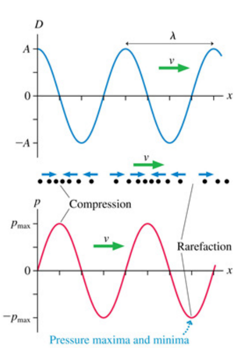
is associated with a pressure wave

$$p(x, t) = -B\frac{\partial D}{\partial x} = -kBA\cos(kx - \omega t + \phi_0)$$
$$= -p_{max}\cos(kx - \omega t + \phi_0)$$

- The pressure amplitude, or maximum excess pressure, is

$$p_{max} = kBA = \frac{2\pi fBA}{v_{sound}}$$

- **A sound wave is also a traveling pressure wave.**



Predicting the Speed of Sound

- Applying Newton's second law along x to the displacement $D(x,t)$ of a small, cylindrical piece of fluid gives a wave equation:

$$\frac{\partial^2 D}{\partial t^2} = \frac{B}{\rho}\frac{\partial^2 D}{\partial x^2}$$

- By comparing this to the general wave equation discussed for waves on a string, we can predict the speed of sound in a fluid:

$$v_{\text{sound}} = \sqrt{\frac{B}{\rho}}$$

 Slide 16-76

Example 16.7 The Speed of Sound in Water

EXAMPLE 16.7 | **The speed of sound in water**

Predict the speed of sound in water at 20°C.

SOLVE From Table 16.3, the bulk modulus of water at 20°C is 2.18×10^9 Pa. The density of water is usually given as 1000 kg/m^3, but this is at 4°C. To three significant figures, the density at 20°C is 998 kg/m^3. Thus we predict

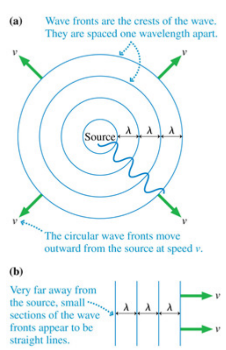
$$v_{\text{sound}} = \sqrt{\frac{2.18 \times 10^9\ \text{Pa}}{998\ \text{kg/m}^3}} = 1480\ \text{m/s}$$

This is exactly the value given earlier in Table 16.1.

 Slide 16-77

Waves in Two and Three Dimensions

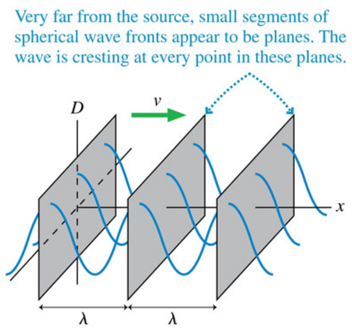
- Consider circular ripples spreading on a pond.
- The lines that locate the crests are called **wave fronts**.
- If you observe circular wave fronts very, very far from the source, they appear to be straight lines.



 Slide 16-78

Waves in Two and Three Dimensions

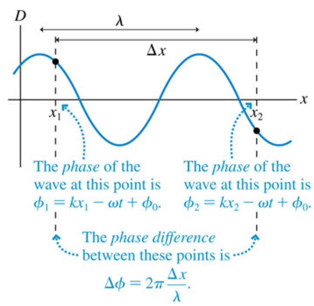
- Loudspeakers and lightbulbs emit **spherical waves**.
- That is, the crests of the wave form a series of concentric spherical shells.
- Far from the source this is a **plane wave**.



 Slide 16-79

Phase and Phase Difference

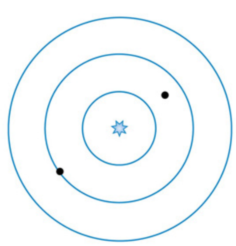
- The quantity $(kx - \omega t + \phi_0)$ is called the **phase** of the wave, denoted ϕ.
- The *phase* difference $\Delta\phi$ between two points on a wave depends on only the ratio of their separation Δx to the wavelength λ.
- The phase difference between two adjacent wave fronts is 2π rad.



 Slide 16-80

QuickCheck 16.9

A spherical wave travels outward from a point source. What is the phase difference between the two points on the wave marked with dots?

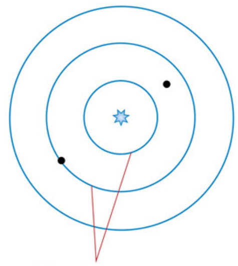


A. $\pi/4$ radians
B. $\pi/2$ radians
C. π radians
D. $7\pi/2$ radians
E. 7π radians

 Slide 16-81

QuickCheck 16.9

A spherical wave travels outward from a point source. What is the phase difference between the two points on the wave marked with dots?



A. $\pi/4$ radians

B. $\pi/2$ radians

✔**C. π radians**

D. $7\pi/2$ radians

E. 7π radians

Slide 16-82

Example 16.8 The Phase Difference Between Two Points on a Sound Wave

EXAMPLE 16.8 **The phase difference between two points on a sound wave**

A 100 Hz sound wave travels with a wave speed of 343 m/s.

a. What is the phase difference between two points 60.0 cm apart along the direction the wave is traveling?

b. How far apart are two points whose phase differs by 90°?

MODEL Treat the wave as a plane wave traveling in the positive x-direction.

SOLVE a. The phase difference between two points is

$$\Delta\phi = 2\pi\frac{\Delta x}{\lambda}$$

In this case, $\Delta x = 60.0 \text{ cm} = 0.600 \text{ m}$. The wavelength is

$$\lambda = \frac{v}{f} = \frac{343 \text{ m/s}}{100 \text{ Hz}} = 3.43 \text{ m}$$

and thus

$$\Delta\phi = 2\pi\frac{0.600 \text{ m}}{3.43 \text{ m}} = 0.350\pi \text{ rad} = 63.0°$$

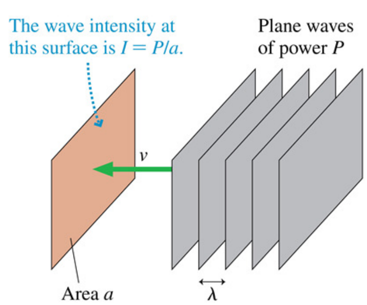
b. A phase difference $\Delta\phi = 90°$ is $\pi/2$ rad. This will be the phase difference between two points when $\Delta x/\lambda = \frac{1}{4}$, or when $\Delta x = \lambda/4$. Here, with $\lambda = 3.43$ m, $\Delta x = 85.8$ cm.

ASSESS The phase difference increases as Δx increases, so we expect the answer to part b to be larger than 60 cm.

Slide 16-83

Power and Intensity

- The *power* of a wave is the rate, in joules per second, at which the wave transfers energy.
- When plane waves of power P impinge on area a, we define the **intensity** I to be



$$I = \frac{P}{a} = \text{power-to-area ratio}$$

Slide 16-84

Example 16.9 The Intensity of a Laser Beam

EXAMPLE 16.9 **The intensity of a laser beam**

A typical red laser pointer emits 1.0 mW of light power into a 1.0-mm-diameter laser beam. What is the intensity of the laser beam?

MODEL The laser beam is a light wave.

Example 16.9 The Intensity of a Laser Beam

EXAMPLE 16.9 **The intensity of a laser beam**

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

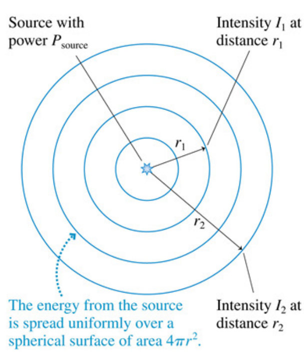
$$I = \frac{P}{a} = \frac{P}{\pi r^2} = \frac{0.0010\ \text{W}}{\pi(0.00050\ \text{m})^2} = 1300\ \text{W/m}^2$$

ASSESS This is roughly the intensity of sunlight at noon on a summer day. The difference between the sun and a small laser is not their intensities, which are about the same, but their powers. The laser has a small power of 1 mW. It can produce a very intense wave only because the area through which the wave passes is very small. The sun, by contrast, radiates a total power $P_{sun} \approx 4 \times 10^{26}$ W. This immense power is spread through *all* of space, producing an intensity of 1400 W/m^2 at a distance of 1.5×10^{11} m, the radius of the earth's orbit.

Intensity of Spherical Waves

- If a source of spherical waves radiates uniformly in all directions, then the power at distance r is spread uniformly over the surface of a sphere of radius r.
- The intensity of a uniform spherical wave is

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



Intensity and Decibels

- Human hearing spans an extremely wide range of intensities, from the *threshold of hearing* at $\approx 1 \times 10^{-12}$ W/m^2 (at midrange frequencies) to the *threshold of pain* at ≈ 10 W/m^2.
- If we want to make a scale of loudness, it's convenient and logical to place the zero of our scale at the threshold of hearing.
- To do so, we define the **sound intensity level**, expressed in **decibels** (dB), as

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

where $I_0 = 1 \times 10^{-12}$ W/m^2.

Intensity and Decibels

TABLE 16.4 Sound intensity levels of common sounds

Sound	β (dB)
Threshold of hearing	0
Person breathing, at 3 m	10
A whisper, at 1 m	20
Quiet room	30
Outdoors, no traffic	40
Quiet restaurant	50
Normal conversation, at 1 m	60
Busy traffic	70
Vacuum cleaner, for user	80
Niagara Falls, at viewpoint	90
Snowblower, at 2 m	100
Stereo, at maximum volume	110
Rock concert	120
Threshold of pain	130
Loudest football stadium	140

QuickCheck 16.11

The sound intensity level from one solo flute is 70 db. If 10 flutists standing close together play in unison, the sound intensity level will be

A. 700 db
B. 80 db
C. 79 db
D. 71 db
E. 70 db

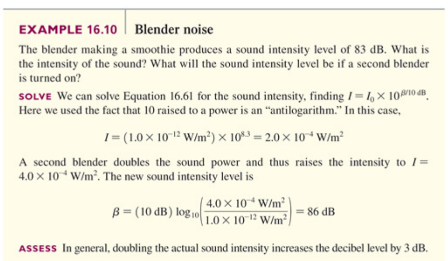
QuickCheck 16.11

The sound intensity level from one solo flute is 70 db. If 10 flutists standing close together play in unison, the sound intensity level will be

A. 700 db
✔**B. 80 db**
C. 79 db
D. 71 db
E. 70 db

Slide 16-91

Example 16.10 Blender Noise



EXAMPLE 16.10 | **Blender noise**

The blender making a smoothie produces a sound intensity level of 83 dB. What is the intensity of the sound? What will the sound intensity level be if a second blender is turned on?

SOLVE We can solve Equation 16.61 for the sound intensity, finding $I = I_0 \times 10^{\beta/10\text{ dB}}$. Here we used the fact that 10 raised to a power is an "antilogarithm." In this case,

$$I = (1.0 \times 10^{-12}\text{ W/m}^2) \times 10^{8.3} = 2.0 \times 10^{-4}\text{ W/m}^2$$

A second blender doubles the sound power and thus raises the intensity to $I = 4.0 \times 10^{-4}\text{ W/m}^2$. The new sound intensity level is

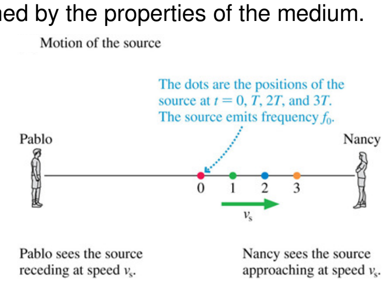
$$\beta = (10\text{ dB})\log_{10}\left(\frac{4.0 \times 10^{-4}\text{ W/m}^2}{1.0 \times 10^{-12}\text{ W/m}^2}\right) = 86\text{ dB}$$

ASSESS In general, doubling the actual sound intensity increases the decibel level by 3 dB.

Slide 16-92

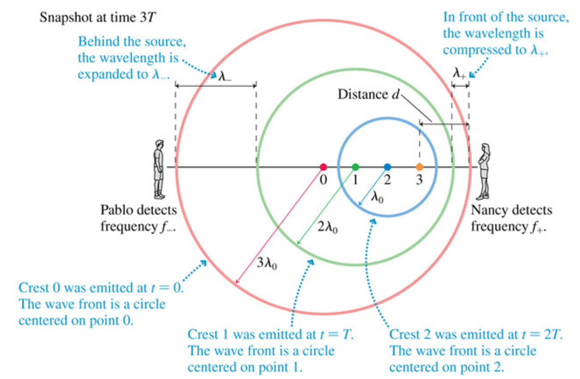
The Doppler Effect

- A source of sound waves moving away from Pablo and toward Nancy at a steady speed v_s.
- After a wave crest leaves the source, its motion is governed by the properties of the medium.



Slide 16-93

The Doppler Effect



 Slide 16-94

The Doppler Effect

- As the wave source approaches Nancy, she detects a frequency f_+ which is slightly higher than f_0, the natural frequency of the source.
- If the source moves at a steady speed directly toward Nancy, this frequency f_+ does not change with time.
- As the wave source recedes away from Pablo, he detects a frequency f_- which is slightly lower than f_0, the natural frequency of the source.
- Again, as long as the speed of the source is constant, f_- is constant in time.

 Slide 16-95

The Doppler Effect

- The frequencies heard by a stationary observer when the sound source is moving at speed v_0 are

$$f_+ = \frac{f_0}{1 - v_s/v} \quad \text{(Doppler effect for an approaching source)}$$

$$f_- = \frac{f_0}{1 + v_s/v} \quad \text{(Doppler effect for a receding source)}$$

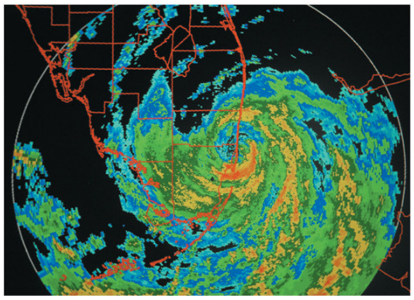
- The frequencies heard by an observer moving at speed v_0 relative to a stationary sound source emitting frequency f_0 are

$$f_+ = (1 + v_o/v)f_0 \quad \text{(observer approaching a source)}$$

$$f_- = (1 - v_o/v)f_0 \quad \text{(observer receding from a source)}$$

 Slide 16-96

The Doppler Effect

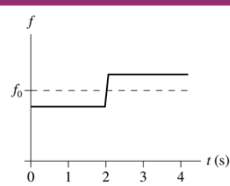


- Doppler weather radar uses the Doppler shift of reflected radar signals to measure wind speeds and thus better gauge the severity of a storm.

Slide 16-97

QuickCheck 16.12

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.

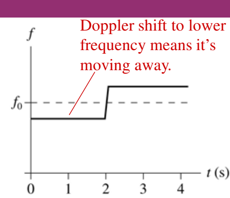
C. It moves toward you for 2 s but doesn't reach you, then reverses direction at $t = 2$ s and moves away.

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.

Slide 16-98

QuickCheck 16.12

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.**

Slide 16-99

Example 16.11 How Fast Are the Police Traveling?

EXAMPLE 16.11 **How fast are the police traveling?**

A police siren has a frequency of 550 Hz as the police car approaches you, 450 Hz after it has passed you and is receding. How fast are the police traveling? The temperature is 20°C.

MODEL The siren's frequency is altered by the Doppler effect. The frequency is f_+ as the car approaches and f_- as it moves away.

Slide 16-100

Example 16.11 How Fast Are the Police Traveling?

EXAMPLE 16.11 **How fast are the police traveling?**

SOLVE To find v_s, we rewrite Equations 16.65 as

$$f_0 = (1 + v_s/v)f_-$$
$$f_0 = (1 - v_s/v)f_+$$

We subtract the second equation from the first, giving

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

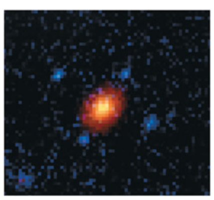
This is easily solved to give

$$v_s = \frac{f_+ - f_-}{f_+ + f_-}v = \frac{100 \text{ Hz}}{1000 \text{ Hz}} \times 343 \text{ m/s} = 34.3 \text{ m/s}$$

ASSESS If you now solve for the siren frequency when at rest, you will find $f_0 = 495$ Hz. Surprisingly, the at-rest frequency is not halfway between f_- and f_+.

Slide 16-101

The Doppler Effect for Light Waves



- Shown is a Hubble Space Telescope picture of a *quasar*.
- Quasars are extraordinarily powerful and distant sources of light and radio waves.
- This quasar is receding away from us at more than 90% of the speed of light.
- Any receding source of light is red shifted.
- Any approaching source of light is blue shifted.

$$\lambda_- = \sqrt{\frac{1 + v_s/c}{1 - v_s/c}}\,\lambda_0 \quad \text{(receding source)}$$

$$\lambda_+ = \sqrt{\frac{1 - v_s/c}{1 + v_s/c}}\,\lambda_0 \quad \text{(approaching source)}$$

Slide 16-102

Example 16.12 Measuring the Velocity of a Galaxy

EXAMPLE 16.12 **Measuring the velocity of a galaxy**

Hydrogen atoms in the laboratory emit red light with wavelength 656 nm. In the light from a distant galaxy, this "spectral line" is observed at 691 nm. What is the speed of this galaxy relative to the earth?

MODEL The observed wavelength is longer than the wavelength emitted by atoms at rest with respect to the observer (i.e., red shifted), so we are looking at light emitted from a galaxy that is receding from us.

Example 16.12 Measuring the Velocity of a Galaxy

EXAMPLE 16.12 **Measuring the velocity of a galaxy**

SOLVE Squaring the expression for λ_- in Equations 16.67 and solving for v_s give

$$v_s = \frac{(\lambda_-/\lambda_0)^2 - 1}{(\lambda_-/\lambda_0)^2 + 1}c$$

$$= \frac{(691\text{ nm}/656\text{ nm})^2 - 1}{(691\text{ nm}/656\text{ nm})^2 + 1}c$$

$$= 0.052c = 1.56 \times 10^7\text{ m/s}$$

ASSESS The galaxy is moving away from the earth at about 5% of the speed of light!

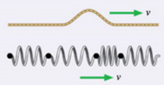
Chapter 16 Summary Slides

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 displacement is perpendicular to the direction in which the wave travels.
- In longitudinal waves the particles of the medium are displaced parallel to the direction in which the wave travels.



A wave transfers **energy**, but no material or substance is transferred outward from the source.

General Principles

Two basic classes of waves:

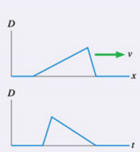
- Mechanical waves travel through a material medium such as water or air.
- Electromagnetic waves require no material medium and can travel through a vacuum.

For mechanical waves, such as sound waves and waves on strings, the speed of the wave is a property of the medium. Speed does not depend on the size or shape of the wave.

Important Concepts

The **displacement** D of a wave is a function of both position (where) and time (when).

- A snapshot graph shows the wave's displacement as a function of position at a single instant of time.
- A history graph shows the wave's displacement as a function of time at a single point in space.



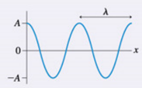
For a transverse wave on a string, the snapshot graph is a picture of the wave. The displacement of a longitudinal wave is parallel to the motion; thus the snapshot graph of a longitudinal sound wave is *not* a picture of the wave.

Important Concepts

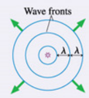
Sinusoidal waves are periodic in both time (period T) and space (wavelength λ):

$$D(x, t) = A \sin[2\pi(x/\lambda - t/T) + \phi_0]$$
$$= A \sin(kx - \omega t + \phi_0)$$

where A is the **amplitude,** $k = 2\pi/\lambda$ is the **wave number,** $\omega = 2\pi f = 2\pi/T$ is the **angular frequency,** and ϕ_0 is the **phase constant** that describes initial conditions.



One-dimensional waves



Two- and three-dimensional waves

The fundamental relationship for any sinusoidal wave is $v = \lambda f$.

Slide 16-109

Applications

- **String** (transverse): $v = \sqrt{T_s/\mu}$
- **Sound** (longitudinal): $v = \sqrt{B/\rho} = 343$ m/s in 20°C air
- **Light** (transverse): $v = c/n$, where $c = 3.00 \times 10^8$ m/s is the speed of light in a vacuum and n is the material's **index of refraction**

Slide 16-110

Applications

The wave **intensity** is the power-to-area ratio: $I = P/a$
For a circular or spherical wave: $I = P_{source}/4\pi r^2$
The **sound intensity level** is

$$\beta = (10 \text{ dB}) \log_{10}(I/1.0 \times 10^{-12} \text{ W/m}^2)$$

Slide 16-111

Applications

The **Doppler effect** occurs when a wave source and detector are moving with respect to each other: the frequency detected differs from the frequency f_0 emitted.

Approaching source

$$f_+ = \frac{f_0}{1 - v_s/v}$$

Observer approaching a source

$$f_+ = (1 + v_o/v)f_0$$

Receding source

$$f_- = \frac{f_0}{1 + v_s/v}$$

Observer receding from a source

$$f_- = (1 - v_o/v)f_0$$

The Doppler effect for light uses a result derived from the theory of relativity.

Slide 16-112