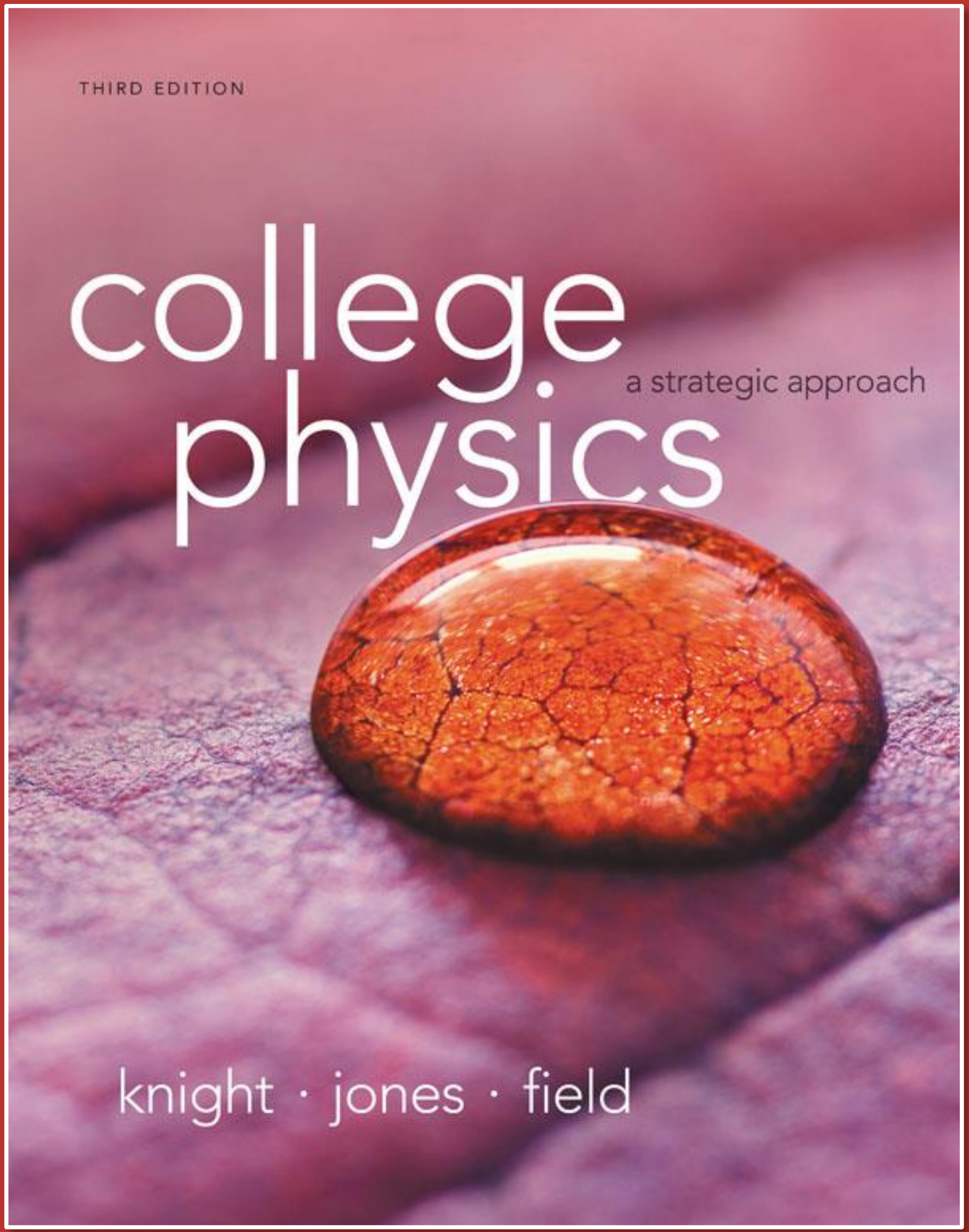


Lecture Presentation

Chapter 16

Superposition and Standing Waves

Suggested Videos for Chapter 16

- **Prelecture Videos**
  - *Constructive and Destructive Interference*
  - *Standing Waves*
  - *Physics of Your Vocal System*
- **Video Tutor Solutions**
  - *Superposition and Standing Waves*
- **Class Videos**
  - *Standing Sound Waves*
  - *Harmonics and Voices*
- **Video Tutor Demos**
  - *Vibrating Rods*
  - *Out-of-Phase Speakers*

Suggested Simulations for Chapter 16

- **ActivPhysics**
  - *10.4–10.7*

- **PhETs**
  - *Wave Interference*
  - *Wave on a String*

Chapter 16 Superposition and Standing Waves

Chapter Goal: To use the idea of superposition to understand the phenomena of interference and standing waves.

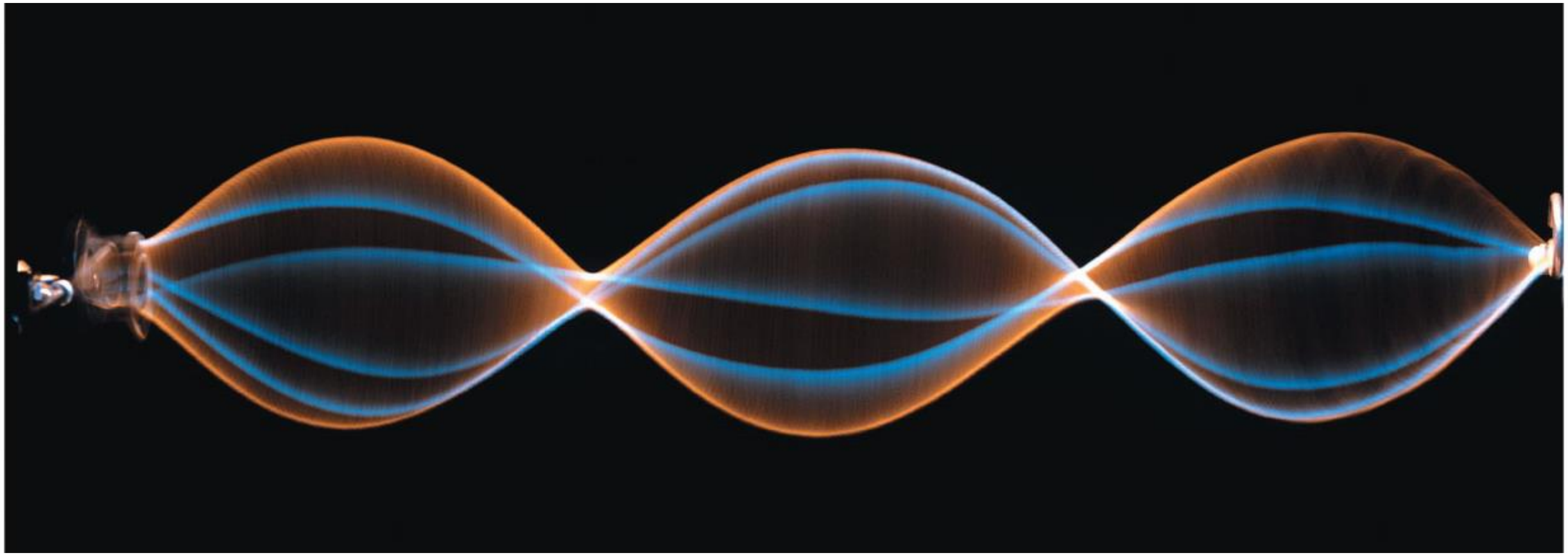
Chapter 16 Preview
Looking Ahead: Superposition

- Where the two water waves meet, the motion of the water is a sum, a **superposition**, of the waves.

- You'll learn how this **interference** can be constructive or destructive, leading to larger or smaller amplitudes.

Chapter 16 Preview
Looking Ahead: Standing Waves

- The superposition of waves on a string can lead to a wave that oscillates in place—a **standing wave**.



- You'll learn the patterns of standing waves on strings and standing sound waves in tubes.

Chapter 16 Preview
Looking Ahead: Speech and Hearing

- Changing the shape of your mouth alters the pattern of standing sound waves in your vocal tract.

- You'll learn how your vocal tract produces, and your ear interprets, different mixes of waves.

Chapter 16 Preview
Looking Ahead

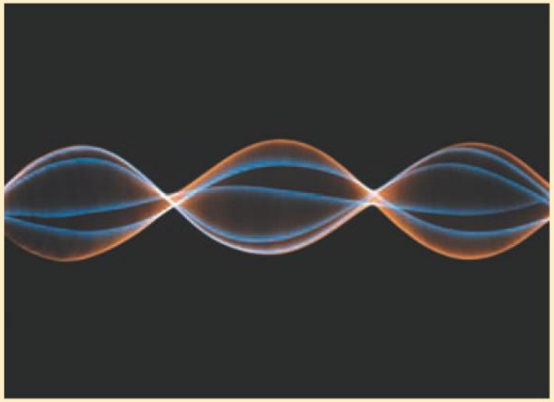
Superposition

Where the two water waves meet, the motion of the water is a sum, a **superposition,** of the waves.

You'll learn how this **interference** can be constructive or destructive, leading to larger or smaller amplitudes.

Standing Waves

The superposition of waves on a string can lead to a wave that oscillates in place—a **standing wave.**



You'll learn the patterns of standing waves on strings and standing sound waves in tubes.

Speech and Hearing

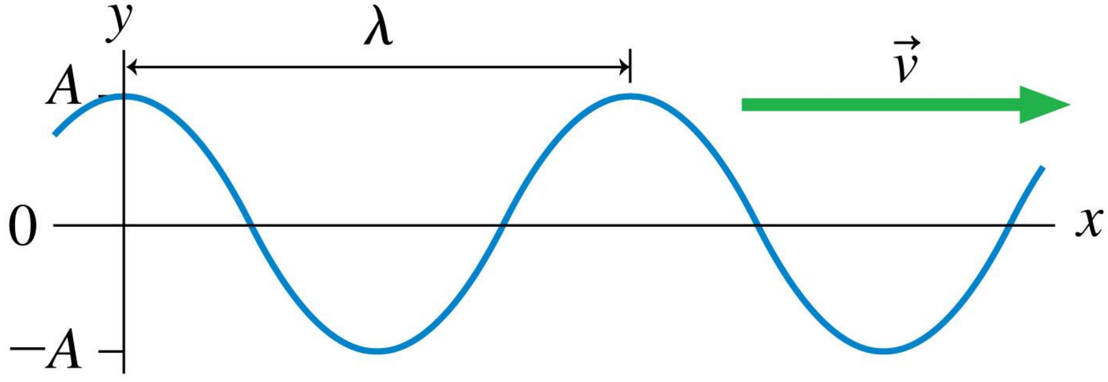
Changing the shape of your mouth alters the pattern of standing sound waves in your vocal tract.

You'll learn how your vocal tract produces, and your ear interprets, different mixes of waves.

Text: p. 500

Chapter 16 Preview
Looking Back: Traveling Waves

- In Chapter 15 you learned the properties of traveling waves and relationships among the variables that describe them.
- In this chapter, you'll extend the analysis to understand the interference of waves and the properties of standing waves.



$$v = \lambda f$$

Chapter 16 Preview
Stop to Think

A 170 Hz sound wave in air has a wavelength of 2.0 m. The frequency is now doubled to 340 Hz. What is the new wavelength?

A. 4.0 m
B. 3.0 m
C. 2.0 m
D. 1.0 m

Reading Question 16.1

When two waves overlap, the displacement of the medium is the sum of the displacements of the two individual waves. This is the principle of __________.

A. Constructive interference
B. Destructive interference
C. Standing waves
D. Superposition

Reading Question 16.1

When two waves overlap, the displacement of the medium is the sum of the displacements of the two individual waves. This is the principle of ___________.

A. Constructive interference
B. Destructive interference
C. Standing waves
✔ D. Superposition

Reading Question 16.2

A point on a standing wave that is always stationary is a __________.

A. Maximum
B. Minimum
C. Node
D. Antinode

Reading Question 16.2

A point on a standing wave that is always stationary is a __________.

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B. Minimum
✔ C. Node
D. Antinode

Reading Question 16.3

You can decrease the frequency of a standing wave on a string by

A. Making the string longer.
B. Using a thicker string.
C. Decreasing the tension.
D. All of the above

Reading Question 16.3

You can decrease the frequency of a standing wave on a string by

A. Making the string longer.
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C. Decreasing the tension.
✔ D. All of the above

Reading Question 16.4

We describe sound waves in terms of pressure. Given this, for a standing wave in a tube open at each end, the open ends of the tube are

A. Nodes.
B. Antinodes.
C. Neither nodes or antinodes.

Reading Question 16.4

We describe sound waves in terms of pressure. Given this, for a standing wave in a tube open at each end, the open ends of the tube are

✔ A. Nodes.
B. Antinodes.
C. Neither nodes or antinodes.

Reading Question 16.5

The interference of two sound waves of similar amplitude but slightly different frequencies produces a loud-soft-loud oscillation we call

A. Constructive and destructive interference.
B. The Doppler effect.
C. Beats.
D. Vibrato.

Reading Question 16.5

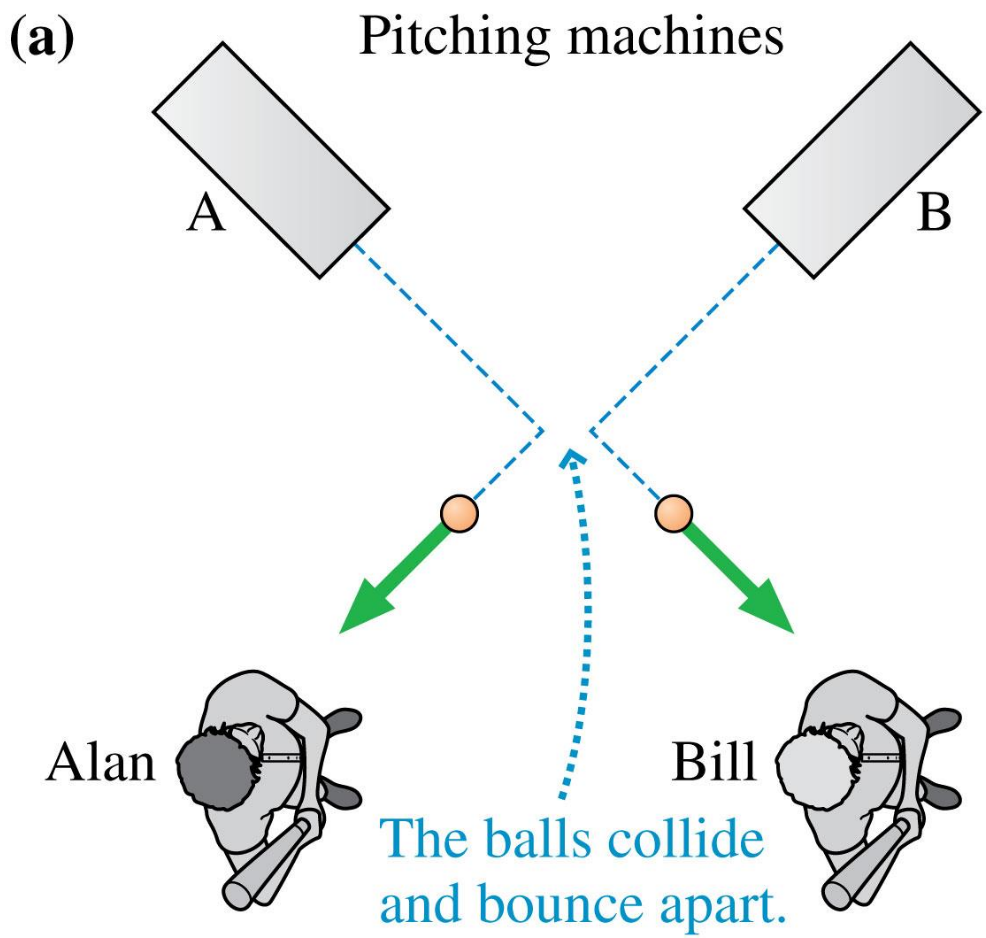
The interference of two sound waves of similar amplitude but slightly different frequencies produces a loud-soft-loud oscillation we call

A. Constructive and destructive interference.
B. The Doppler effect.
✔ C. Beats.
D. Vibrato.

Section 16.1 The Principle of Superposition

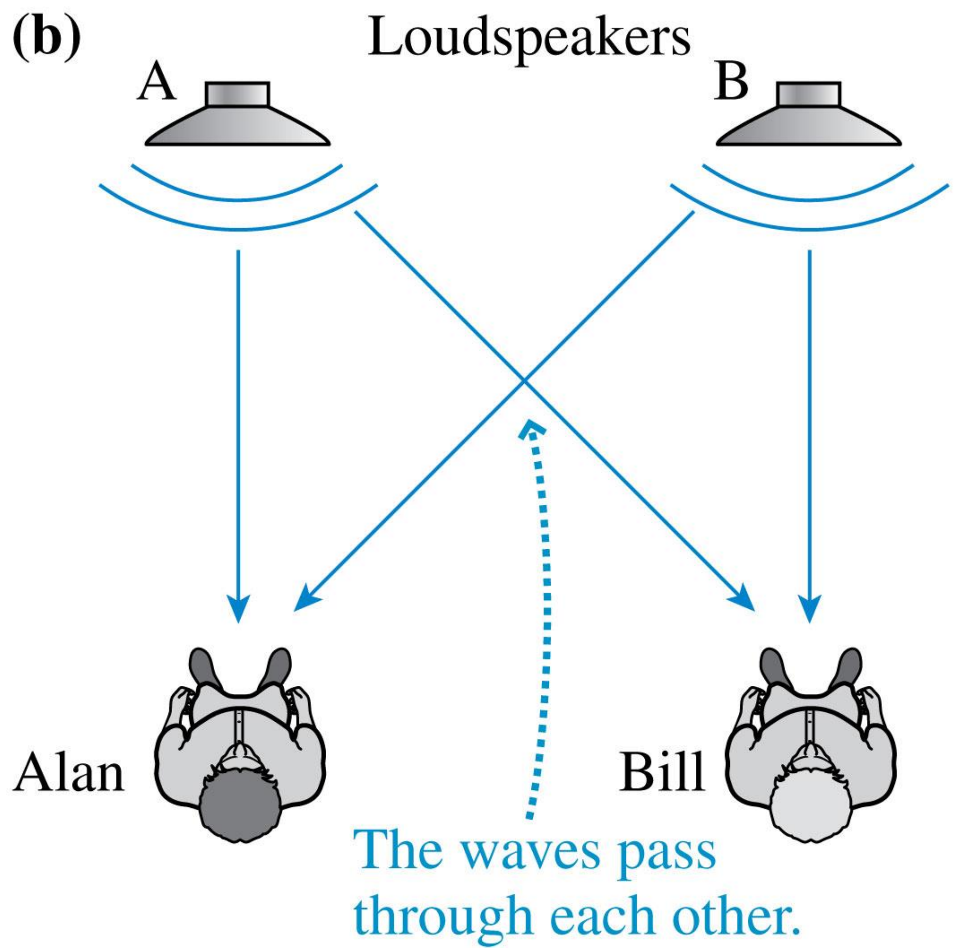
The Principle of Superposition

- If two baseballs are thrown across the same point at the same time, the balls will hit one another and be deflected.



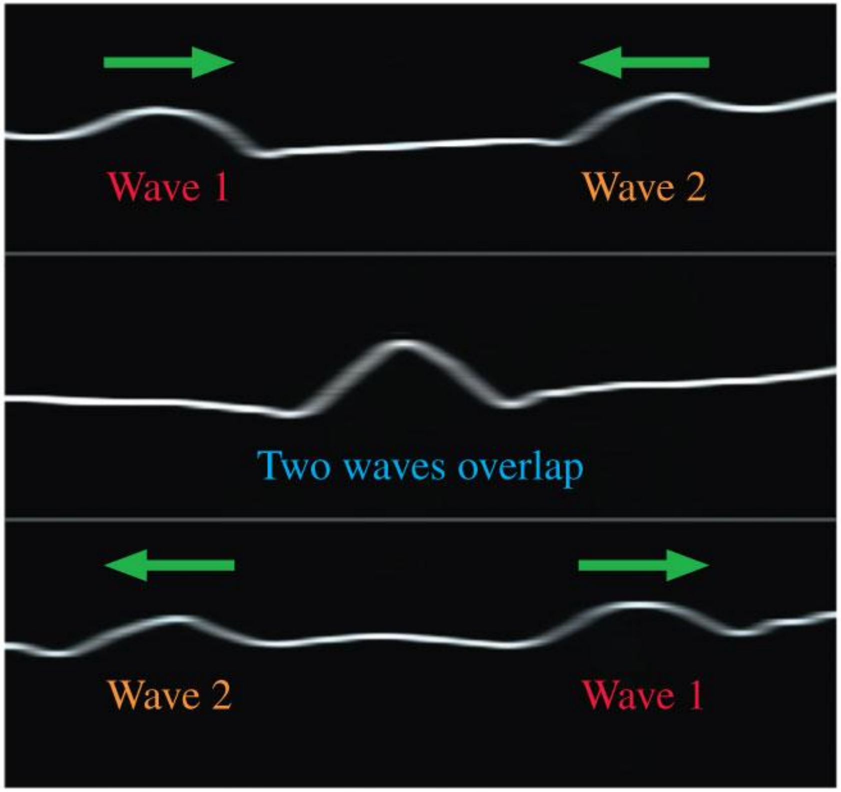
The Principle of Superposition

- Waves, however, can pass through one another. Both observers would hear undistorted sound, despite the sound waves crossing.



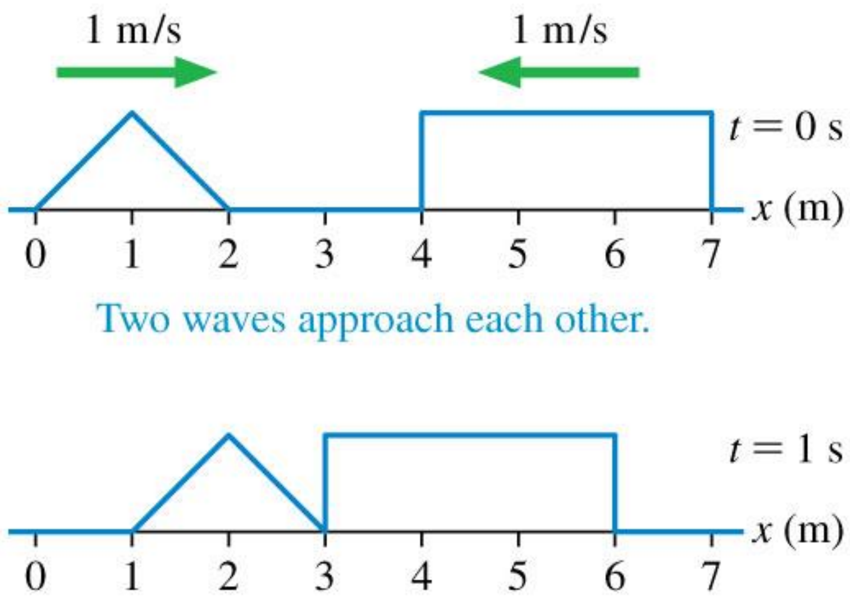
The Principle of Superposition

Principle of superposition When two or more waves are *simultaneously* present at a single point in space, the displacement of the medium at that point is the sum of the displacements due to each individual wave.



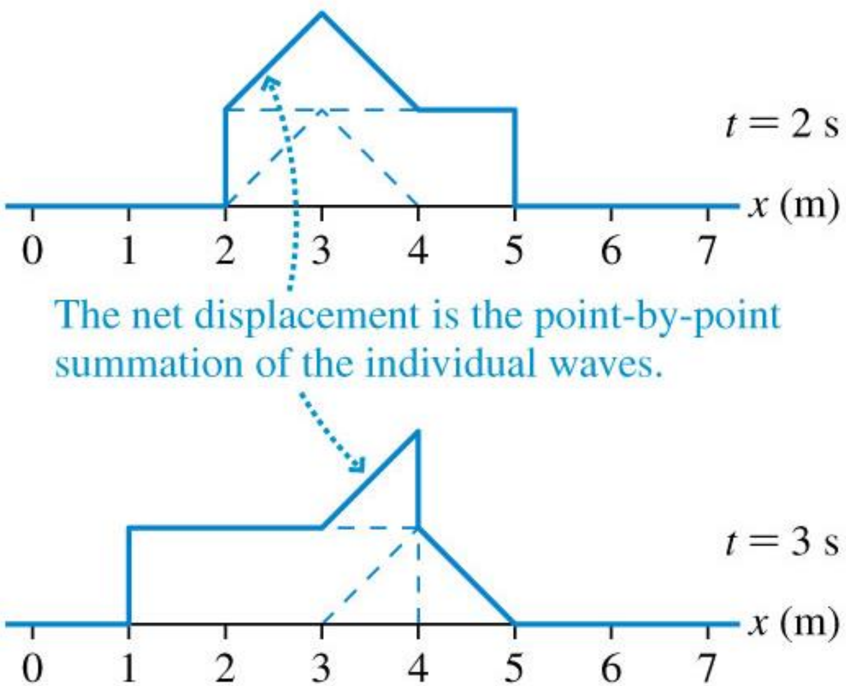
The Principle of Superposition

- To use the principle of superposition, you must know the displacement that each wave would cause if it were alone in the medium.
- Then you must go through the medium *point by point* and add the displacements due to each wave *at that point*.



Constructive and Destructive Interference

- The superposition of two waves is called **interference**.
- **Constructive interference** occurs when both waves are positive and the total displacement of the medium is larger than it would be for either wave separately.



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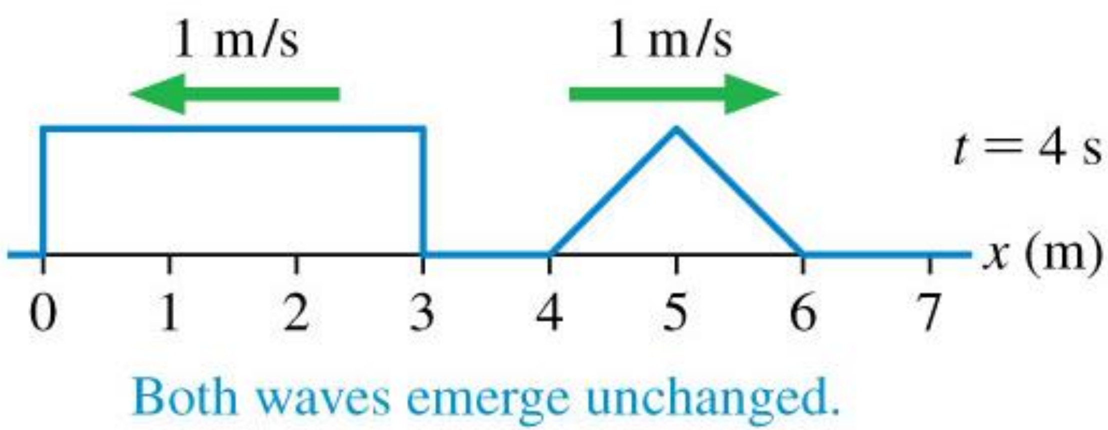
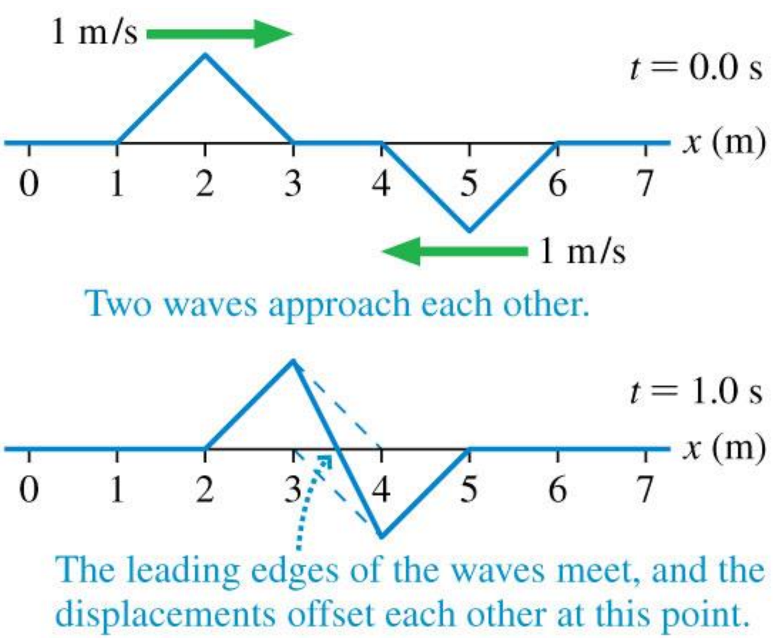


Constructive and Destructive Interference

- **Destructive interference** is when the displacement of the medium where the waves overlap is *less* than it would be due to either of the waves separately.
- During destructive interference, the energy of the wave is in the form of kinetic energy of the medium.



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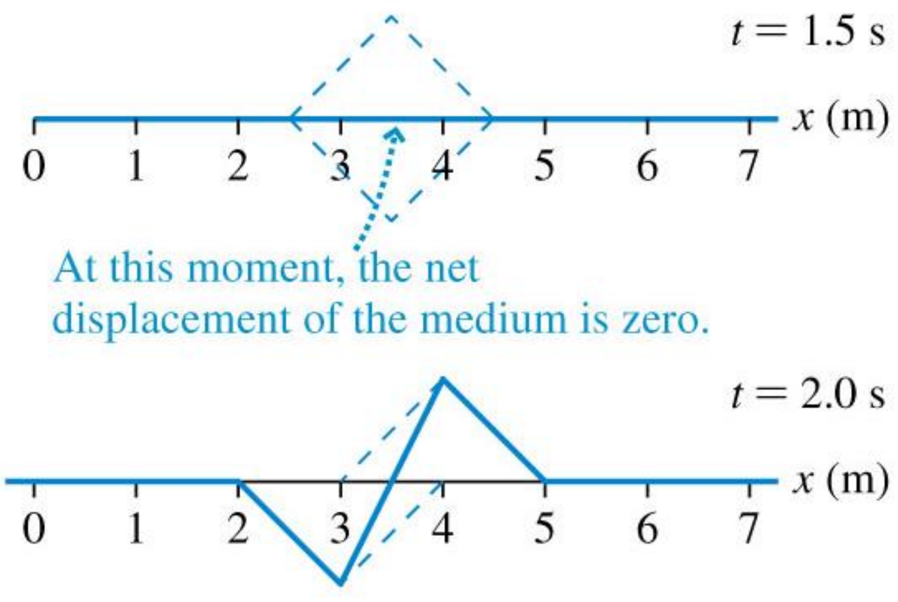

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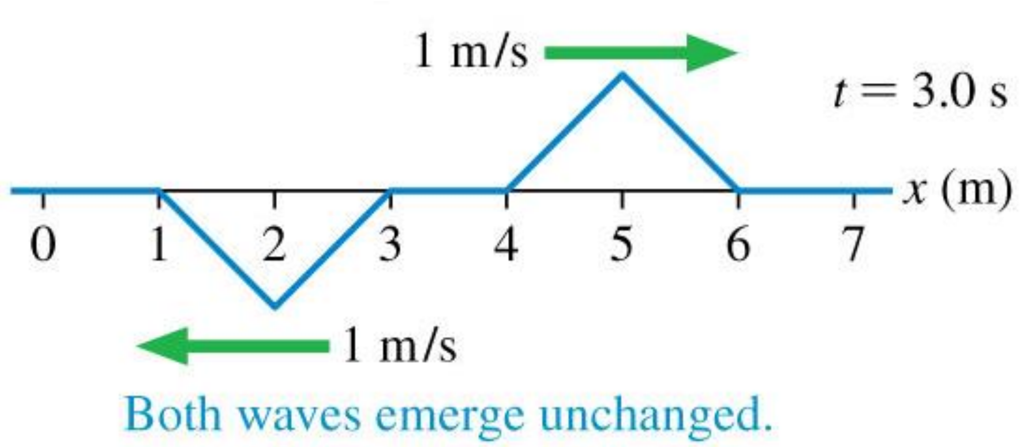
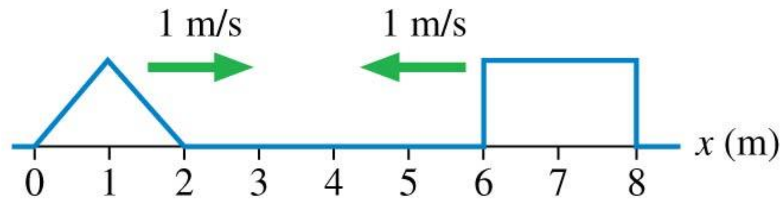


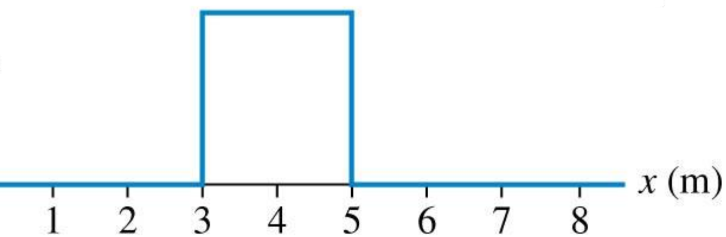
QuickCheck 16.1

Two wave pulses on a string approach each other at speeds of 1 m/s. How does the string look at t = 3 s?

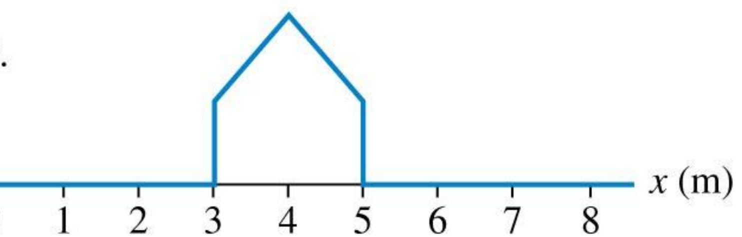


Approaching pulses at $t = 0$ s

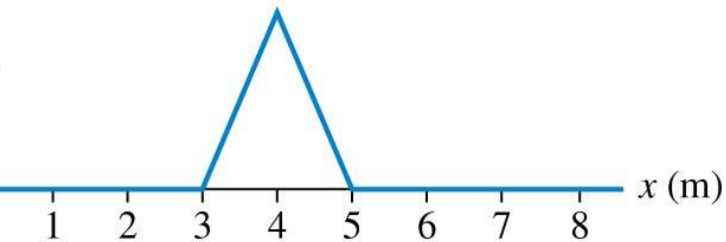
A.



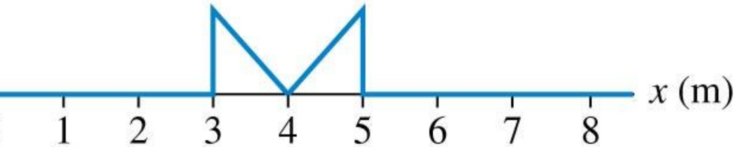
C.



B.



D.



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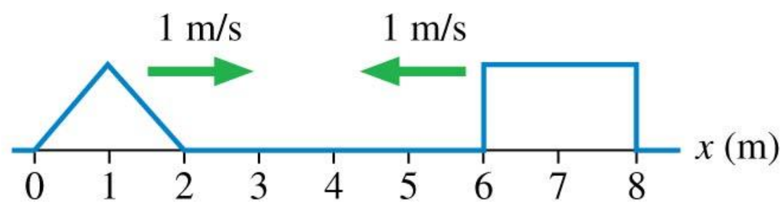
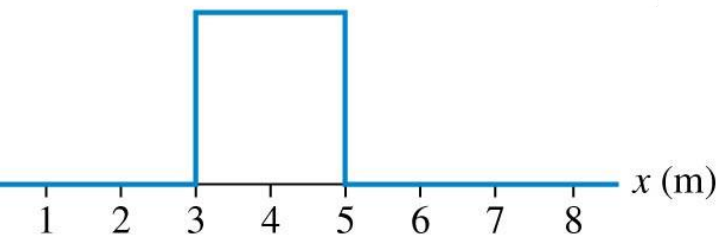
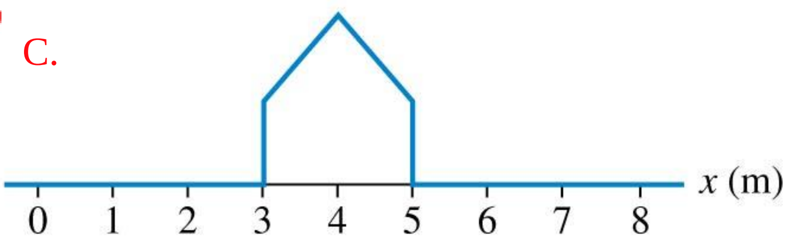


Approaching pulses at $t = 0$ s

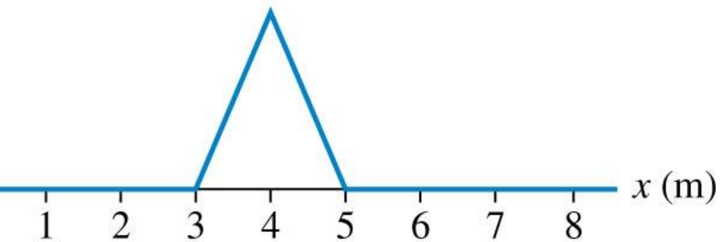
A.



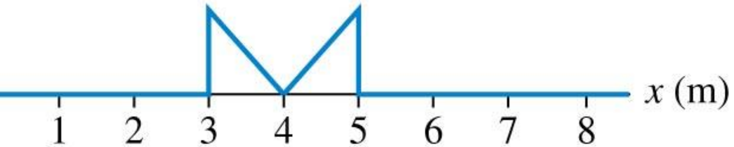
✔ C.



B.

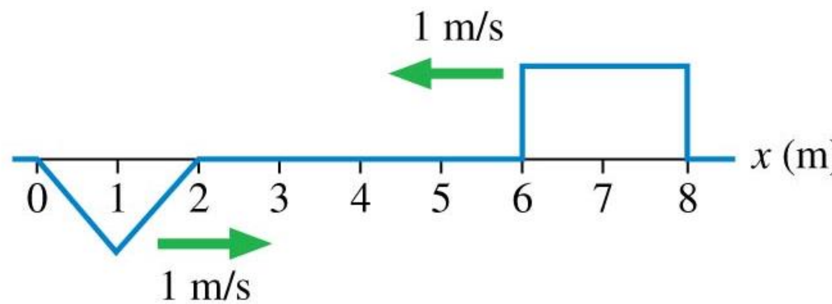


D.



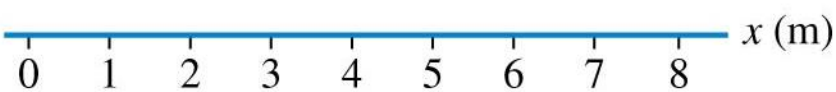
QuickCheck 16.2

Two wave pulses on a string approach each other at speeds of 1 m/s. How does the string look at $t = 3$ s?

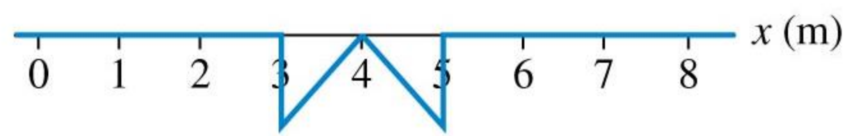


Approaching pulses at $t = 0$ s

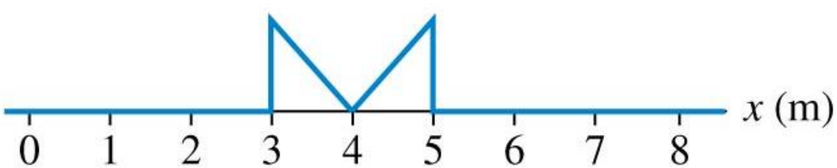
A.



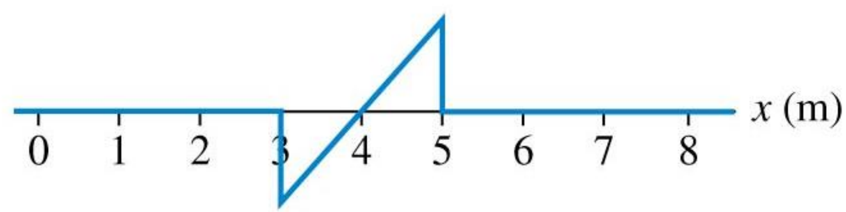
C.



B.



D.



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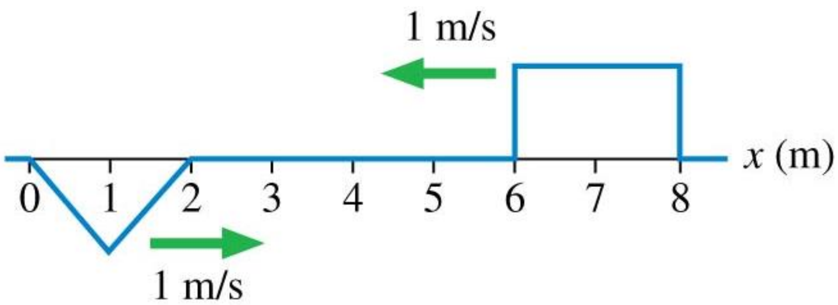
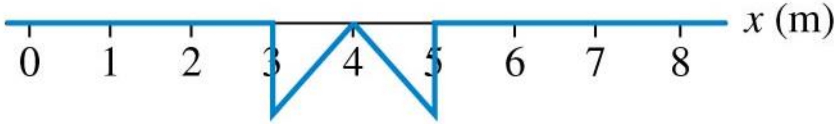


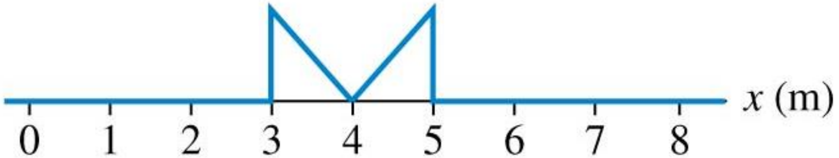
Approaching pulses at $t = 0$ s

A.

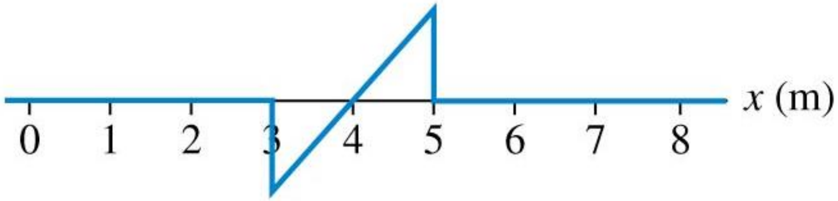
C.



✔ B.

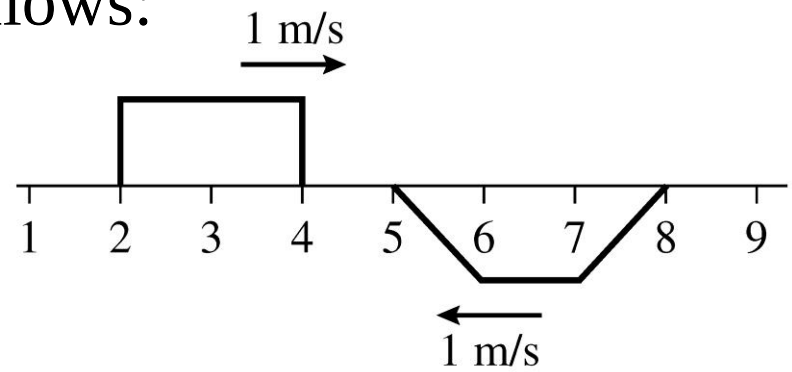


D.

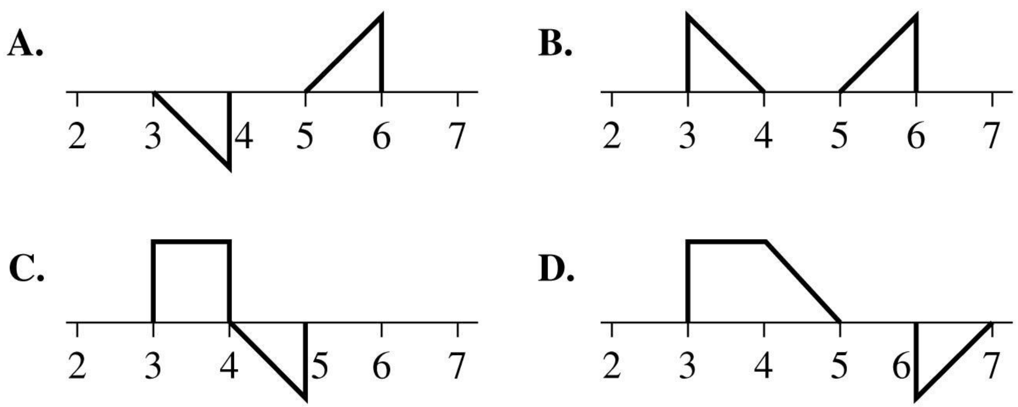


QuickCheck 16.3

Two waves on a string are moving toward each other. A picture at $t = 0$ s appears as follows:



How does the string appear at $t = 2$ s?



QuickCheck 16.3

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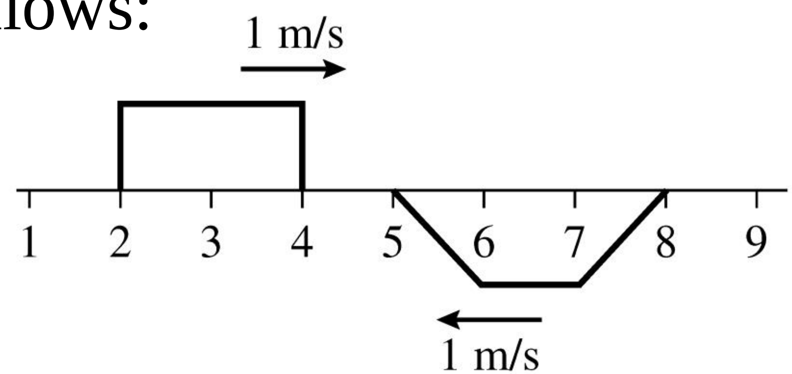
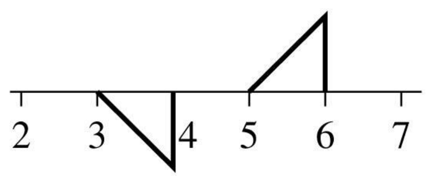
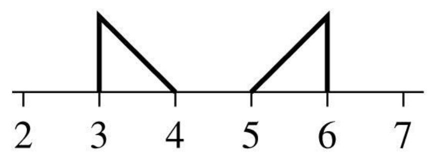


How does the string appear at $t = 2$ s?

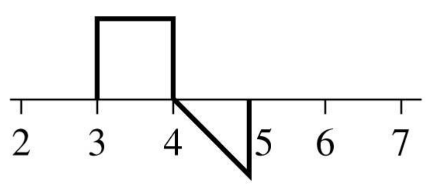
A.



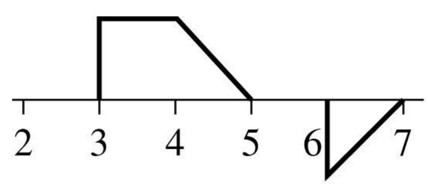
B.



C.



D.



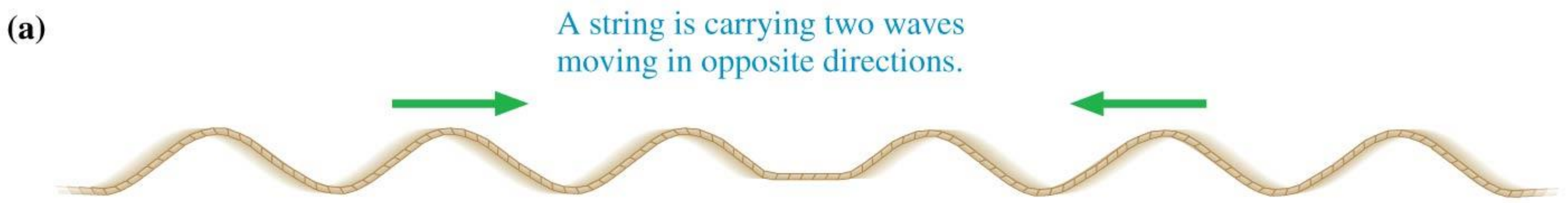
Section 16.2 Standing Waves

Standing Waves

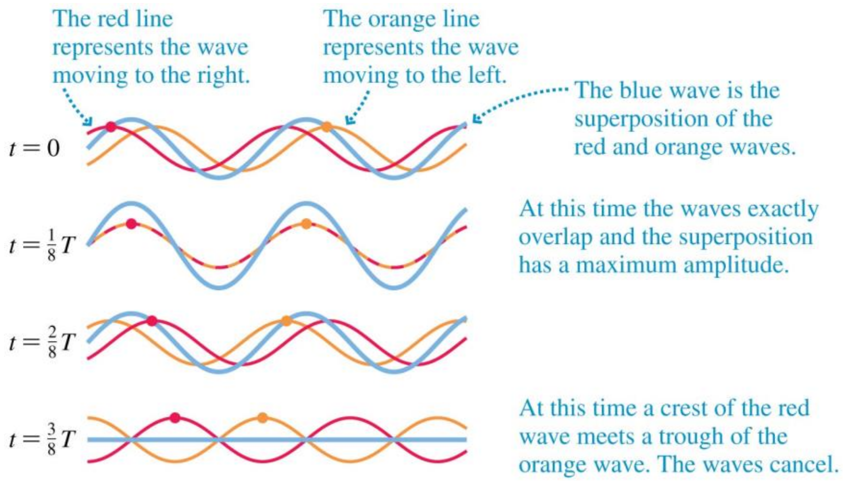
- Waves that are “trapped” and cannot travel in either direction are called *standing waves*.
- **Individual points on a string oscillate up and down, but the wave itself does not travel.**
- It is called a **standing wave** because the crests and troughs “stand in place” as it oscillates.

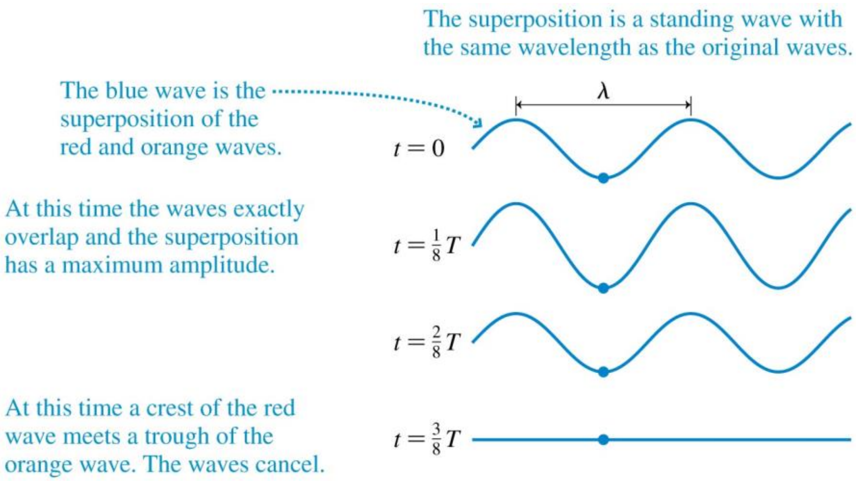
Superposition Creates a Standing Wave

- As two sinusoidal waves of equal wavelength and amplitude travel in opposite directions along a string, superposition will occur when the waves interact.

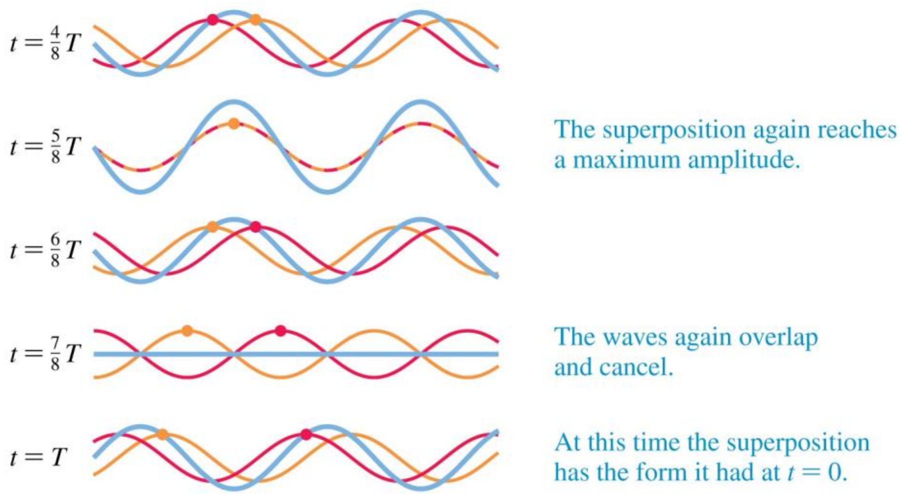


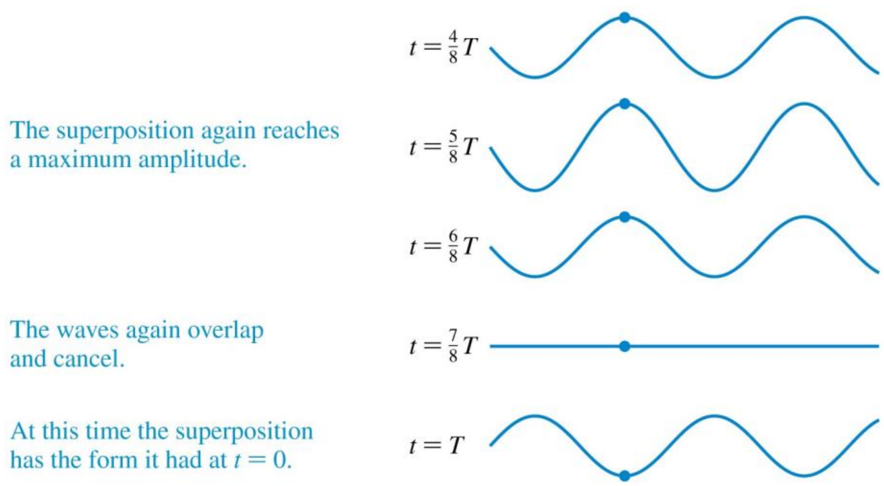
Superposition Creates a Standing Wave





Superposition Creates a Standing Wave



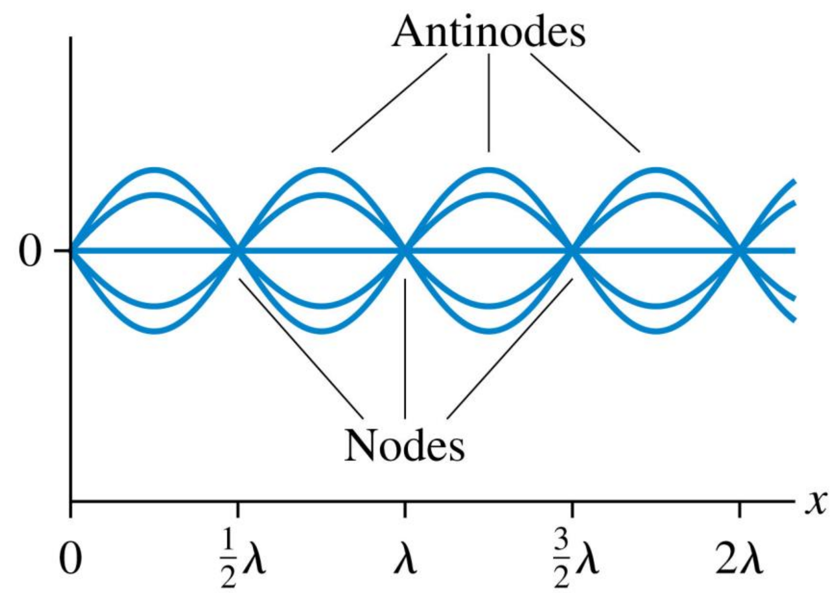


Superposition Creates a Standing Wave

- The two waves are represented by red and by orange in the previous figures. At *each point*, the net displacement of the medium is found by adding the red displacement and the orange displacement. The blue wave is the resulting wave due to superposition.

Nodes and Antinodes

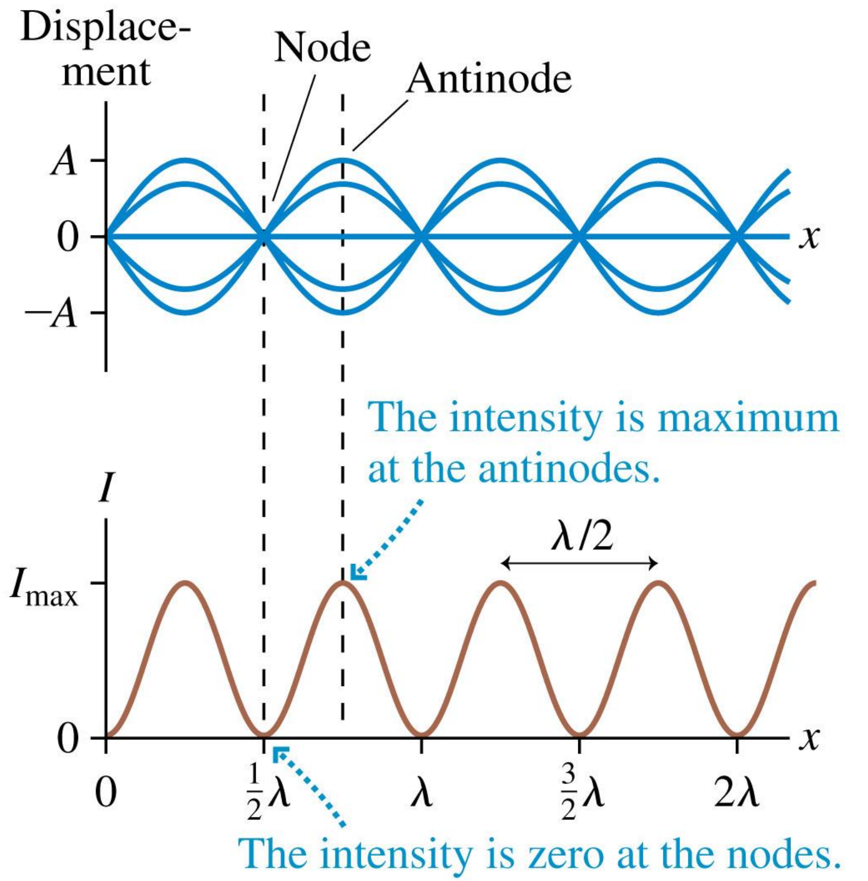
- In a standing wave pattern, there are some points that *never move*. These points are called **nodes** and are spaced $\lambda/2$ apart.
- **Antinodes** are halfway between the nodes, where the particles in the medium oscillate with maximum displacement.



The nodes and antinodes are spaced $\lambda/2$ apart.

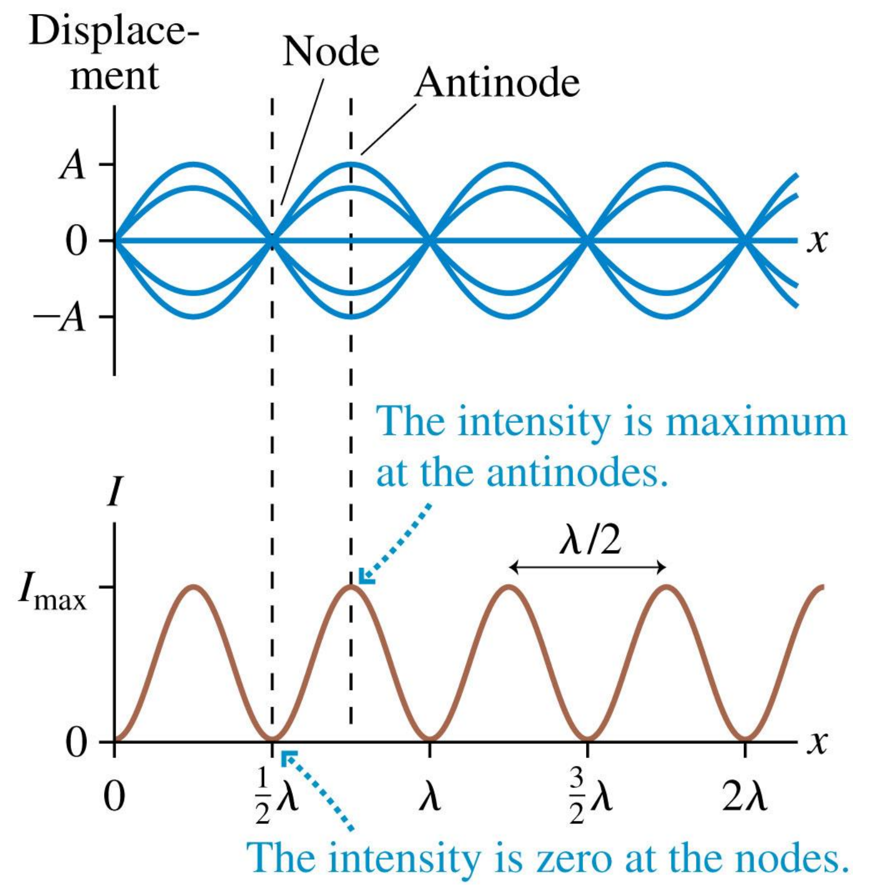
Nodes and Antinodes

- **The wavelength of a standing wave is twice the distance between successive nodes or antinodes.**
- At the nodes, the displacement of the two waves cancel one another by destructive interference. The particles in the medium at a node have no motion.



Nodes and Antinodes

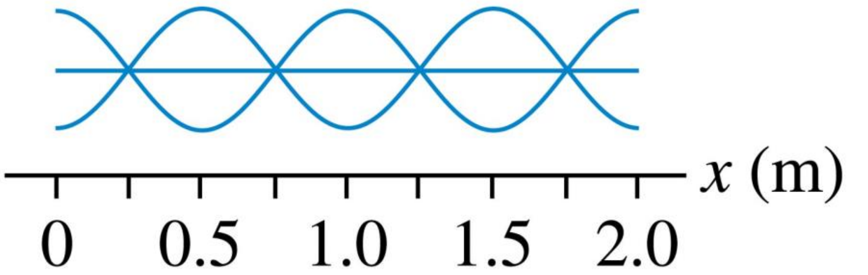
- At the antinodes, the two waves have equal magnitude and the *same sign*, so constructive interference at these points give a displacement twice that of the individual waves.
- **The intensity is maximum at points of constructive interference and zero at points of destructive interference.**



QuickCheck 16.4

What is the wavelength of this standing wave?

A. 0.25 m
B. 0.5 m
C. 1.0 m
D. 2.0 m
E. Standing waves don't have a wavelength.



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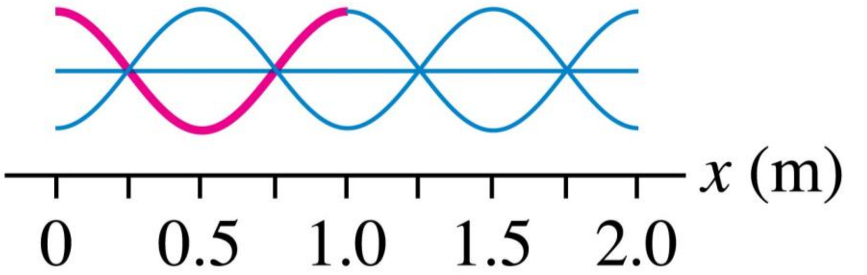
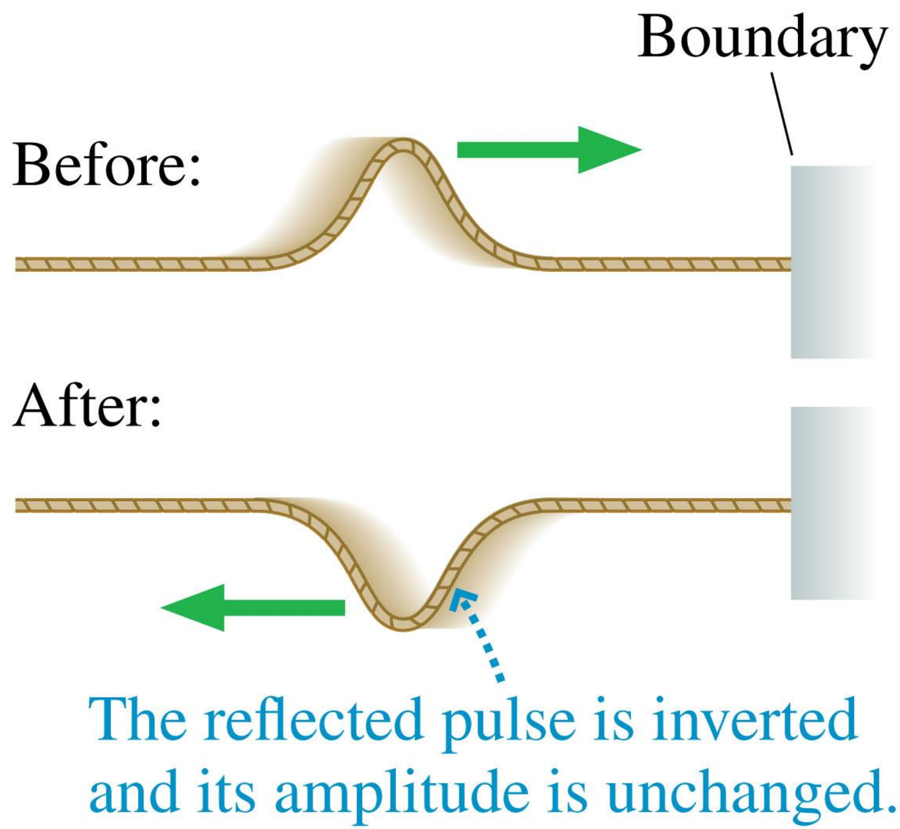


Section 16.3 Standing Waves on a String

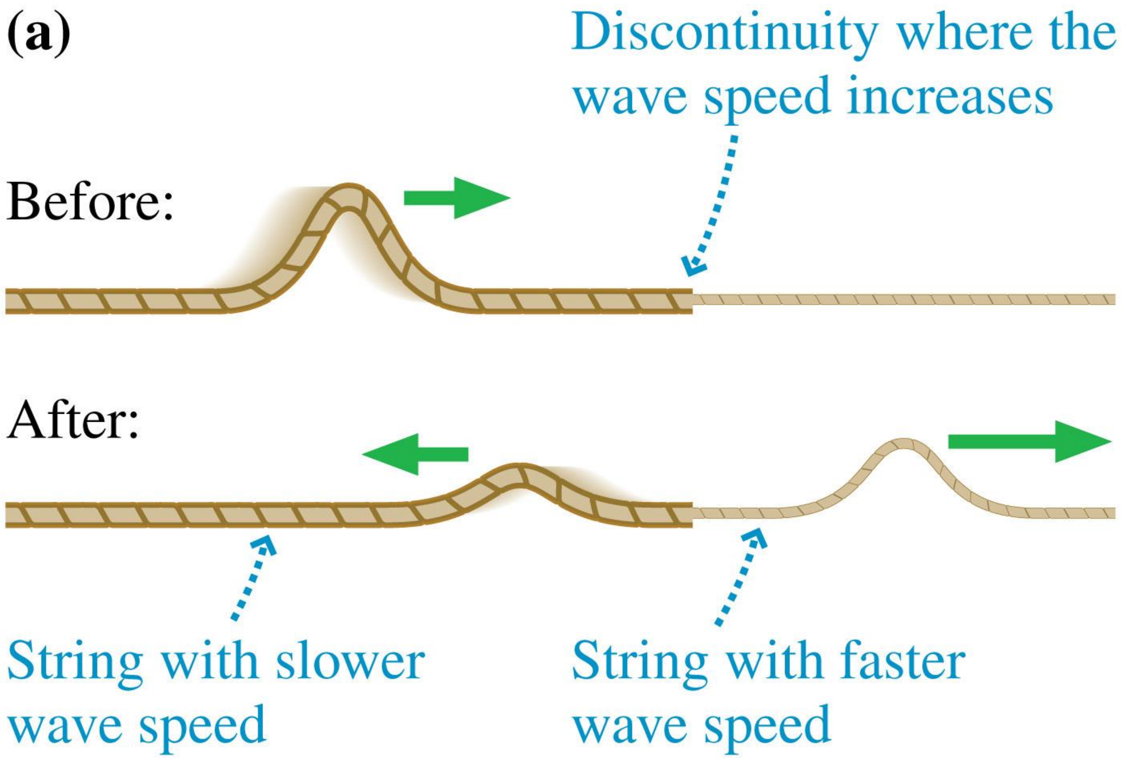
Reflections

- A wave pulse traveling along a string attached to a wall will be reflected when it reaches the wall, or *the boundary*.
- *All* of the wave's energy is reflected; hence **the amplitude of a wave reflected from a boundary is unchanged.**
- The amplitude does not change, but the pulse is inverted.



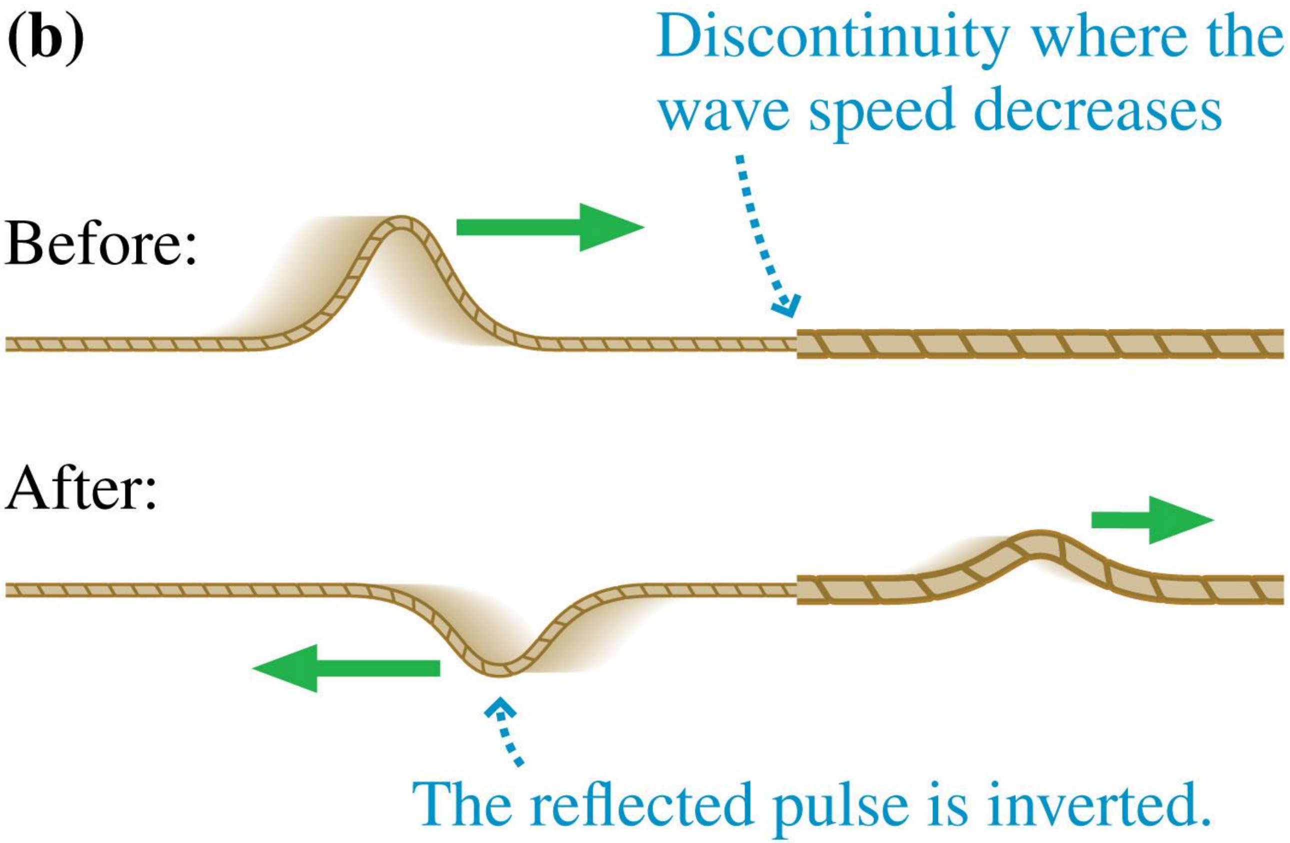
Reflections

- Waves also reflect from a *discontinuity*, a point where there is a change in the properties of the medium.
- At a discontinuity, some of the wave's energy is *transmitted* forward and some is reflected.



Reflections

- When the string on the right is more massive, it acts like a boundary so the reflected pulse is inverted.

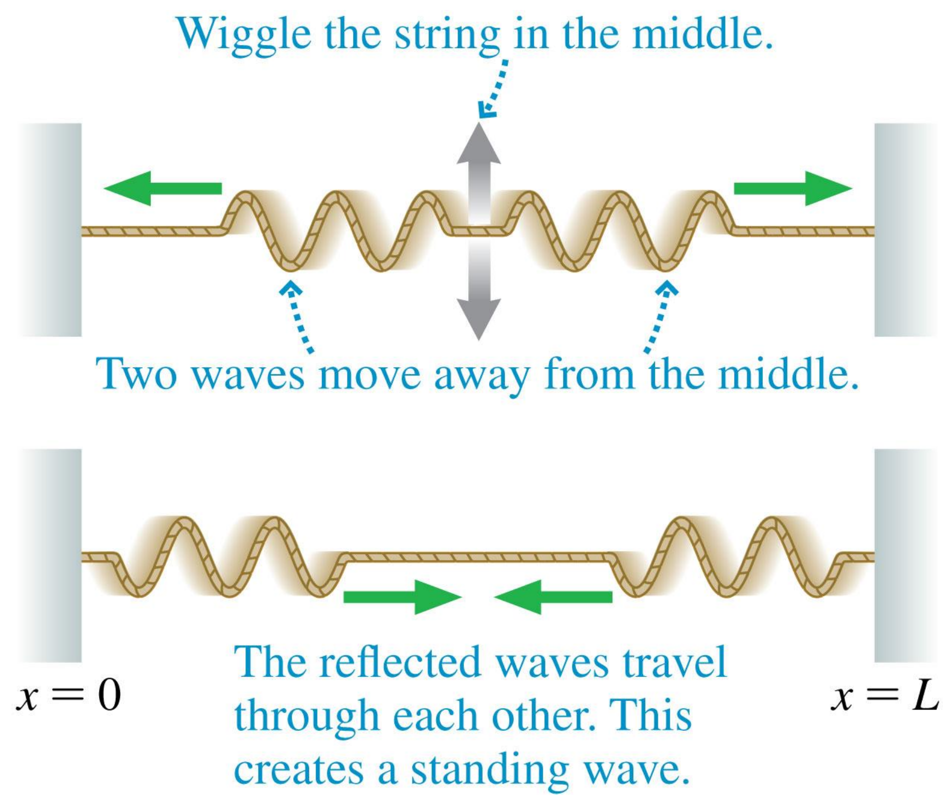


Try It Yourself: Through the Glass Darkly

A piece of window glass is a discontinuity to a light wave, so it both transmits and reflects light. To verify this, look at the windows in a brightly lit room at night. The small percentage of the interior light that reflects from windows is more intense than the light coming in from outside, so reflection dominates and the windows show a mirror-like reflection of the room. Now turn out the lights. With no more reflected interior light you will be able to see the transmitted light from outside.

Creating a Standing Wave

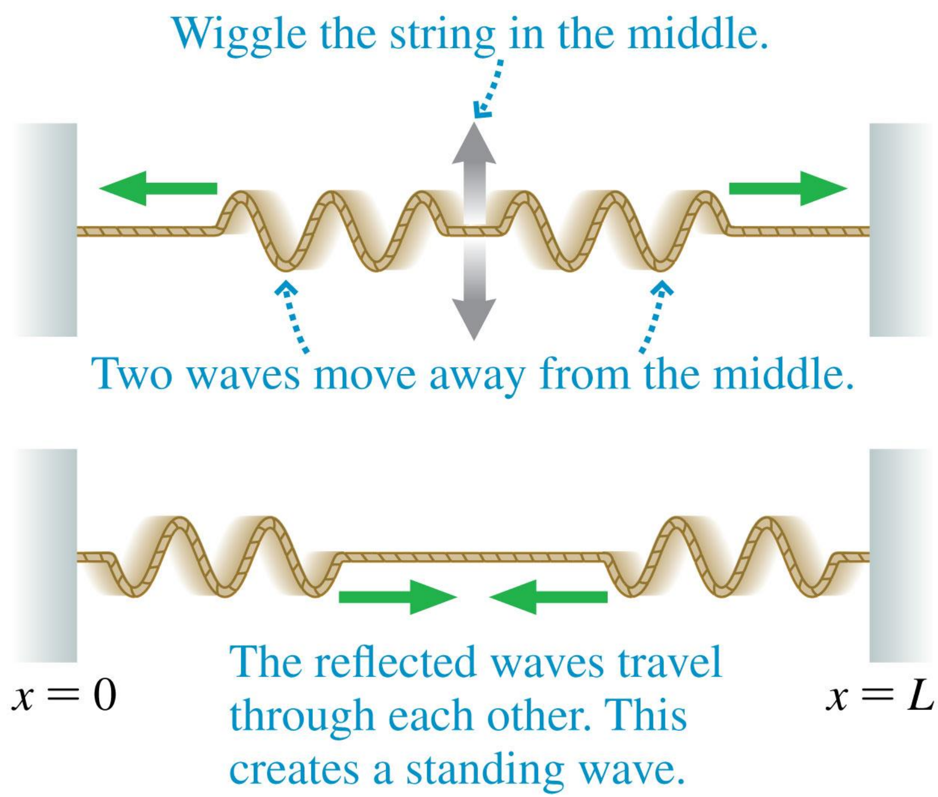
- Standing waves can be created by a string with two boundaries where reflections occur. A disturbance in the middle of the string causes waves to travel outward in both directions.



- The reflections at the ends of the string cause two waves of *equal amplitude and wavelength* to travel in opposite directions along the string.

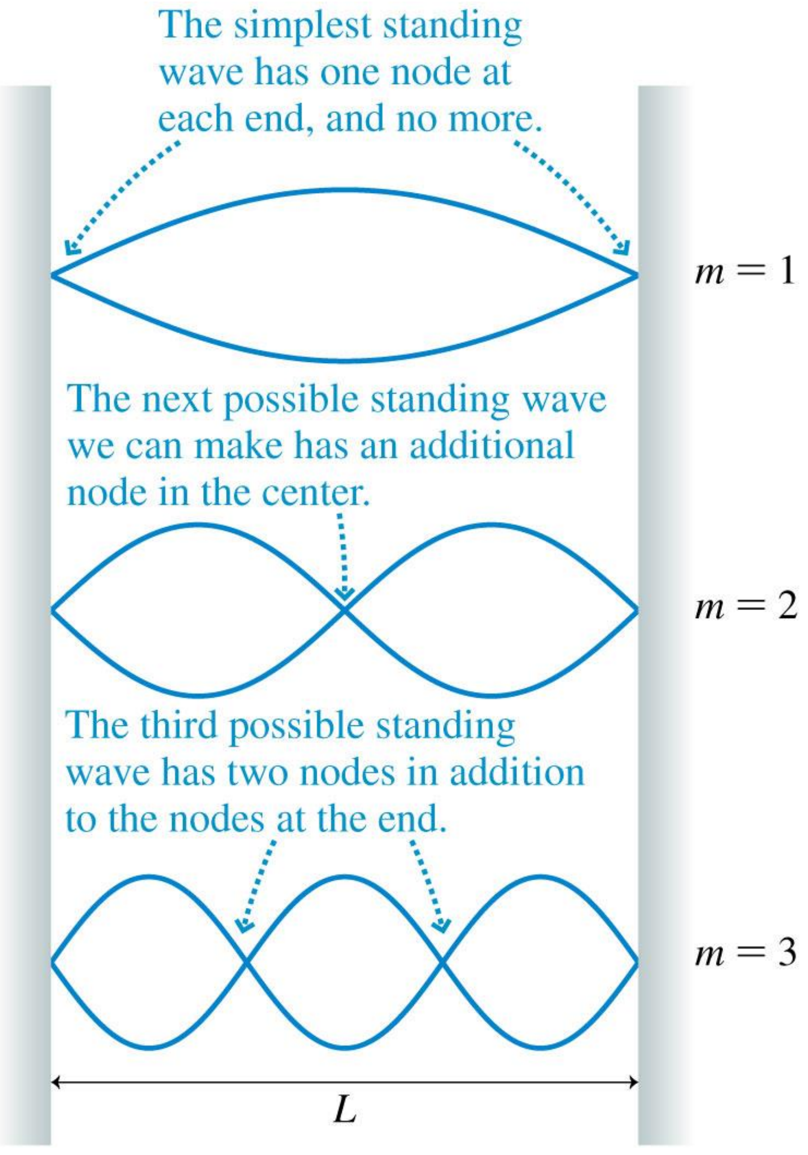
Creating a Standing Wave

- Two conditions must be met in order to create standing waves on the string:
  - Because the string is fixed at the ends, the displacements at $x = 0$ and $x = L$ must be zero at all times. Stated another way, we require nodes at both ends of the string.
  - We know that standing waves have a spacing of $\lambda/2$ between nodes. This means that the nodes must be equally spaced.



Creating a Standing Wave

- There are three possible standing-wave **modes** of a string.
- The **mode number** m helps quantify the number of possible waves in a standing wave. A mode number $m = 1$ indicates only one wave, $m = 2$ indicates 2 waves, etc.



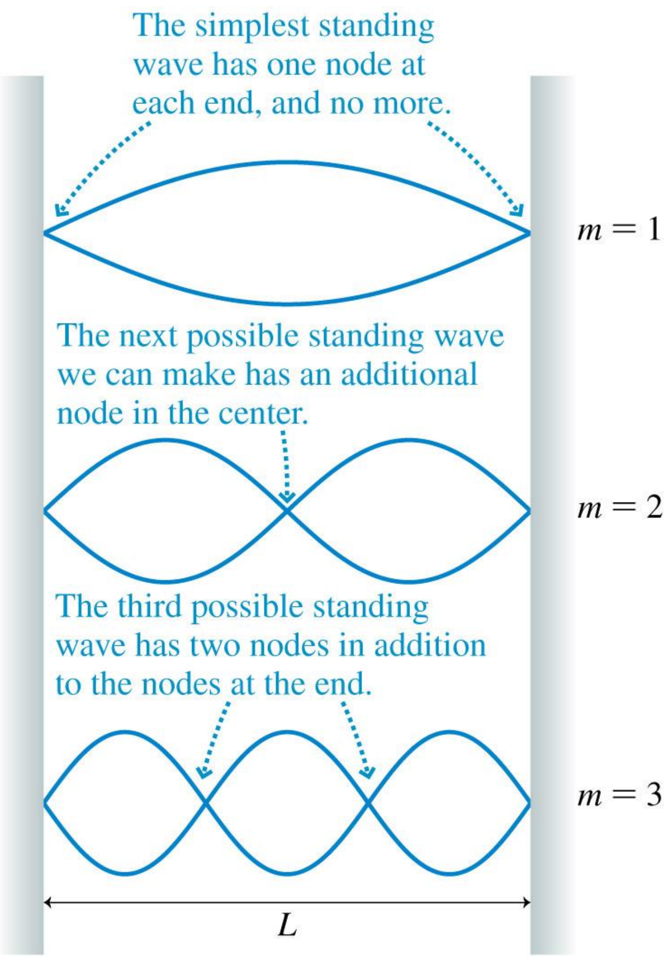
Creating a Standing Wave

- Different modes have different wavelengths.
- For any mode m the wavelength is given by the equation

$$\lambda_m = \frac{2L}{m} \qquad m = 1, 2, 3, 4, \ldots$$

Wavelengths of standing-wave modes of a string of length L

- **A standing wave can exist on the string *only* if its wavelength is one of the values given by this equation.**



Creating a Standing Wave

- The oscillation frequency corresponding to wavelength λ_m is

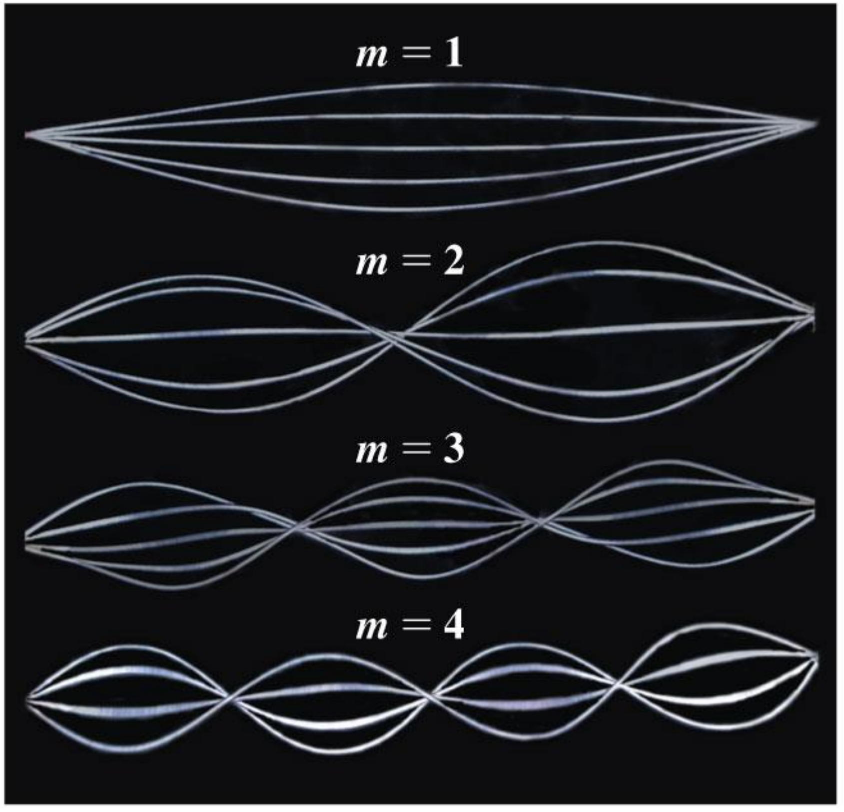
$$f_m = \frac{v}{\lambda_m} = \frac{v}{2L/m} = m\left(\frac{v}{2L}\right) \qquad m = 1, 2, 3, 4, \ldots$$

Frequencies of standing-wave modes of a string of length L

- **The mode number *m* is equal to the number of antinodes of the standing wave.**

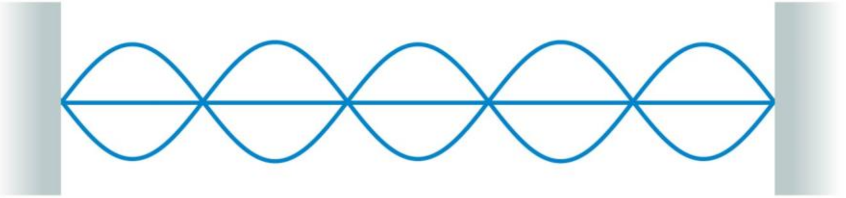
Creating a Standing Wave

- The standing-wave modes are frequencies at which the wave "wants" to oscillate. They can be called **resonant modes** or **resonances**.



QuickCheck 16.5

What is the mode number of this standing wave?

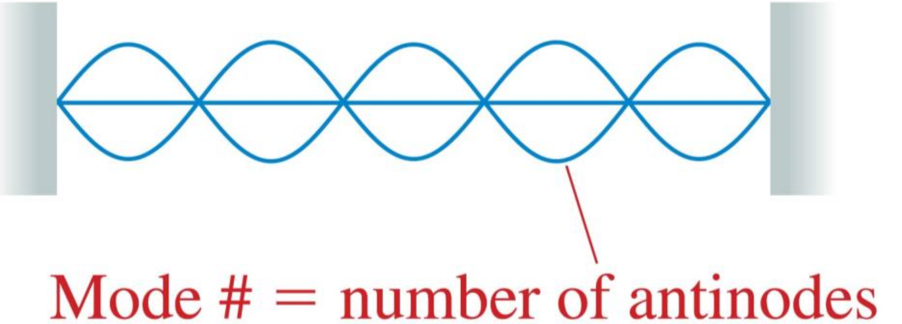


A. 4
B. 5
C. 6
D. Can’t say without knowing what kind of wave it is

QuickCheck 16.5

What is the mode number of this standing wave?

A. 4
B. 5
C. 6
D. Can’t say without knowing what kind of wave it is



The Fundamental and Higher Harmonics

- The first mode of the standing-wave modes has the frequency

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

- This frequency is the **fundamental frequency** of the string.

The Fundamental and Higher Harmonics

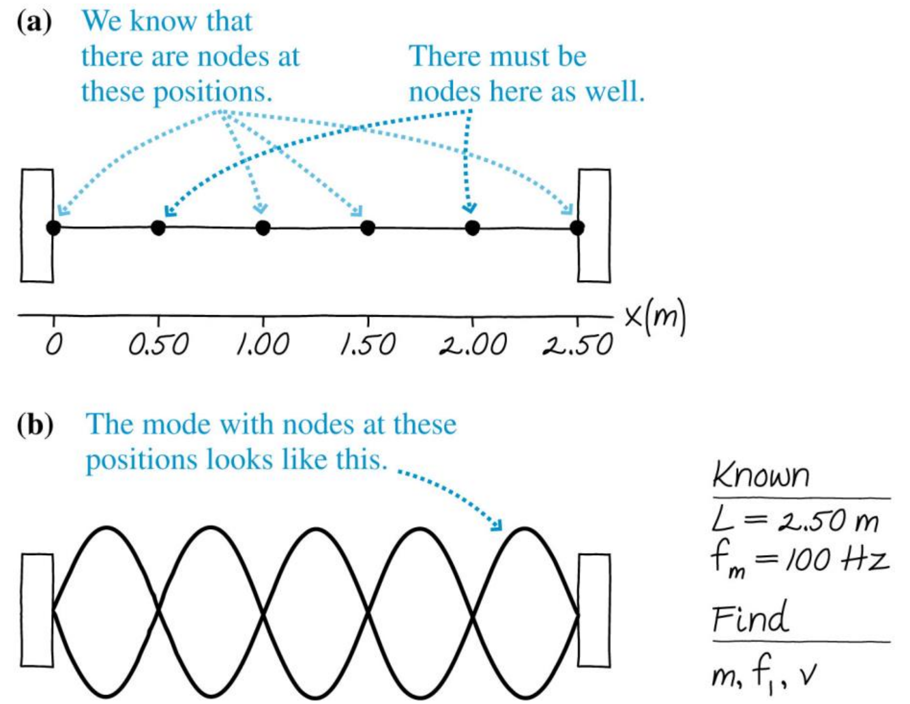
- The frequency in terms of the fundamental frequency is

$$f_m = mf_1 \qquad m = 1, 2, 3, 4, \ldots$$

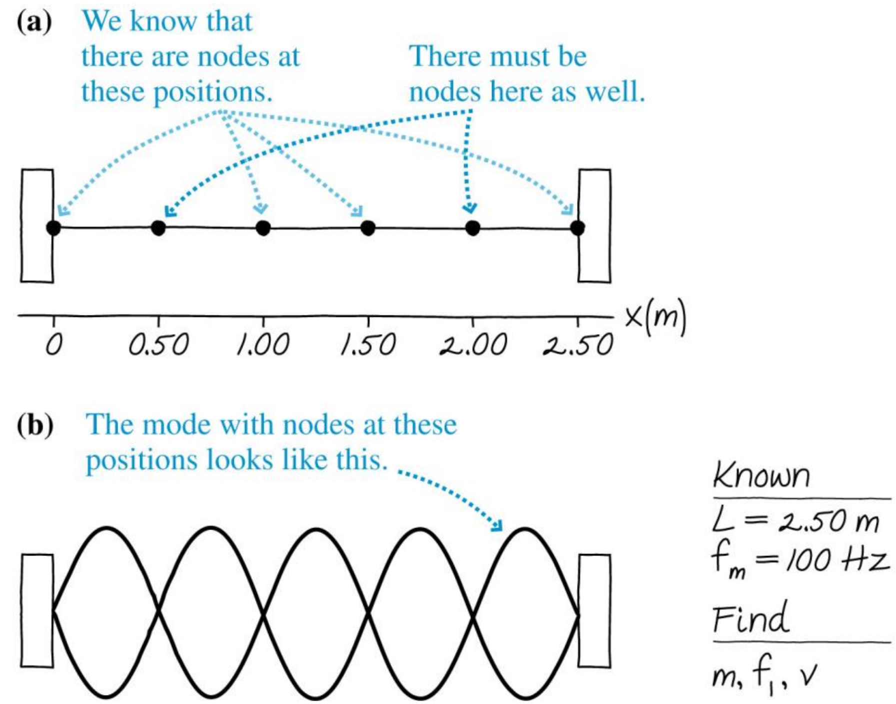
- **The allowed standing-wave frequencies are all integer multiples of the fundamental frequency.**
- The sequence of possible frequencies is called a set of **harmonics.**
- Frequencies above the fundamental frequency are referred to as **higher harmonics.**

Example 16.2 Identifying harmonics on a string

A 2.50-m-long string vibrates as a 100 Hz standing wave with nodes at 1.00 m and 1.50 m from one end of the string and at no points in between these two. Which harmonic is this? What is the string's fundamental frequency? And what is the speed of the traveling waves on the string?



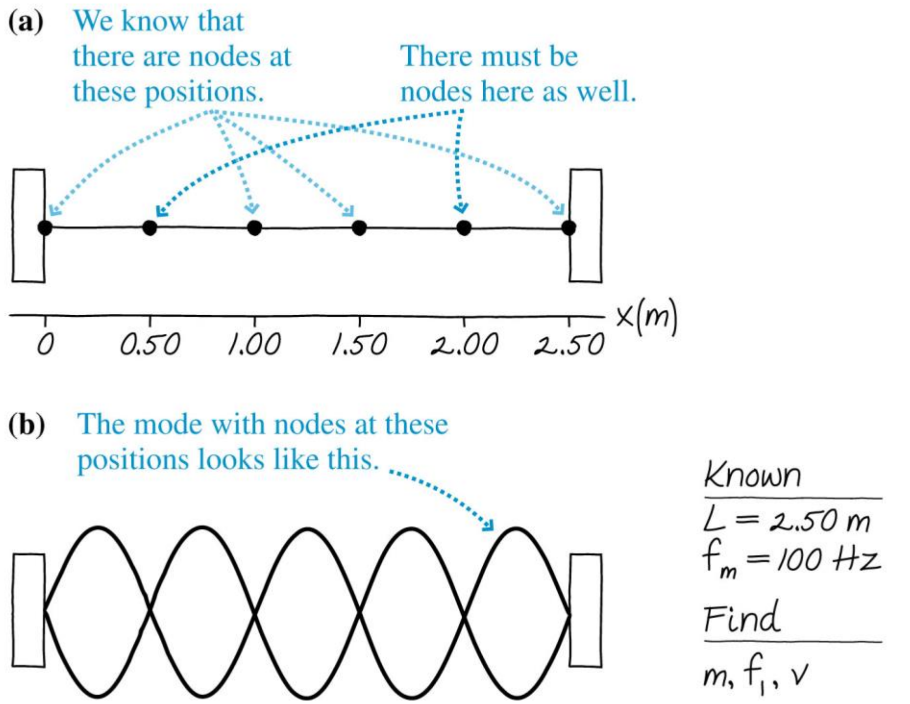
Example 16.2 Identifying harmonics on a string (cont.)



PREPARE We begin with the visual overview in FIGURE 16.15, in which we sketch this particular standing wave and note the known and unknown quantities. We set up an *x*-axis with one end of the string at $x = 0$ m and the other end at $x = 2.50$ m. The ends of the string are nodes, and there are nodes at 1.00 m and 1.50 m as well, with no nodes in between.

Example 16.2 Identifying harmonics on a string (cont.)

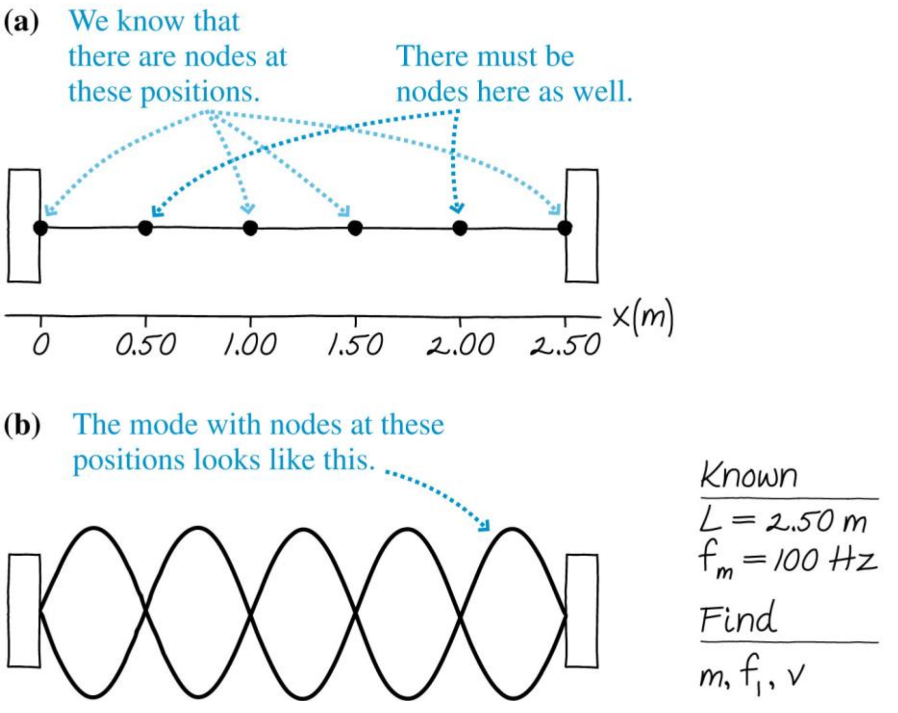
We know that standing-wave nodes are equally spaced, so there must be other nodes on the string, as shown in Figure 16.15a. Figure 16.15b is a sketch of the standing-wave mode with this node structure.



Example 16.2 Identifying harmonics on a string (cont.)

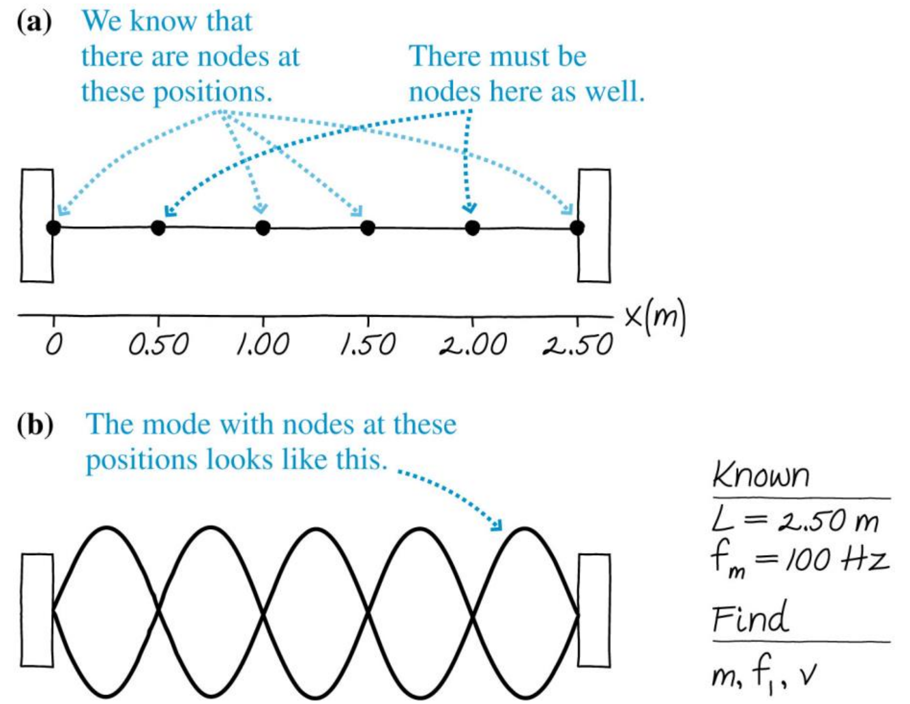
SOLVE We count the number of antinodes of the standing wave to deduce the mode number; this is mode $m = 5$. This is the fifth harmonic. The frequencies of the harmonics are given by $f_m = mf_1$, so the fundamental frequency is

$$f_1 = \frac{f_5}{5} = \frac{100\text{ Hz}}{5} = 20\text{ Hz}$$



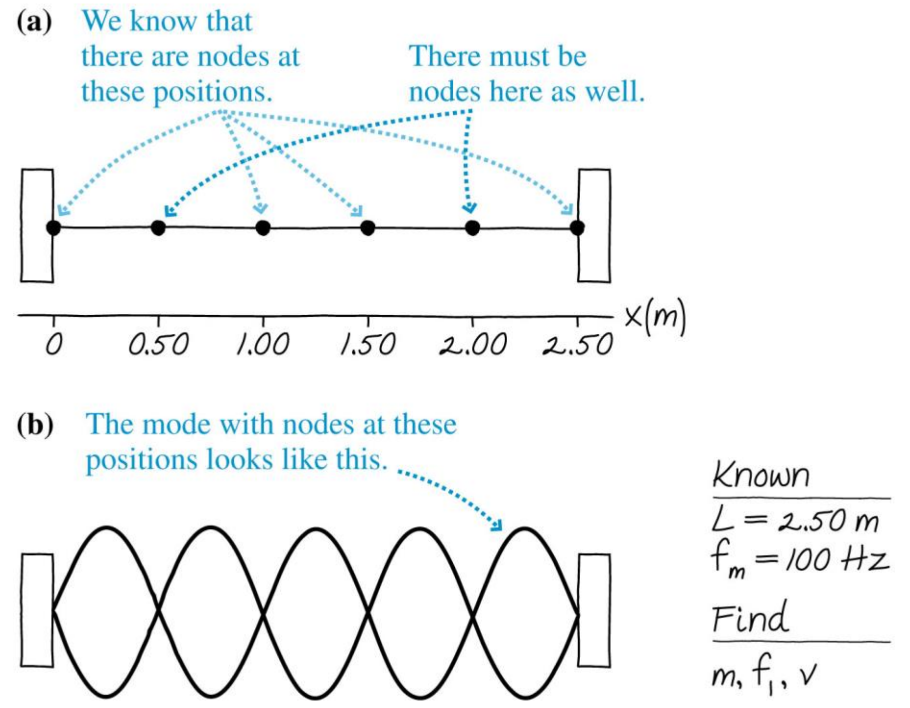
Example 16.2 Identifying harmonics on a string (cont.)

The wavelength of the fundamental mode is $\lambda_1 = 2L = 2(2.50\text{ m}) = 5.00\text{ m}$, so we can find the wave speed using the fundamental relationship for sinusoidal waves:



$$v = \lambda_1 f_1 = (20\text{ Hz})(5.00\text{ m}) = 100\text{ m/s}$$

Example 16.2 Identifying harmonics on a string (cont.)



ASSESS We can calculate the speed of the wave using any possible mode, which gives us a way to check our work. The distance between successive nodes is λ/2. Figure 16.15 shows that the nodes are spaced by 0.50 m, so the wavelength of the *m* = 5 mode is 1.00 m. The frequency of this mode is 100 Hz, so we calculate

$$v = \lambda_5 f_5 = (100\text{ Hz})\,(1.00\text{ m}) = 100\text{ m/s}$$

This is the same speed that we calculated earlier, which gives us confidence in our results.

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 passing insect brushes a 12-cm-long strand of the web, which has a tension of 1.0 mN, and excites the lowest frequency standing wave. With what frequency will the strand vibrate?

Stringed Musical Instruments

- The fundamental frequency can be written in terms of the tension in the string and the linear density:

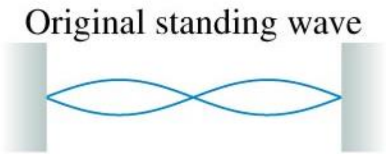
$$f_1 = \frac{v}{2L} = \frac{1}{2L}\sqrt{\frac{T_s}{\mu}}$$

- When you pluck a bow or string of an instrument, initially you excite a wide range of frequencies; however the resonance sees to it that the only frequencies to persist are those of the possible standing waves.
- On many instruments, the length and tension of the strings are nearly the same; the strings have different frequencies because they differ in linear density.

QuickCheck 16.6

A standing wave on a string vibrates as shown. Suppose the string tension is reduced to 1/4 its original value while the frequency and length are kept unchanged.

Which standing wave pattern is produced?



QuickCheck 16.6

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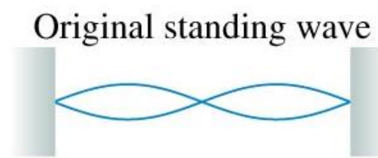
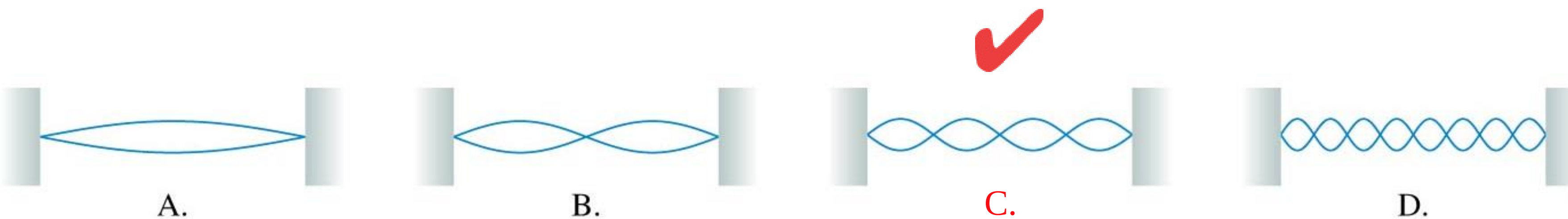
Which standing wave pattern is produced?





The frequency is $f_m = m\frac{v}{2L}$.

Quartering the tension reduces v by one half.
Thus m must double to keep the frequency constant.

QuickCheck 16.7

Which of the following changes will increase the frequency of the lowest-frequency standing sound wave on a stretched string? Choose all that apply.

A. Replacing the string with a thicker string
B. Increasing the tension in the string
C. Plucking the string harder
D. Doubling the length of the string

QuickCheck 16.7

Which of the following changes will increase the frequency of the lowest-frequency standing sound wave on a stretched string? Choose all that apply.

A. Replacing the string with a thicker string

✔ B. Increasing the tension in the string

C. Plucking the string harder

D. Doubling the length of the string

Example 16.4 Setting the tension in a guitar string

The fifth string on a guitar plays the musical note A, at a frequency of 110 Hz. On a typical guitar, this string is stretched between two fixed points 0.640 m apart, and this length of string has a mass of 2.86 g. What is the tension in the string?

PREPARE Strings sound at their fundamental frequency, so 110 Hz is f_1.

Example 16.4 Setting the tension in a guitar string (cont.)

SOLVE The linear density of the string is

$$\mu = \frac{m}{L} = \frac{2.86 \times 10^{-3}\ \text{kg}}{0.640\ \text{m}} = 4.47 \times 10^{-3}\ \text{kg/m}$$

We can rearrange Equation 16.5 for the fundamental frequency to solve for the tension in terms of the other variables:

$$T_s = (2Lf_1)^2\mu = [2(0.640\ \text{m})(110\ \text{Hz})]^2\ (4.47 \times 10^{-3}\ \text{kg/m})$$

$$= 88.6\ \text{N}$$

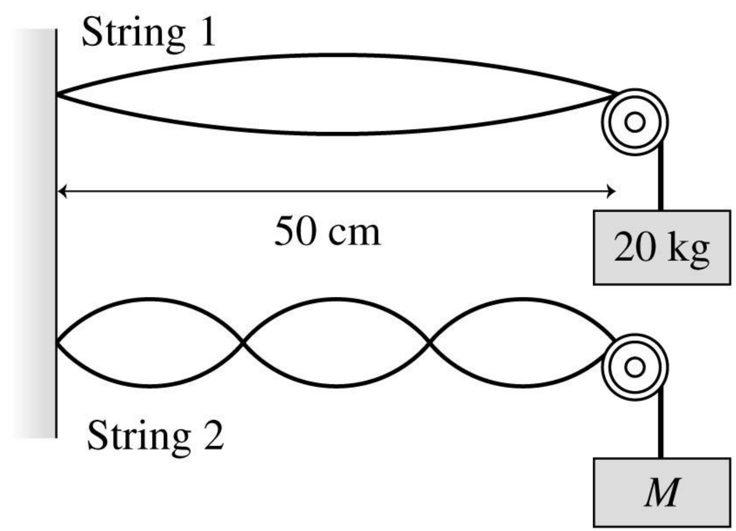
Example 16.4 Setting the tension in a guitar string (cont.)

ASSESS If you have ever strummed a guitar, you know that the tension is quite large, so this result seems reasonable. If each of the guitar's six strings has approximately the same tension, the total force on the neck of the guitar is a bit more than 500 N.

Example Problem

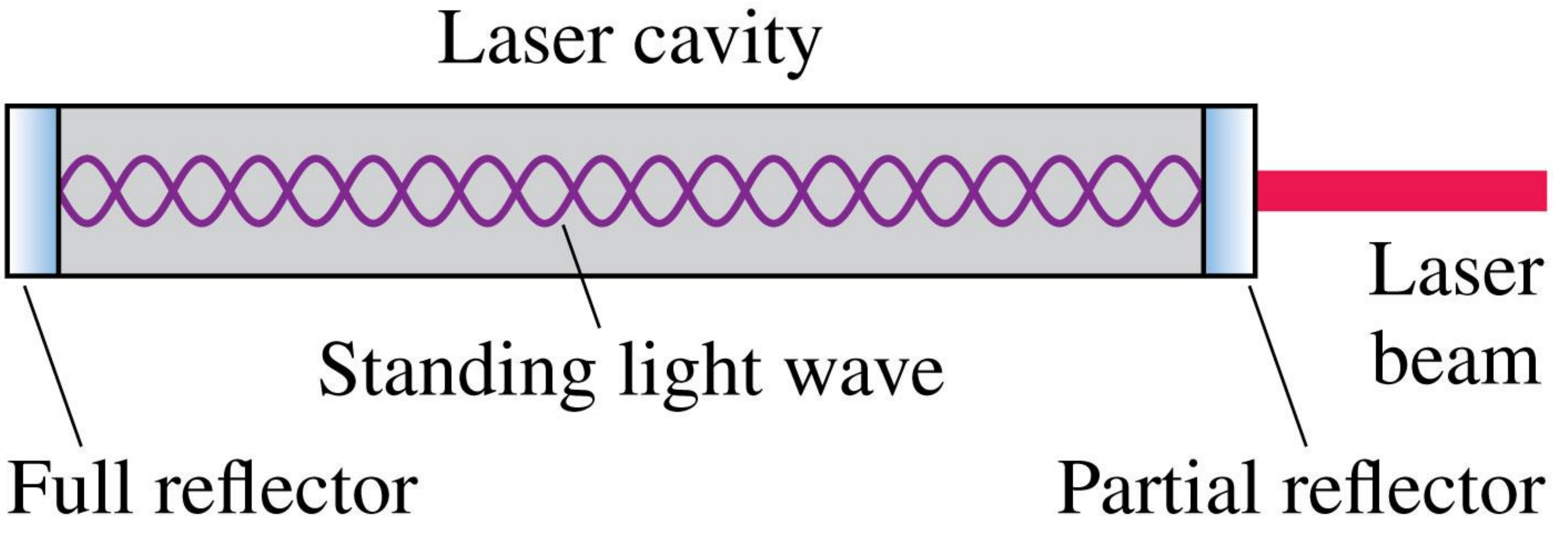
Two strings with linear densities of 5.0 g/m are stretched over pulleys, adjusted to have vibrating lengths of 50 cm, and attached to hanging blocks. The block attached to String 1 has a mass of 20 kg and the block attached to String 2 has mass *M*. When driven at the same frequency, the two strings support the standing waves shown.

A. What is the driving frequency?
B. What is the mass of the block suspended from String 2?



Standing Electromagnetic Waves

- A laser establishes standing light waves between two parallel mirrors that reflect light back and forth.
- The mirrors are the boundaries and therefore the light wave must have a node at the surface of each mirror.



Example 16.5 Finding the mode number for a laser

A helium-neon laser emits light of wavelength $\lambda = 633$ nm. A typical cavity for such a laser is 15.0 cm long. What is the mode number of the standing wave in this cavity?

PREPARE Because a light wave is a transverse wave, Equation 16.1 for λ_m applies to a laser as well as a vibrating string.

Example 16.5 Finding the mode number for a laser (cont.)

SOLVE The standing light wave in a laser cavity has a mode number *m* that is roughly

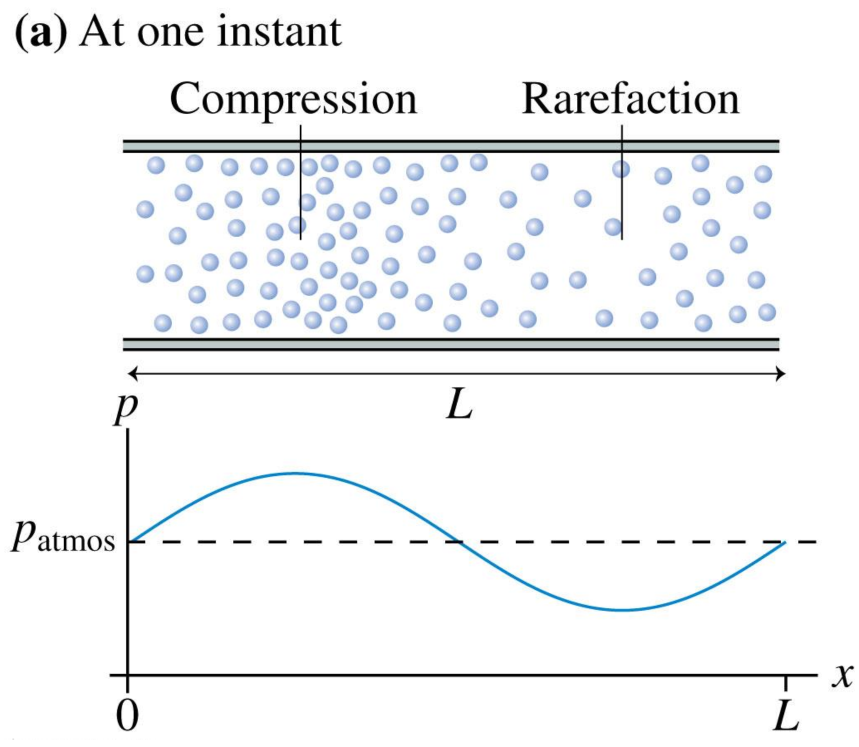
$$m = \frac{2L}{\lambda} = \frac{2 \times 0.150 \text{ m}}{633 \times 10^{-9} \text{ m}} = 474{,}000$$

ASSESS The wavelength of light is very short, so we'd expect the nodes to be closely spaced. A high mode number seems reasonable.

Section 16.4 Standing Sound Waves

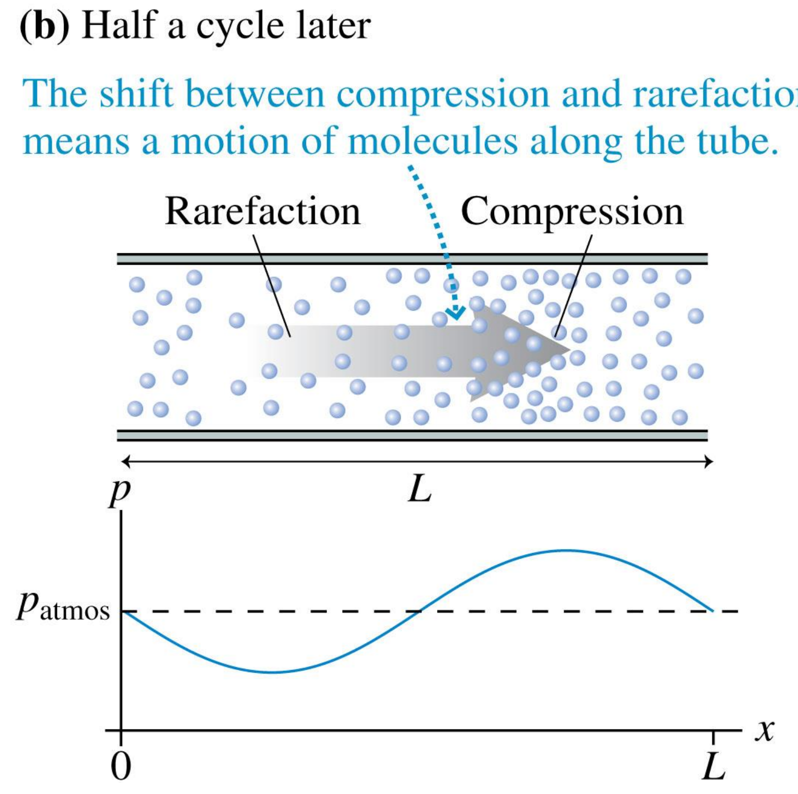
Standing Sound Waves

- Sound waves are longitudinal pressure waves. The air molecules oscillate, creating *compressions* (regions of higher pressure) and *rarefactions* (regions of lower pressure).



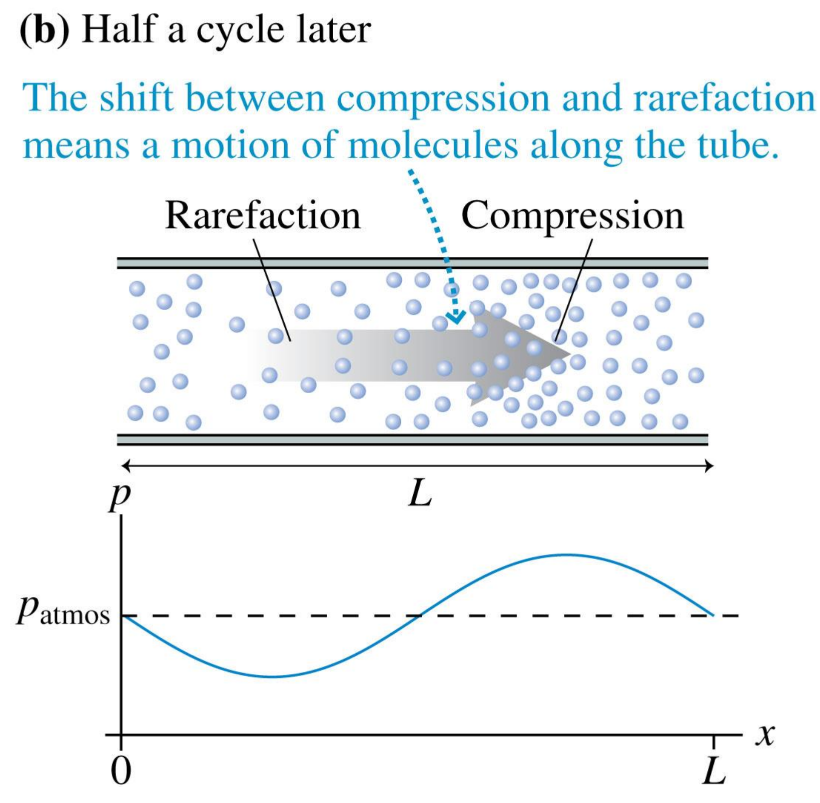
Standing Sound Waves

- Sound waves traveling in a tube eventually reach the end where they encounter the atmospheric pressure of the surrounding environment: a discontinuity.
- Part of the wave's energy is transmitted out into the environment, allowing you to hear the sound, and part is reflected back into the tube.



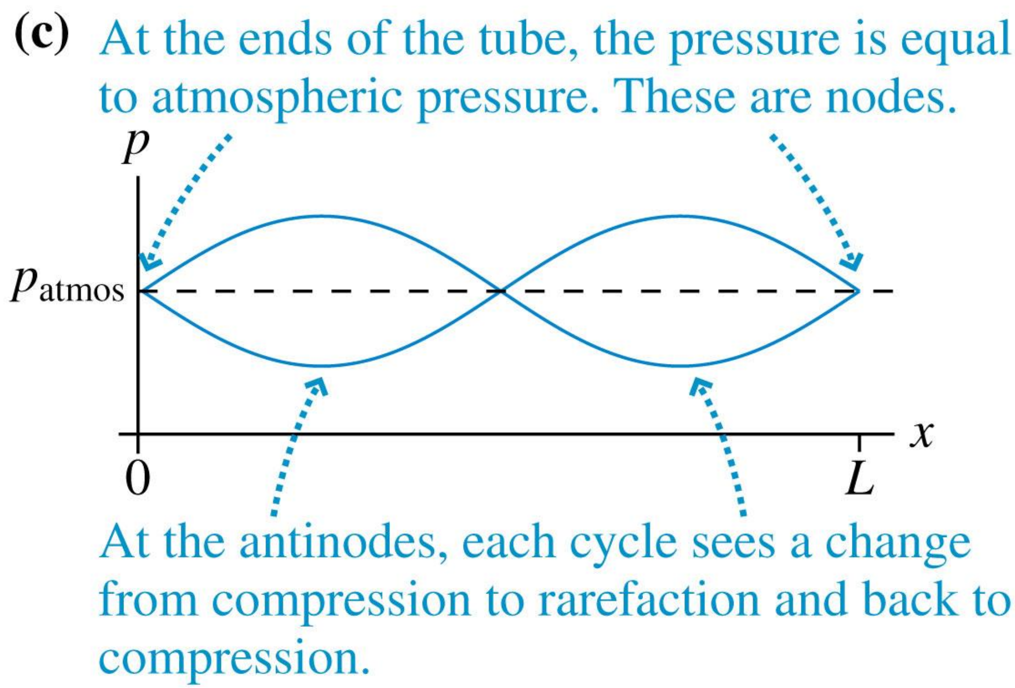
Standing Sound Waves

- Air molecules "slosh" back and forth, alternately pushing together (compression) and pulling apart (rarefaction).



Standing Sound Waves

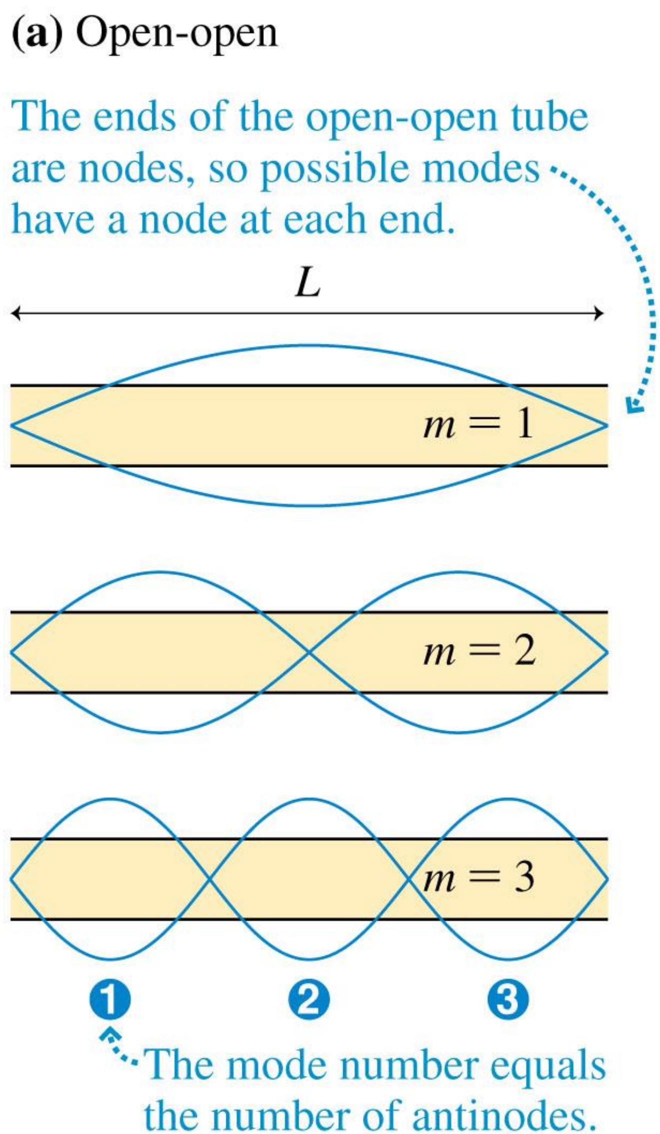
- A column of air open at both ends is an *open-open tube.*
- The antinodes of a standing sound wave are where the pressure has the largest variation: maximum compressions and rarefactions.



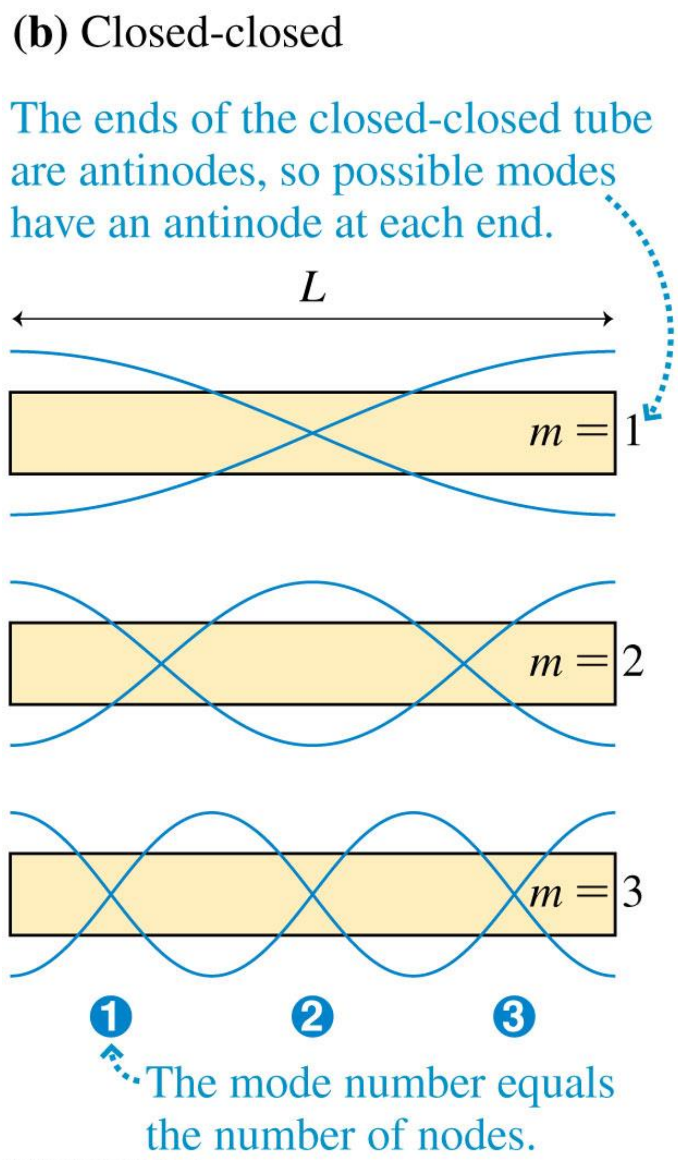
Standing Sound Waves

- Air molecules in tubes that are closed at one or both ends will rush toward the wall, creating a compression, and then rush away leaving a rarefaction.
- Thus **a closed end of an air column is an antinode of pressure.**

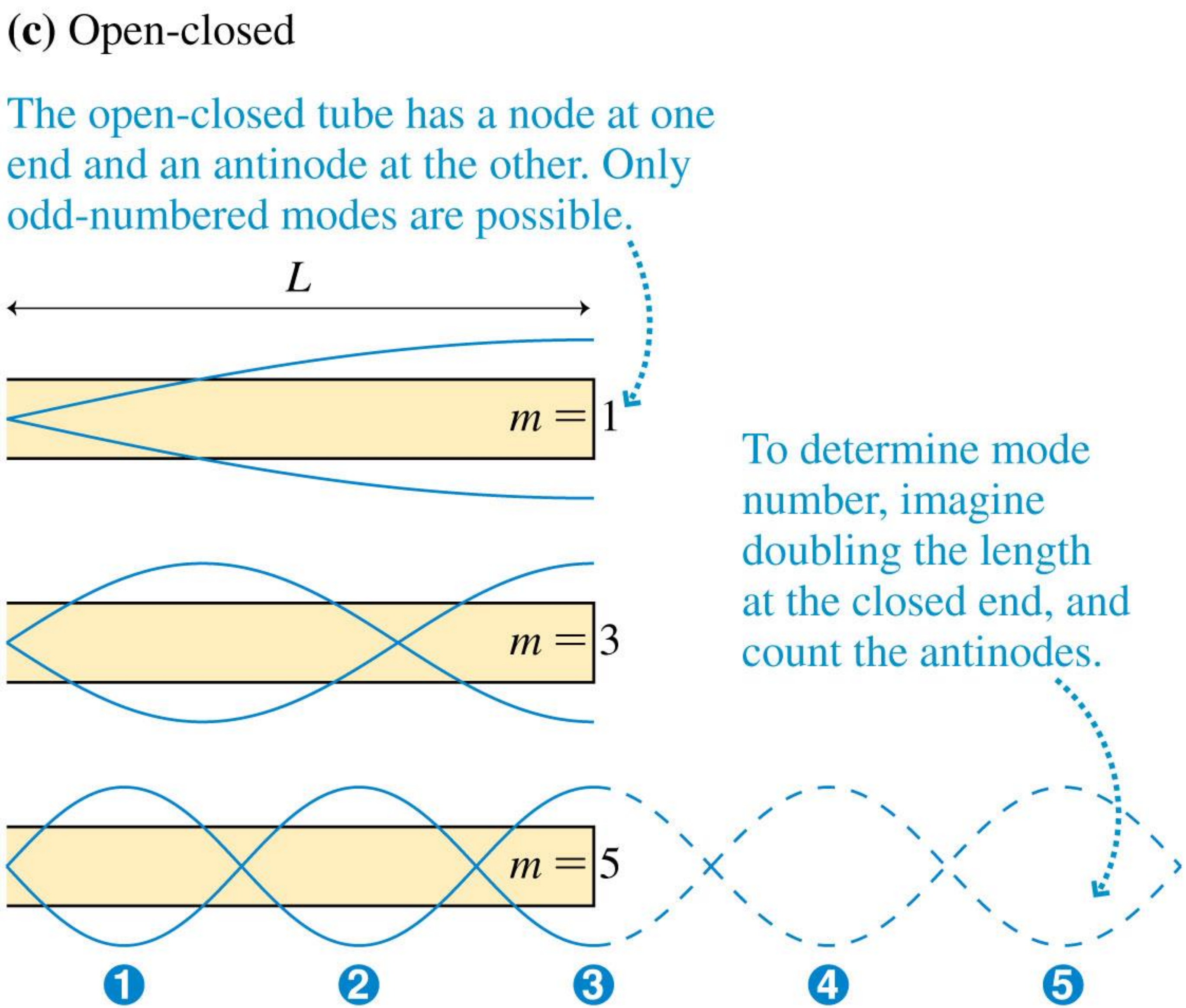
Standing Sound Waves



Standing Sound Waves

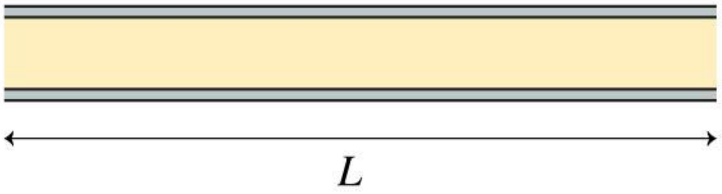


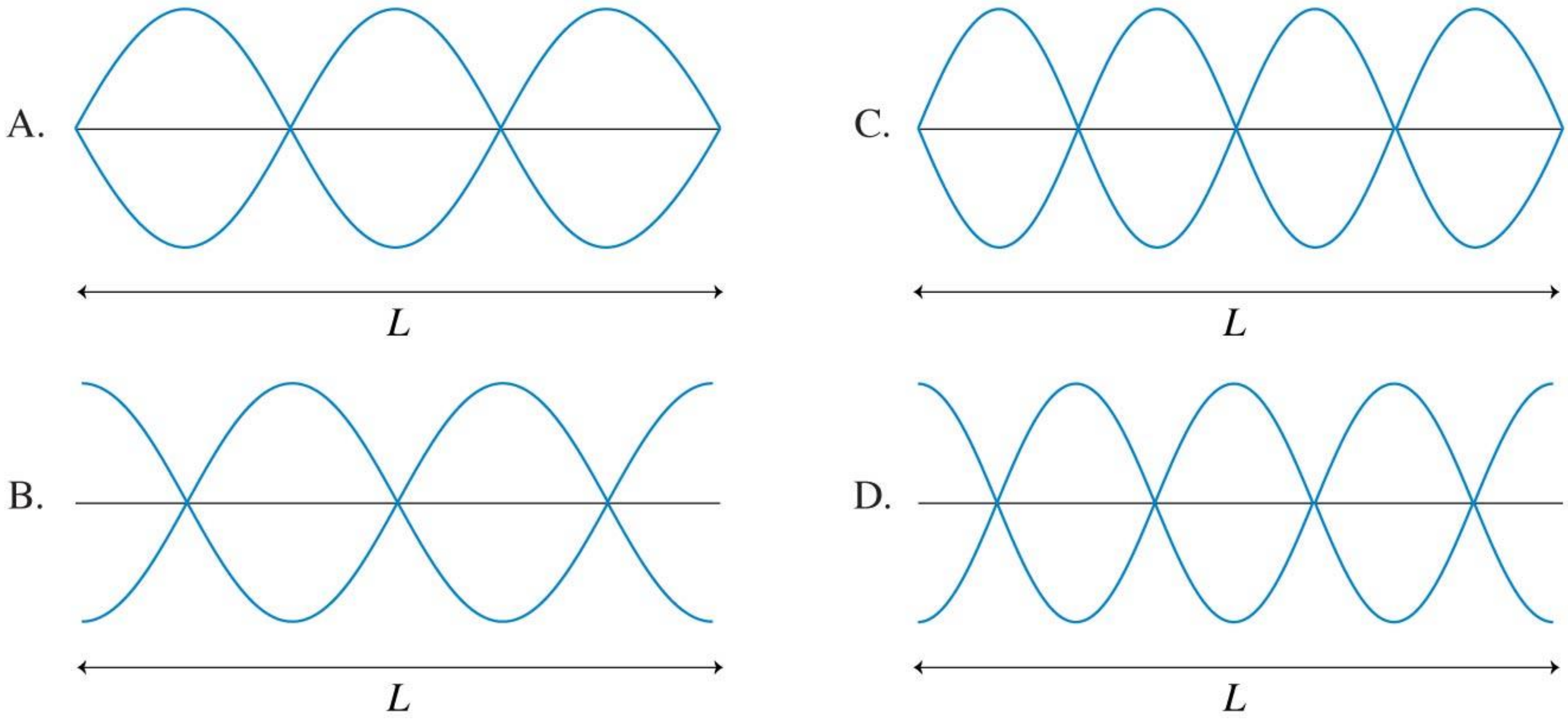
Standing Sound Waves



QuickCheck 16.8

An open-open tube of air has length *L*. Which graph shows the $m = 3$ standing wave in this tube?





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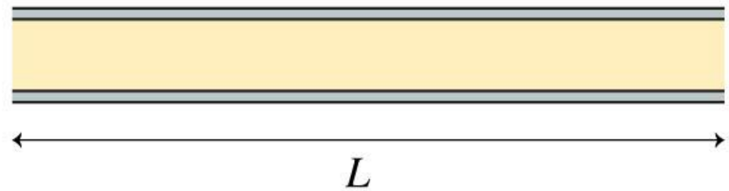
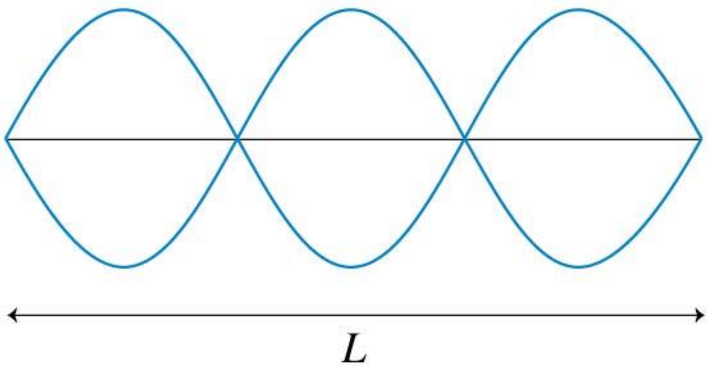
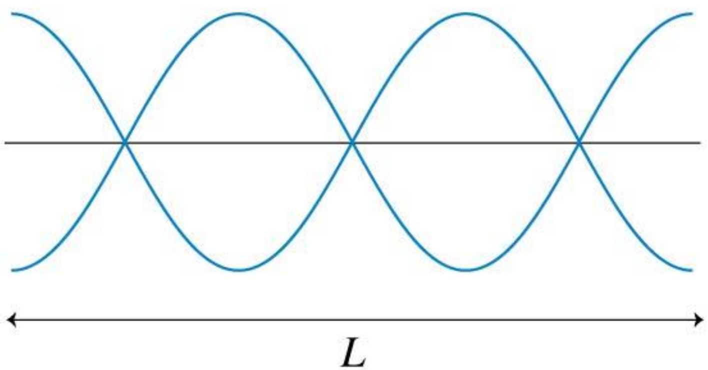


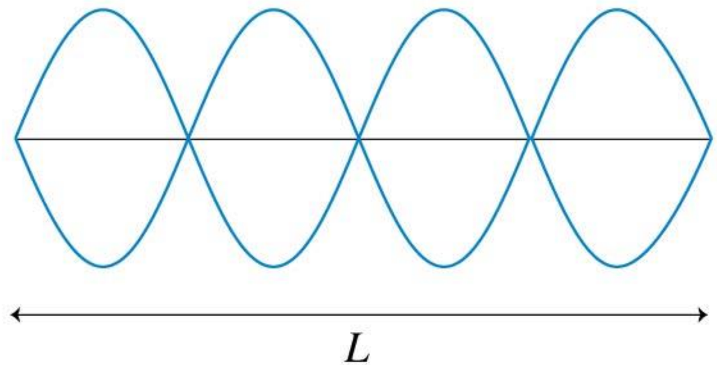
✔ A.



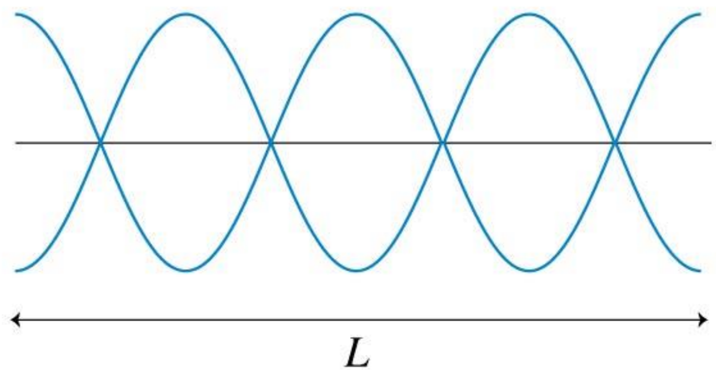
B.



C.

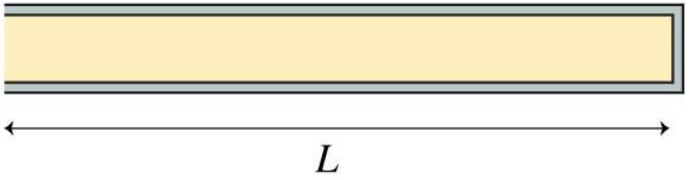


D.

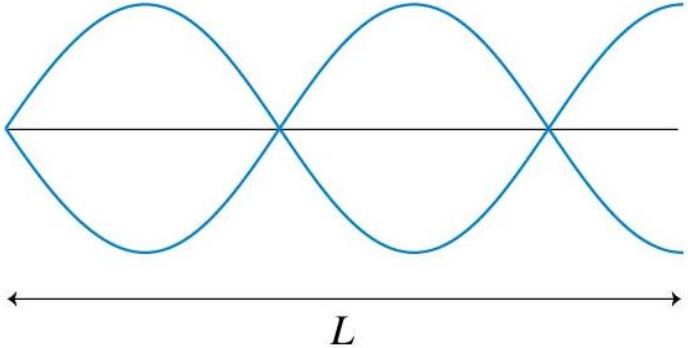


QuickCheck 16.9

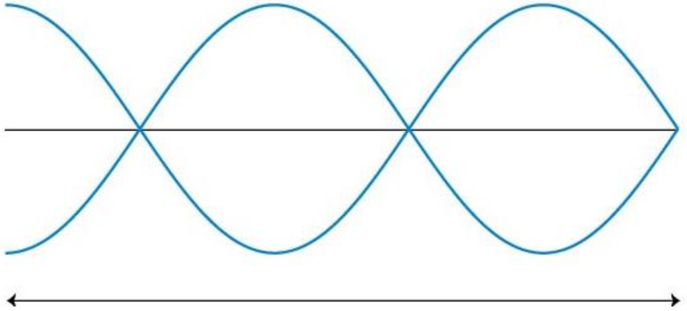
An open-closed tube of air of length L has the closed end on the right. Which graph shows the $m = 3$ standing wave in this tube?



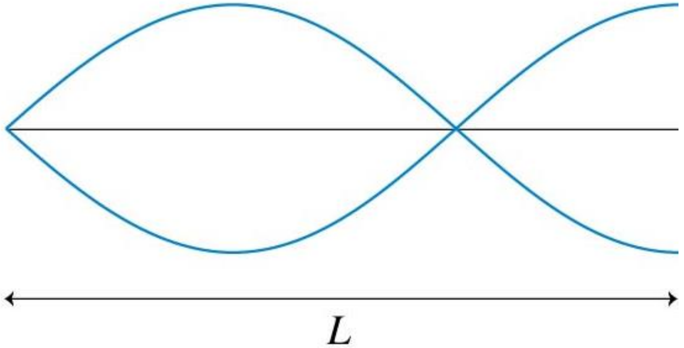
A.



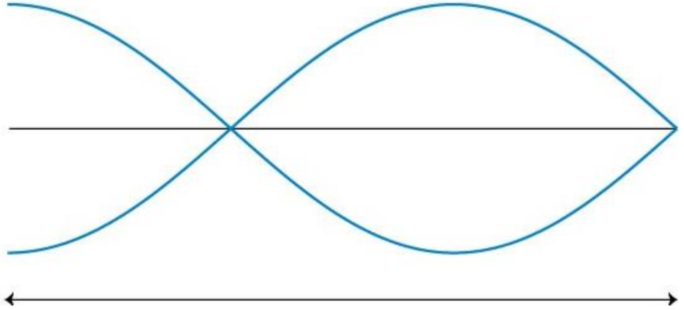
B.



C.



D.



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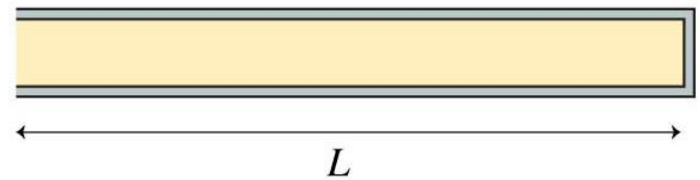
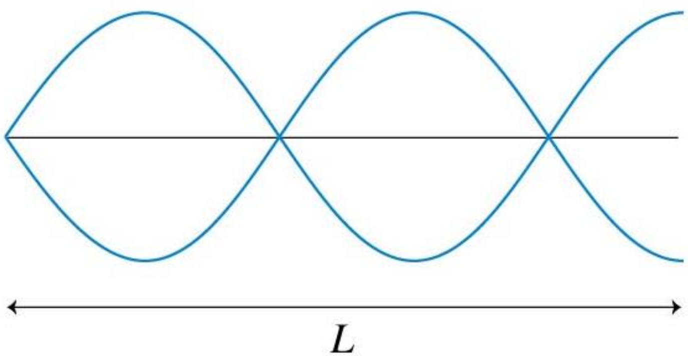
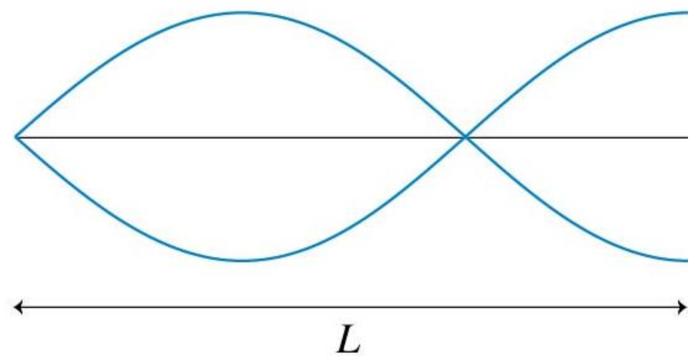


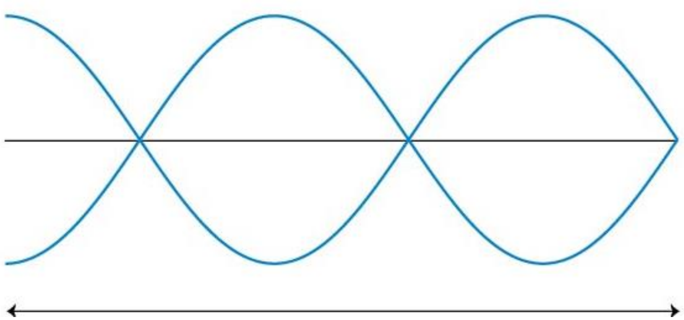
A.



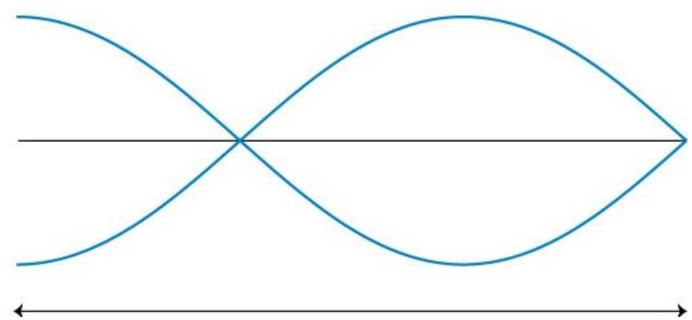
✔ C.



B.



D.



Standing Sound Waves

- The wavelengths and frequencies of an open-open tube and a closed-closed tube are

$$\lambda_m = \frac{2L}{m} \qquad f_m = m\left(\frac{v}{2L}\right) = mf_1 \qquad m = 1, 2, 3, 4, \ldots$$

Wavelengths and frequencies of standing sound wave modes in an open-open or closed-closed tube

- **The fundamental frequency of an open-closed tube is half that of an open-open or a closed-closed tube of the same length.**

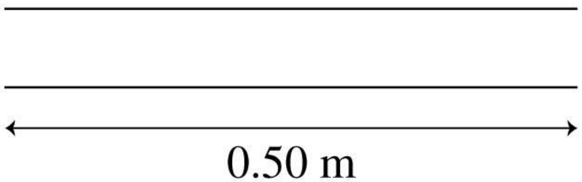
$$\lambda_m = \frac{4L}{m} \qquad f_m = m\left(\frac{v}{4L}\right) = mf_1 \qquad m = 1, 3, 5, 7, \ldots$$

Wavelengths and frequencies of standing sound wave modes in an open-closed tube

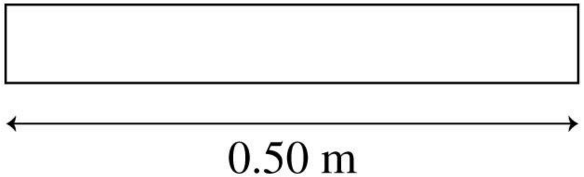
QuickCheck 16.10

The following tubes all support sound waves at their fundamental frequency. Which tube has the lowest fundamental frequency?

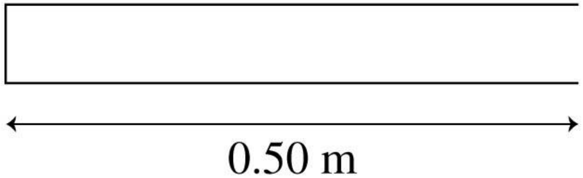
A.



B.

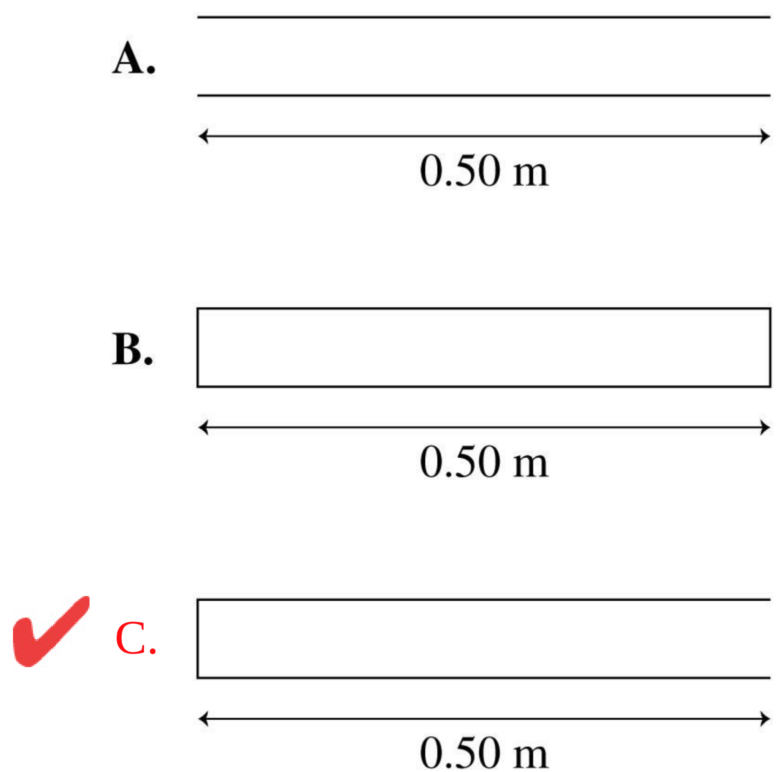


C.



QuickCheck 16.10

The following tubes all support sound waves at their fundamental frequency. Which tube has the lowest fundamental frequency?



QuickCheck 16.11

Which of the following changes will increase the frequency of the lowest-frequency standing sound wave in an open-open tube? Choose all that apply.

A. Closing one end of the tube
B. Replacing the air in the tube with helium
C. Reducing the length of the tube
D. Increasing the temperature of the air in the tube

QuickCheck 16.11

Which of the following changes will increase the frequency of the lowest-frequency standing sound wave in an open-open tube? Choose all that apply.

A. Closing one end of the tube
✔ B. Replacing the air in the tube with helium
✔ C. Reducing the length of the tube
✔ D. Increasing the temperature of the air in the tube

QuickCheck 16.12

At room temperature, the fundamental frequency of an open-open tube is 500 Hz. If taken outside on a cold winter day, the fundamental frequency will be

A. Less than 500 Hz
B. 500 Hz
C. More than 500 Hz

QuickCheck 16.12

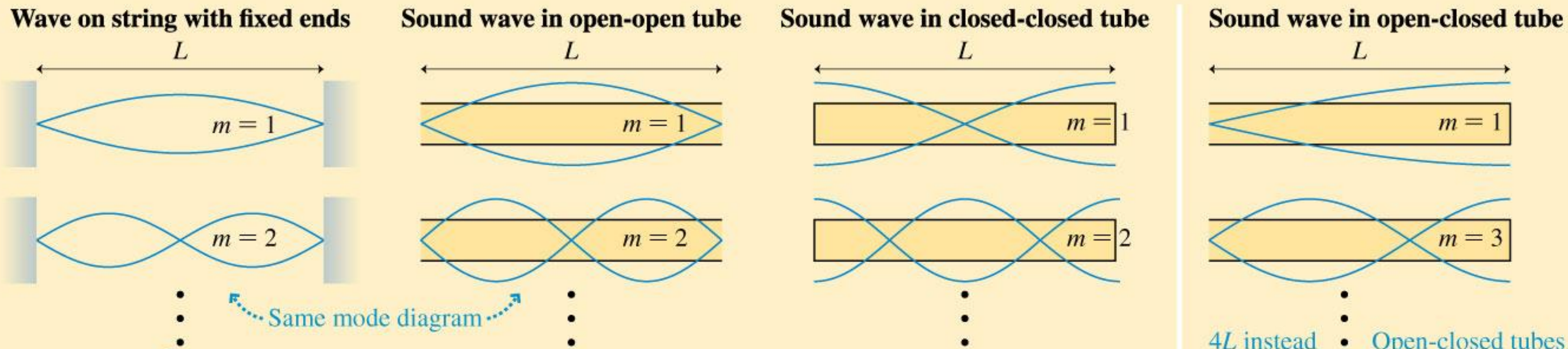
At room temperature, the fundamental frequency of an open-open tube is 500 Hz. If taken outside on a cold winter day, the fundamental frequency will be

✔ A. Less than 500 Hz
B. 500 Hz
C. More than 500 Hz

Standing Sound Waves

SYNTHESIS 16.1 Standing-wave modes

There are only two sets of frequency/wavelength relationships for standing-wave modes.



We show the first two modes; the pattern continues.

For waves on a string, v is the wave speed on the string.

For sound waves in tubes, v is the speed of sound.

The mode number m can be any positive integer.

$$\lambda_m = \frac{2L}{m} \qquad f_m = m\left(\frac{v}{2L}\right) = mf_1 \qquad m = 1, 2, 3, \ldots$$

All three systems have the same relationships for wavelength and frequency.

Higher-order modes are multiples of the lowest (the fundamental) frequency.

$4L$ instead of $2L$

Open-closed tubes have only odd-numbered modes.

$$\lambda_m = \frac{4L}{m} \qquad m = 1, 3, 5, \ldots$$

$$f_m = m\left(\frac{v}{4L}\right) = mf_1$$

Text: p. 511

Standing Sound Waves

PROBLEM-SOLVING STRATEGY 16.1 **Standing waves**

We can use the same general strategy for any standing wave.

PREPARE

- For sound waves, determine what sort of pipe or tube you have: open-open, closed-closed, or open-closed.
- For string or light waves, the ends will be fixed points.
- For other types of standing waves, such as electromagnetic or water waves, the mode diagram will be similar to one of the cases outlined in Synthesis 16.1. You can then work by analogy with waves on strings or sound waves in tubes.
- Determine known values: length of the tube or string, frequency, wavelength, positions of nodes or antinodes.
- It may be useful to sketch a visual overview, including a picture of the relevant mode.

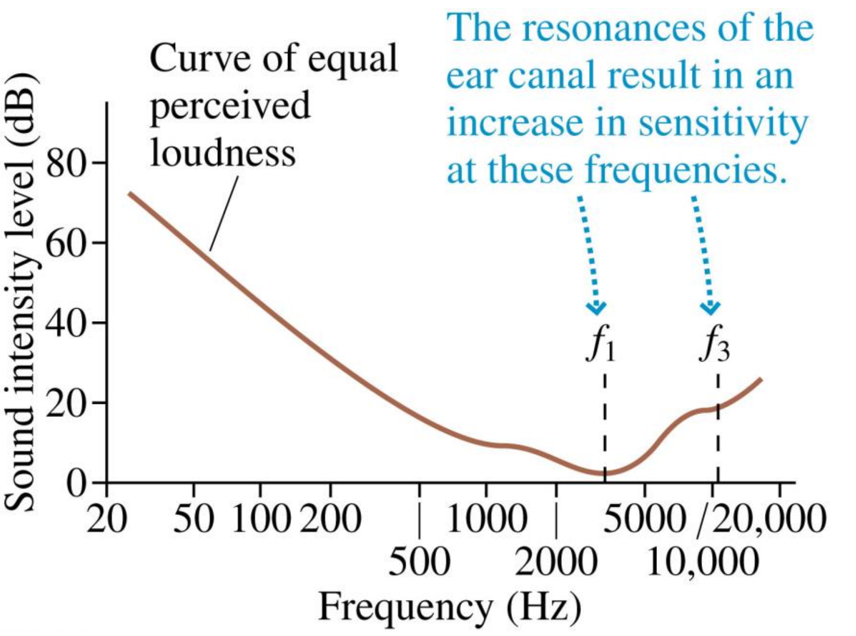
SOLVE Once you have determined the mode diagram, you can use the appropriate set of equations in Synthesis 16.1 to find the wavelength and frequency. These equations work for any type of wave.

ASSESS Does your final answer seem reasonable? Is there another way to check on your results? For example, the frequency times the wavelength for any mode should equal the wave speed—you can check to see that it does.

Text: p. 512

Standing Sound Waves

- The curve of *equal perceived loudness* shows the intensity level required for different frequencies to give the *impression* of equal loudness.



- The two dips on the curve are resonances in the ear canal where pitches that should seem quieter produce the same perceived loudness.

Wind Instruments

- Wind instruments use holes to change the effective length of the tube. The first hole open becomes a node because the tube is open to atmosphere at that point.

- Instruments with buzzers at the end or that use vibrations of the musician's lips generate a continuous range of frequencies. The ones that match the resonances produce the musical notes.

Example 16.8 The importance of warming up

Wind instruments have an adjustable joint to change the tube length. Players know that they may need to adjust this joint to stay in tune—that is, to stay at the correct frequency. To see why, suppose a "cold" flute plays the note A at 440 Hz when the air temperature is 20°C.

a. How long is the tube? At 20°C, the speed of sound in air is 343 m/s.

Example 16.8 The importance of warming up

b. As the player blows air through the flute, the air inside the instrument warms up. Once the air temperature inside the flute has risen to 32°C, increasing the speed of sound to 350 m/s, what is the frequency?

c. At the higher temperature, how must the length of the tube be changed to bring the frequency back to 440 Hz?

Example 16.8 The importance of warming up (cont.)

SOLVE A flute is an open-open tube with fundamental frequency $f_1 = v/2L$.

a. At 20°C, the length corresponding to 440 Hz is

$$L = \frac{v}{2f_1} = \frac{343 \text{ m/s}}{2(440 \text{ Hz})} = 0.390 \text{ m}$$

Example 16.8 The importance of warming up (cont.)

b. As the speed of sound increases, the frequency changes to

$$f_1(\text{at } 32°\text{C}) = \frac{350 \text{ m/s}}{2(0.390 \text{ m})} = 449 \text{ Hz}$$

c. To bring the flute back into tune, the length must be increased to give a frequency of 440 Hz with a speed of 350 m/s. The new length is

$$L = \frac{v}{2f_1} = \frac{350 \text{ m/s}}{2(440 \text{ Hz})} = 0.398 \text{ m}$$

Thus the flute must be increased in length by 8 mm.

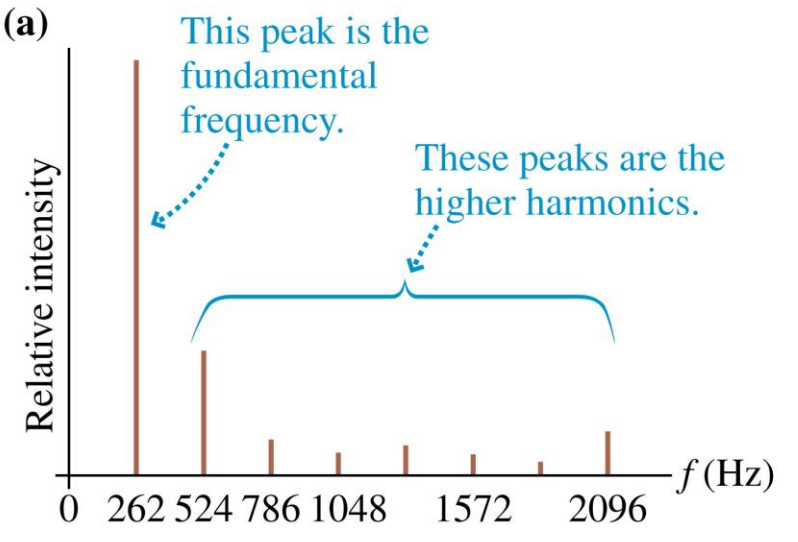
Example 16.8 The importance of warming up (cont.)

ASSESS A small change in the absolute temperature produces a correspondingly small change in the speed of sound. We expect that this will require a small change in length, so our answer makes sense.

Section 16.5 Speech and Hearing

The Frequency Spectrum

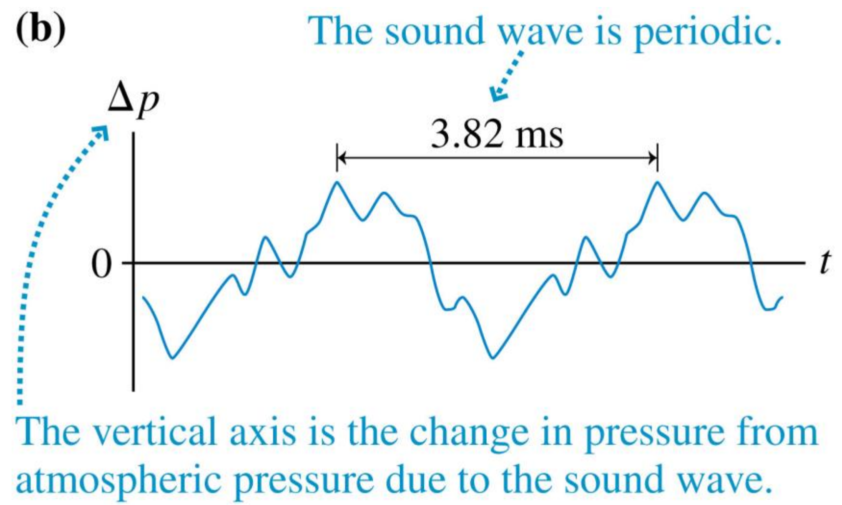
- Most sounds are a mix, or superposition, of different frequencies.
- The **frequency spectrum** of a sound is a bar chart showing the relative intensities of different frequencies.



- Your brain interprets the fundamental frequency as the *pitch* and uses the higher harmonics to determine the **tone quality**, or *timbre*.

The Frequency Spectrum

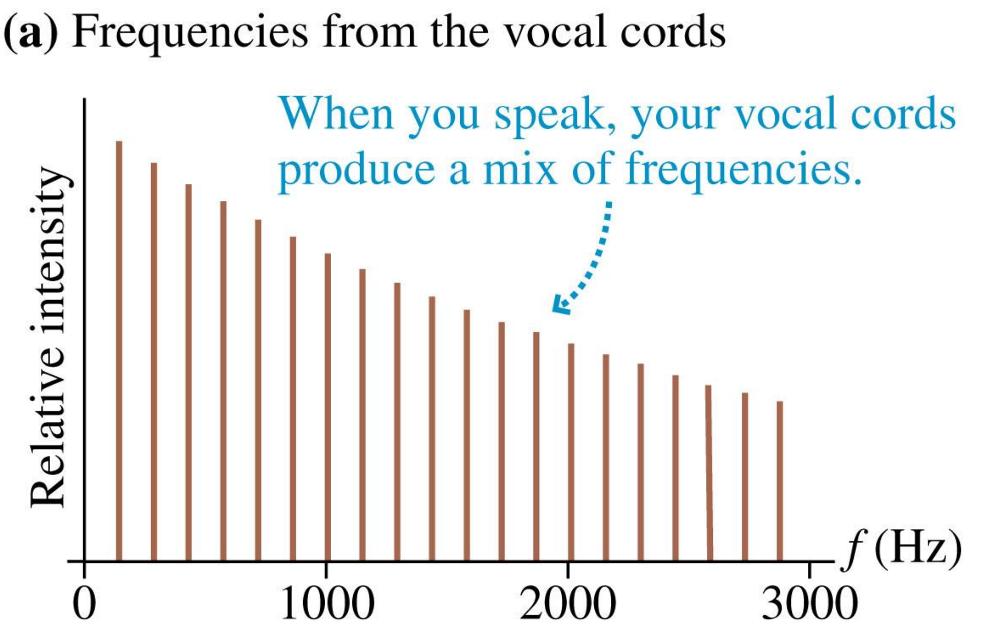
- The tone quality is what makes a note on the trumpet sound differently from the same note (frequency) played on a guitar. The frequency spectrum is different.



- **The higher harmonics don't change the period of the sound wave; they change only its shape.**

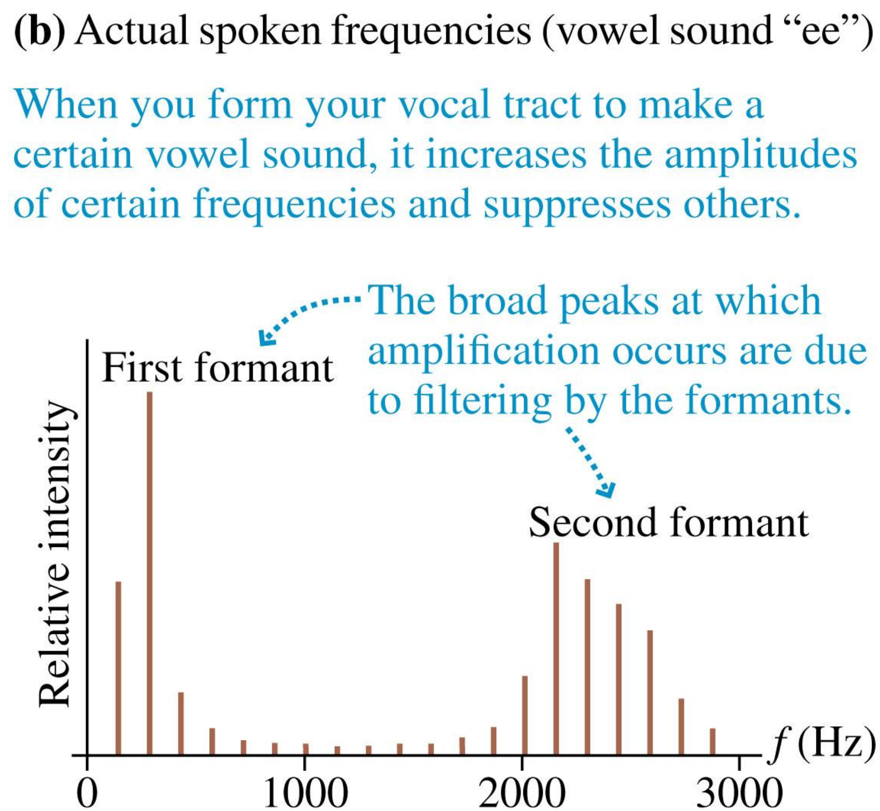
Vowels and Formants

- Speech begins with the vibration of vocal cords, stretched tissue in your throat.
- Your vocal cords produce a mix of different frequencies as they vibrate—the fundamental frequency and a mixture of higher harmonics.
- This creates the pitch of your voice and can be changed by changing the tension in your vocal cords.



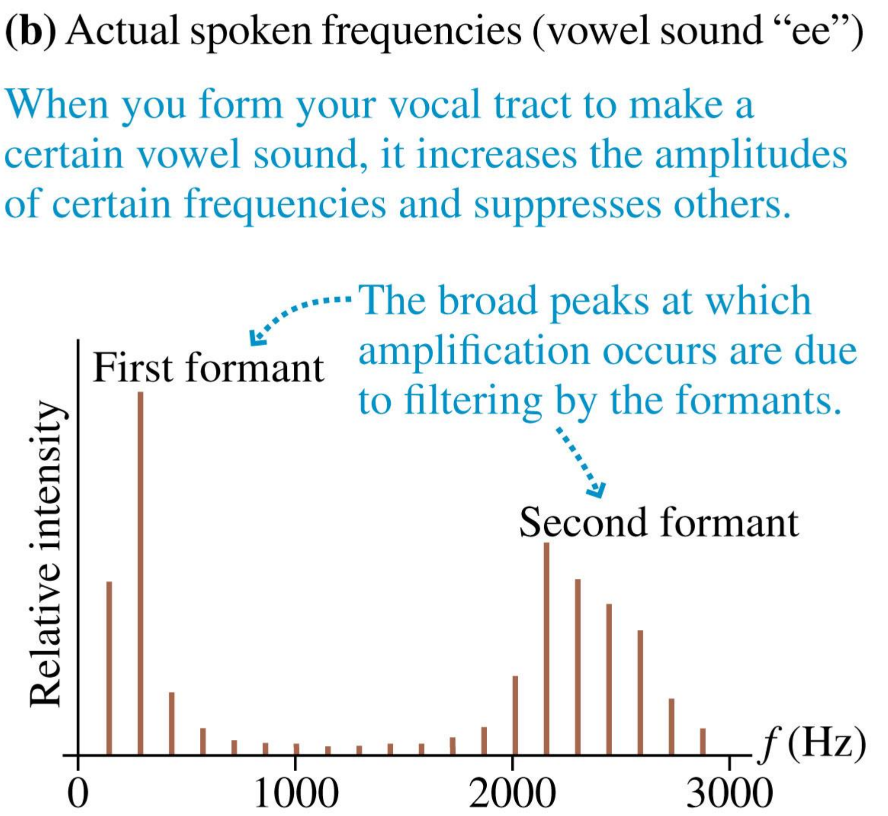
Vowels and Formants

- Sound then passes through your vocal tract—a series of cavities including the throat, mouth, and nose—that act like tubes.
- The standing-wave resonances in the vocal tract are called **formants**.



Vowels and Formants

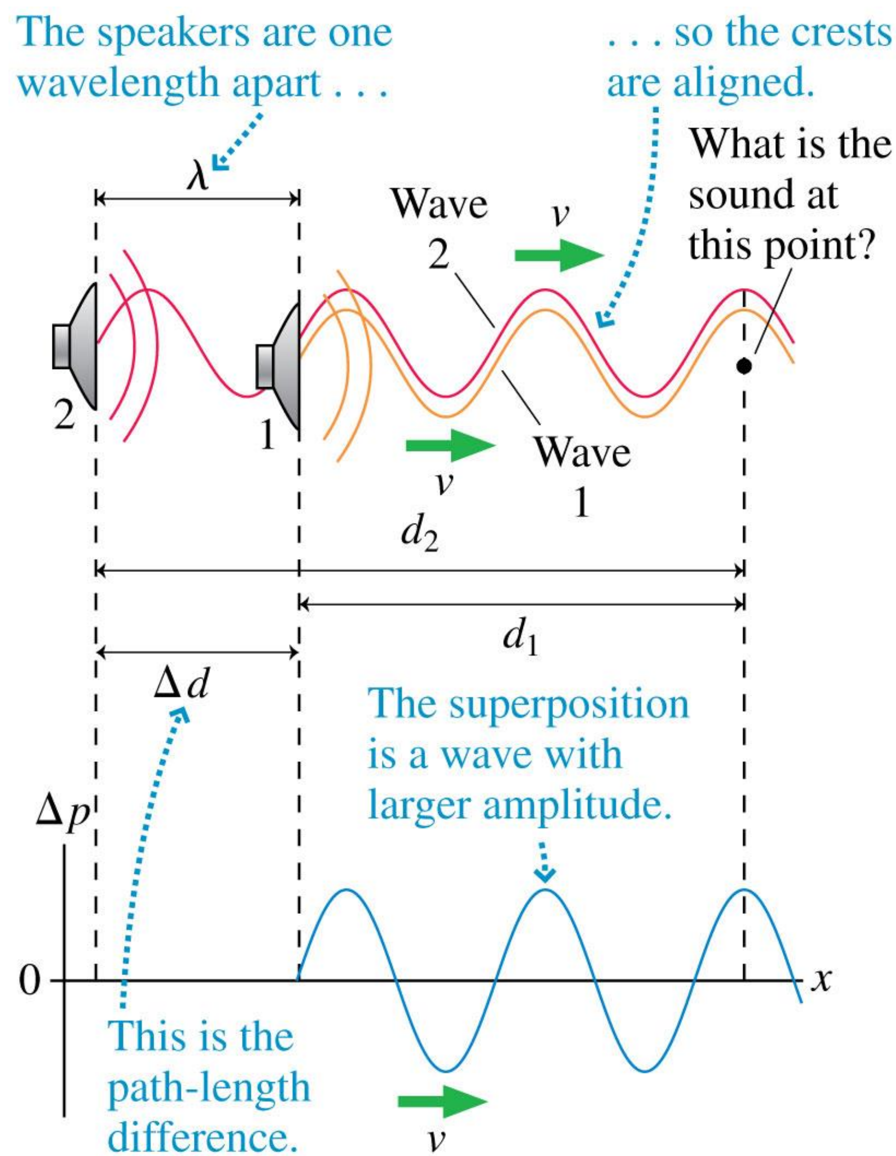
- You change the shape and frequency of the formants, and thus the sounds you make, by changing your mouth opening and the shape and position of your tongue.



Section 16.6 The Interference of Waves from Two Sources

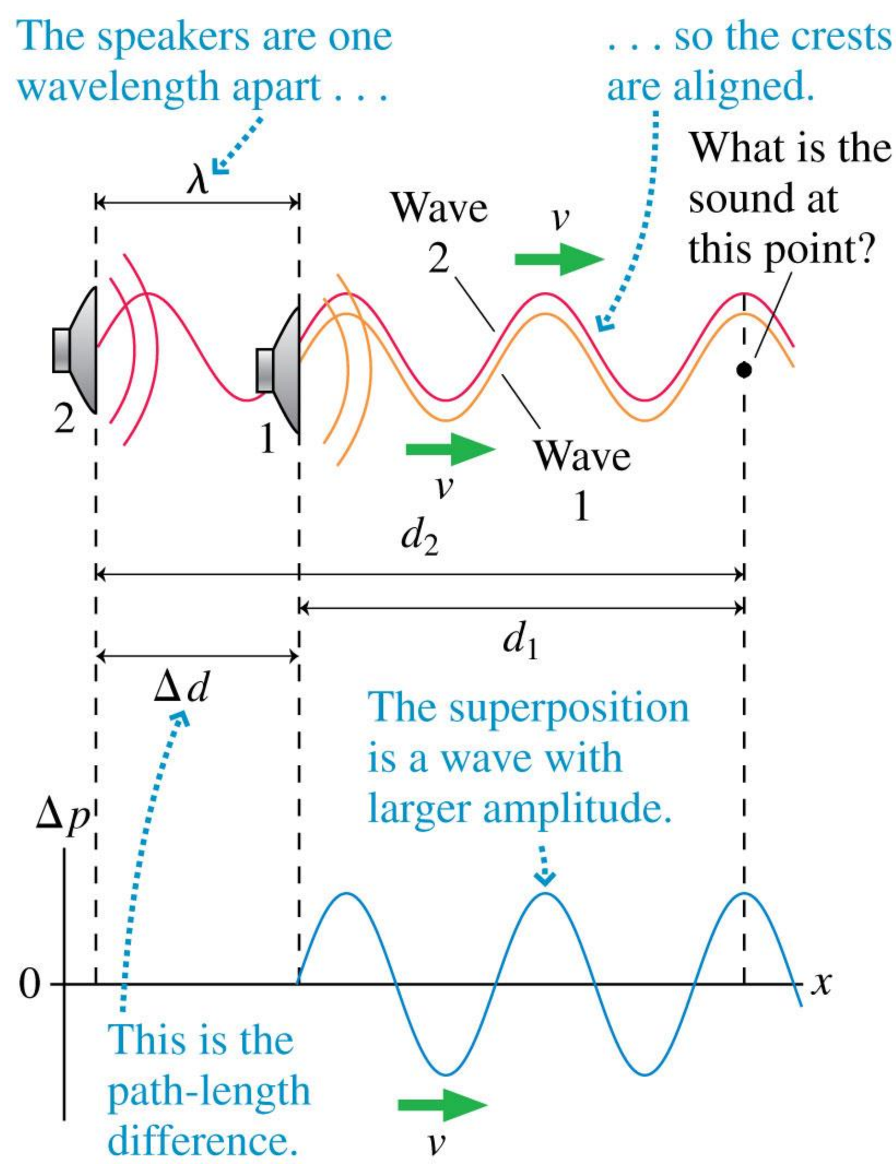
Interference Along a Line

- Two loudspeakers are spaced exactly one wavelength apart. Assuming the sound waves are identical, the waves will travel on top of each other.
- Superposition says that for every point along the line, the net sound pressure will be the sum of the pressures.



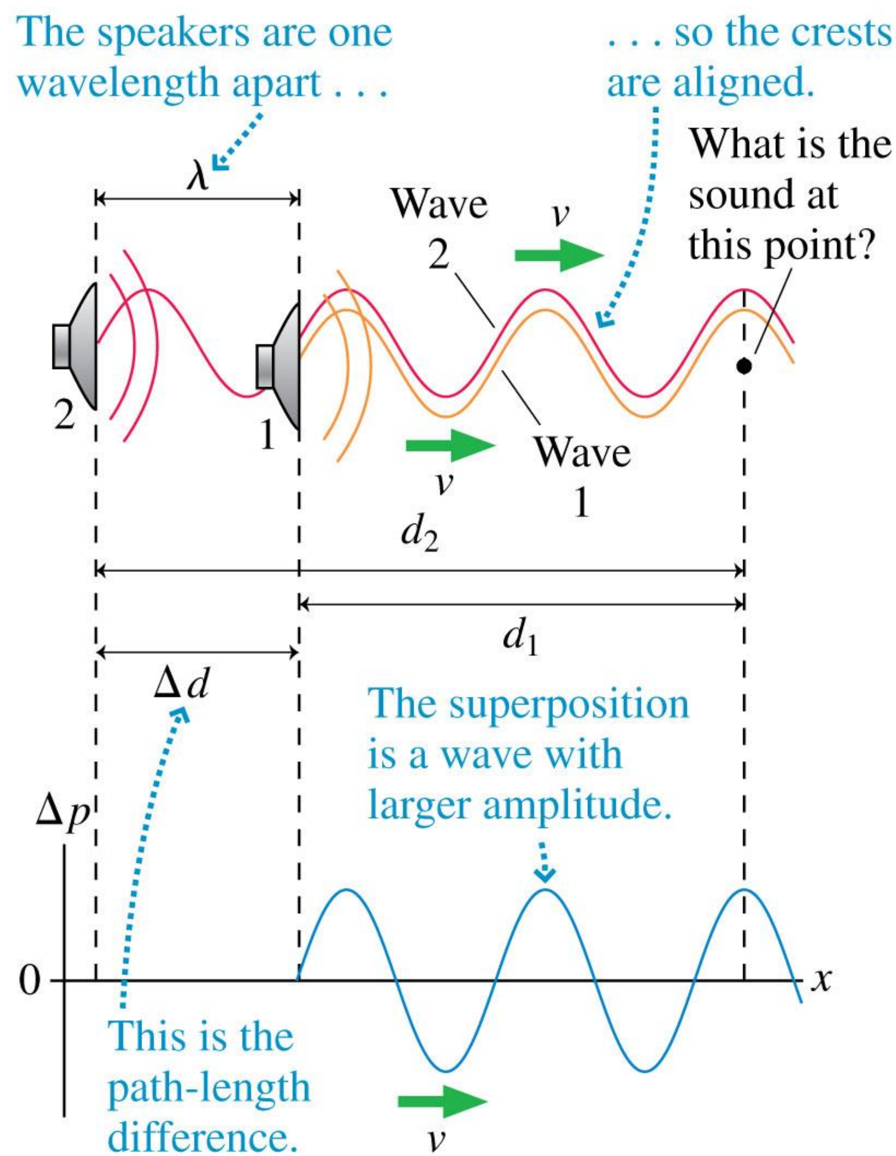
Interference Along a Line

- Because the loudspeakers are spaced one wavelength apart, the crests and troughs are aligned, and therefore are **in phase**.
- Waves that are in phase will have constructive interference.



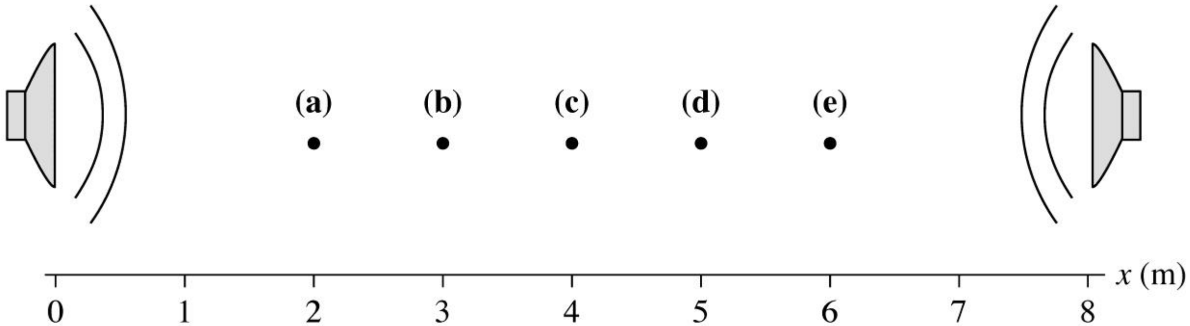
Interference Along a Line

- If d_1 and d_2 are the distances from the loudspeakers to the observer, their difference is called the **path-length difference.**
- **Two waves will be in phase and will produce constructive interference any time their path-length difference is a whole number of wavelengths.**



QuickCheck 16.13

Two speakers are emitting identical sound waves with a wavelength of 4.0 m. The speakers are 8.0 m apart and directed toward each other, as in the following diagram.



At each of the noted points in the previous diagram, the interference is

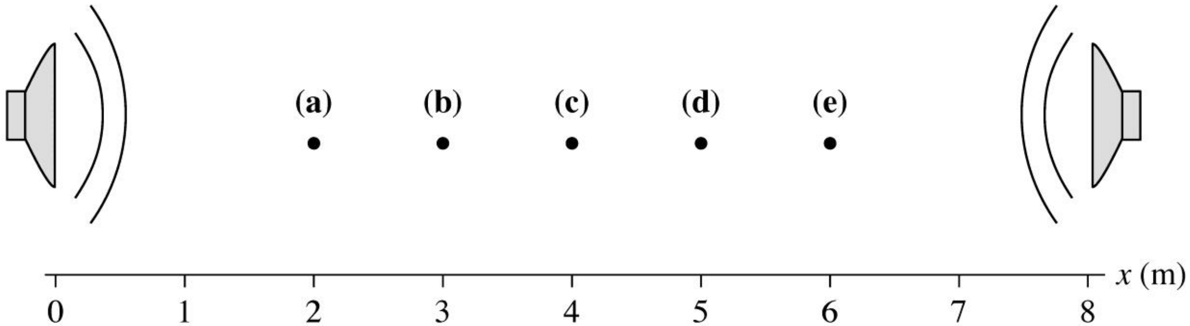
A. Constructive.

B. Destructive.

C. Something in between.

QuickCheck 16.13

Two speakers are emitting identical sound waves with a wavelength of 4.0 m. The speakers are 8.0 m apart and directed toward each other, as in the following diagram.



At each of the noted points in the previous diagram, the interference is

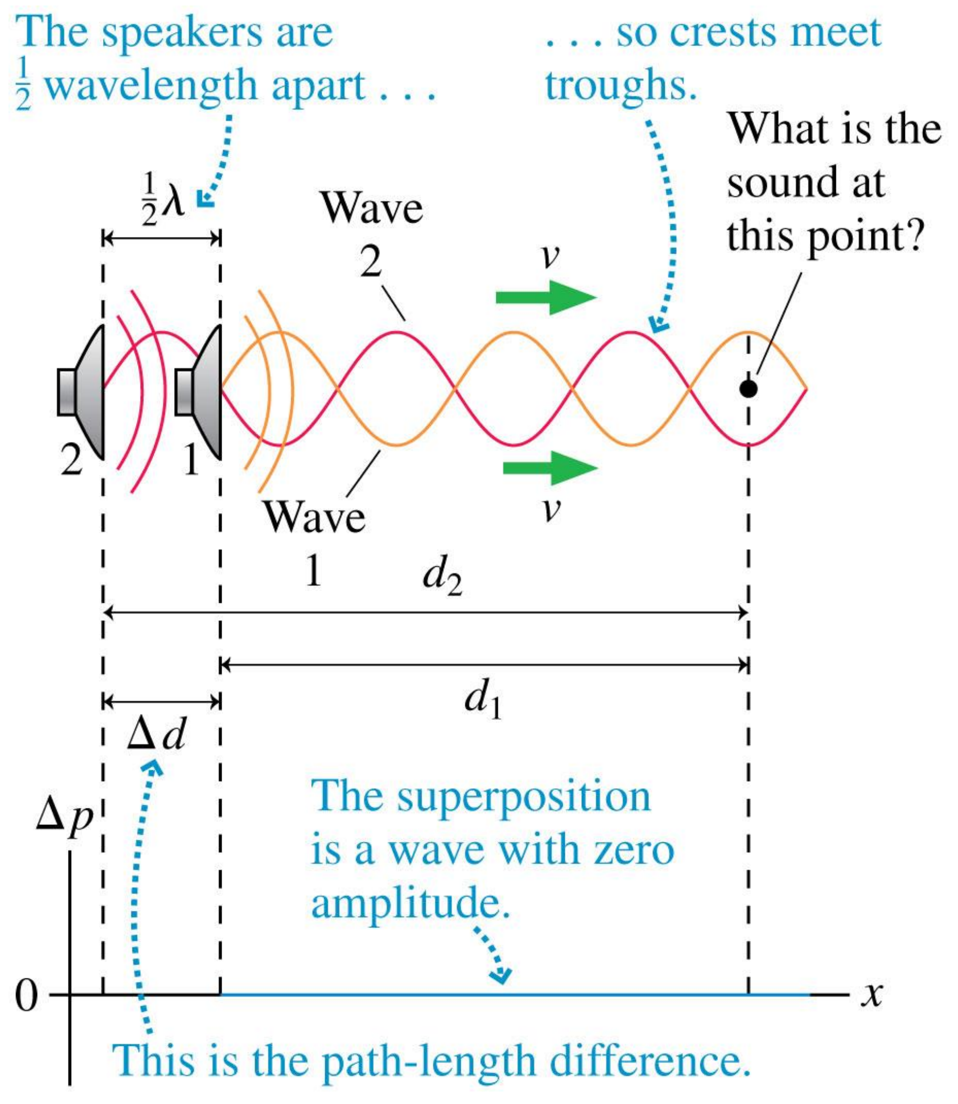
A. Constructive. (a, c, e)

B. Destructive. (b, d)

C. Something in between.

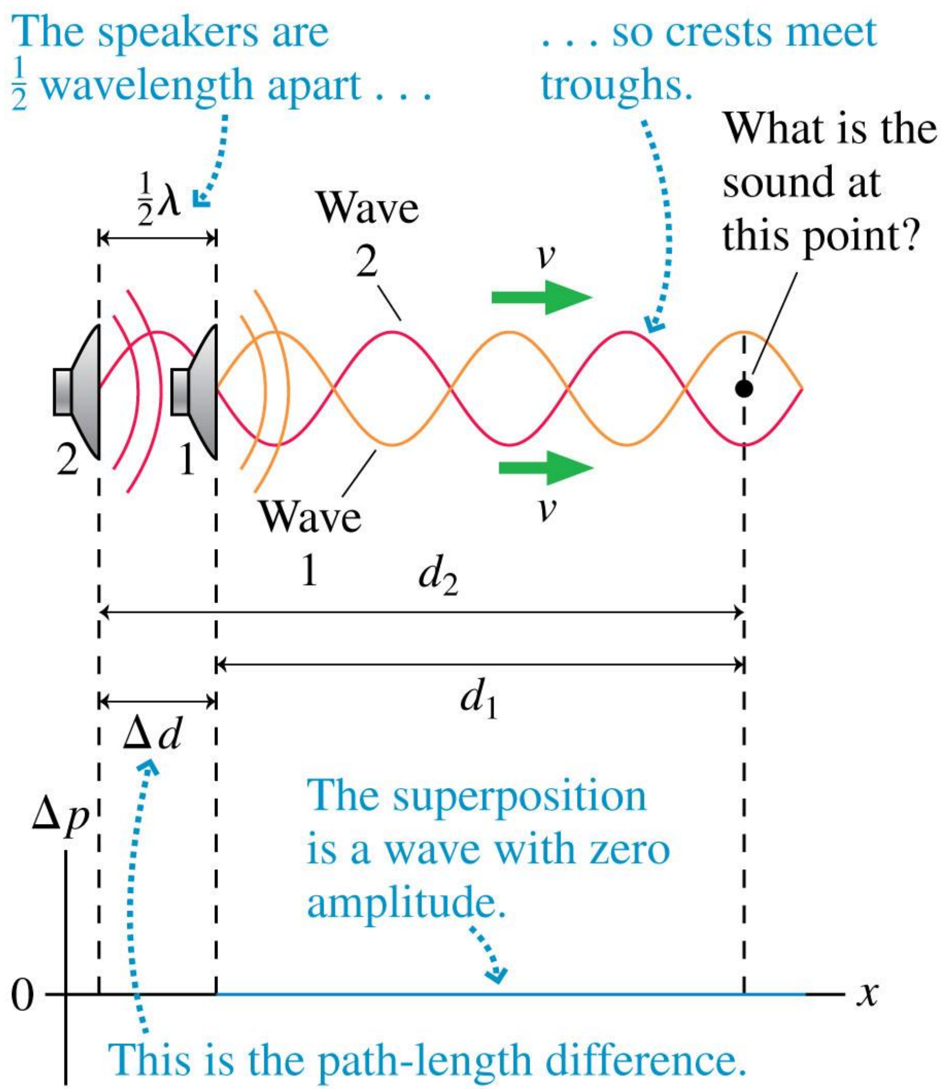
Interference Along a Line

- When the speakers are separated by half a wavelength, the waves are **out of phase.**
- The sum of the two waves is zero at every point; this is destructive interference.



Interference Along a Line

- **Two wavelengths will be out of phase and will produce destructive interference if their path-length difference is a whole number of wavelength plus half a wavelength.**



Interference Along a Line

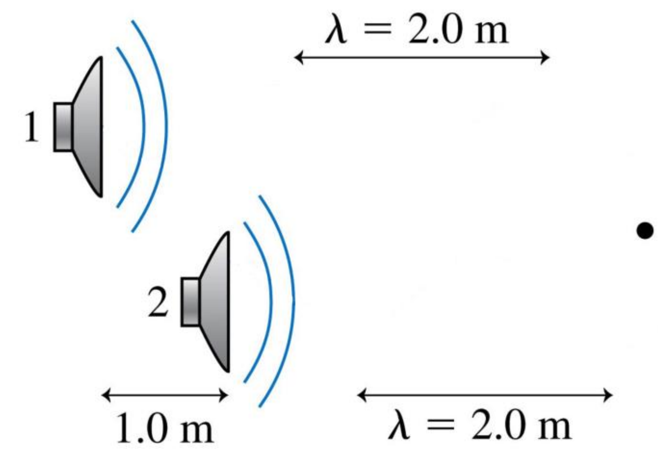
- For two identical sources of waves, constructive interference occurs when the path-length difference is

$$\Delta d = m\lambda \qquad m = 0, 1, 2, 3, \ldots$$

- Destructive interference occurs when the path-length difference is

$$\Delta d = \left(m + \frac{1}{2}\right)\lambda \qquad m = 0, 1, 2, 3, \ldots$$

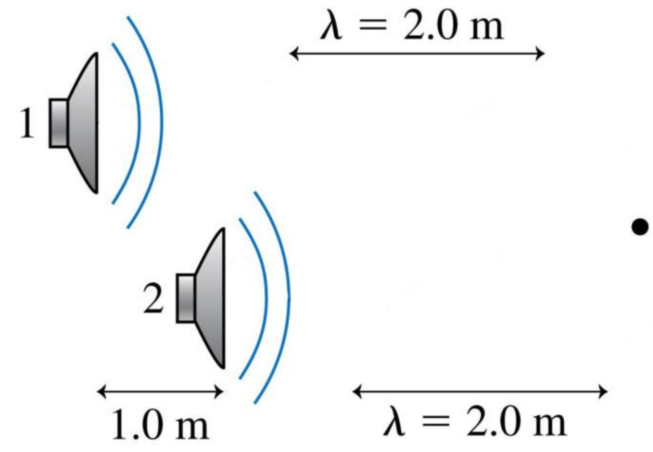
QuickCheck 16.14



Two loudspeakers emit sound waves with the same wavelength and the same amplitude. The waves are shown displaced, for clarity, but assume that both are traveling along the same axis. At the point where the dot is,

A. The interference is constructive.
B. The interference is destructive.
C. The interference is somewhere between constructive and destructive.
D. There's not enough information to tell about the interference.

QuickCheck 16.14



Two loudspeakers emit sound waves with the same wavelength and the same amplitude. The waves are shown displaced, for clarity, but assume that both are traveling along the same axis. At the point where the dot is,

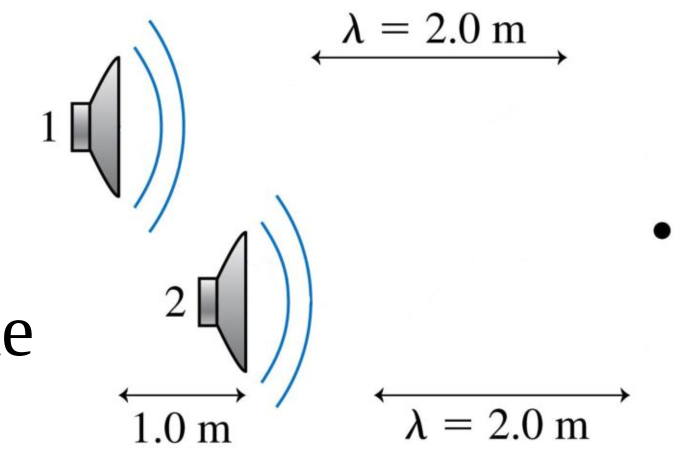
A. The interference is constructive.

B. The interference is destructive.

✔ C. The interference is somewhere between constructive and destructive.

D. There's not enough information to tell about the interference.

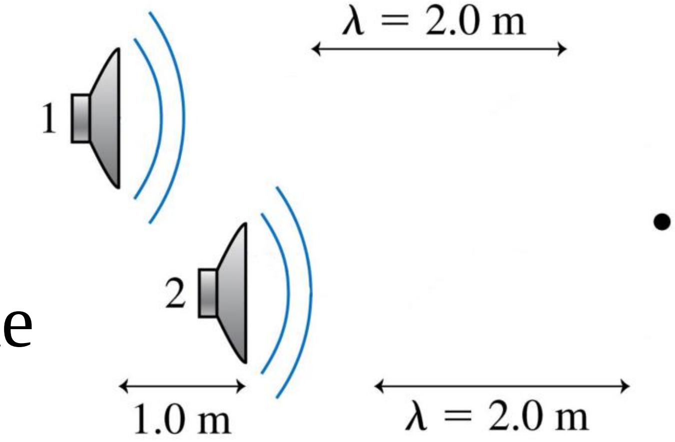
QuickCheck 16.15



Two loudspeakers emit sound waves with the same wavelength and the same amplitude. Which of the following would cause there to be destructive interference at the position of the dot?

A. Move speaker 2 forward (right) 1.0 m
B. Move speaker 2 forward (right) 0.5 m
C. Move speaker 2 backward (left) 0.5 m
D. Move speaker 2 backward (left) 1.0 m
E. Nothing. Destructive interference is not possible in this situation.

QuickCheck 16.15

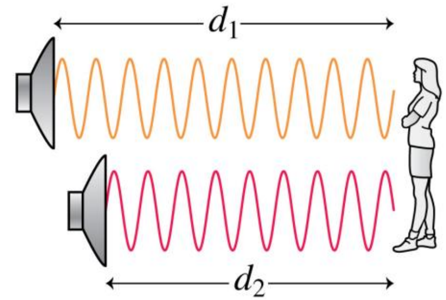


Two loudspeakers emit sound waves with the same wavelength and the same amplitude. Which of the following would cause there to be destructive interference at the position of the dot?

A. Move speaker 2 forward (right) 1.0 m
B. Move speaker 2 forward (right) 0.5 m
✔ C. Move speaker 2 backward (left) 0.5 m
D. Move speaker 2 backward (left) 1.0 m
E. Nothing. Destructive interference is not possible in this situation.

Example 16.10 Interference of sound from two speakers

Susan stands directly in front of two speakers that are in line with each other. The farther speaker is 6.0 m from her; the closer speaker is 5.0 m away. The speakers are connected to the same 680 Hz sound source, and Susan hears the sound loud and clear. The frequency of the source is slowly increased until, at some point, Susan can no longer hear it. What is the frequency when this cancellation occurs? Assume that the speed of sound in air is 340 m/s.



Known

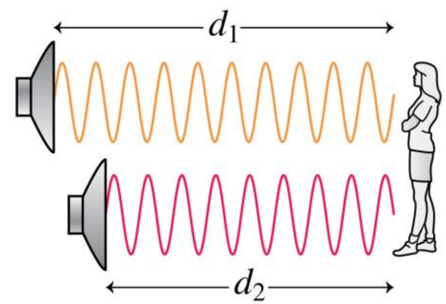
$d_1 = 6.0$ m
$d_2 = 5.0$ m
$v = 340$ m/s

Find

f

Example 16.10 Interference of sound from two speakers (cont.)

PREPARE We'll start with a visual overview of the situation, as shown in FIGURE 16.27. The sound waves from the two speakers overlap at Susan's position. The path-length difference—the extra distance traveled by the wave from speaker 1—is just the difference in the distances from the speakers to Susan's position. In this case,



Known

$d_1 = 6.0$ m
$d_2 = 5.0$ m
$v = 340$ m/s

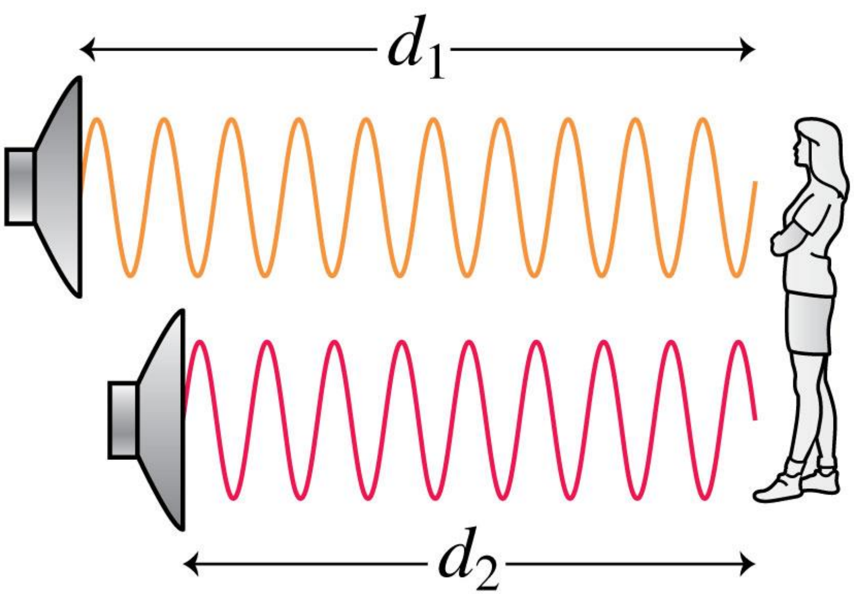
Find

f

$$\Delta d = d_2 - d_1 = 6.0 \text{ m} - 5.0 \text{ m} = 1.0 \text{ m}$$

Example 16.10 Interference of sound from two speakers (cont.)

At 680 Hz, this path-length difference gives constructive interference. When the frequency is increased by some amount, destructive interference results and Susan can no longer hear the sound.



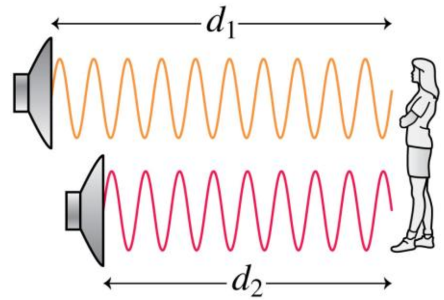
Known

$d_1 = 6.0$ m
$d_2 = 5.0$ m
$v = 340$ m/s

Find

f

Example 16.10 Interference of sound from two speakers (cont.)



Known

$d_1 = 6.0$ m
$d_2 = 5.0$ m
$v = 340$ m/s

Find

f

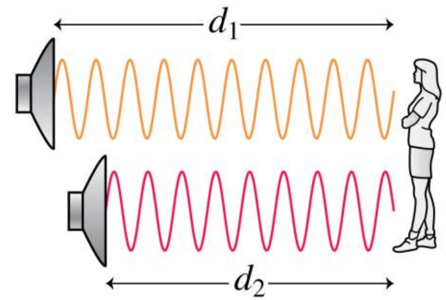
SOLVE The path-length difference and the sound wavelength together determine whether the interference at Susan's position is constructive or destructive. Initially, with a 680 Hz tone and a 340 m/s sound speed, the wavelength is

$$\lambda = \frac{v}{f} = \frac{340 \text{ m/s}}{680 \text{ Hz}} = 0.50 \text{ m}$$

Example 16.10 Interference of sound from two speakers (cont.)

The ratio of the path-length difference to the wavelength is

$$\frac{\Delta d}{\lambda} = 2.0$$



Known

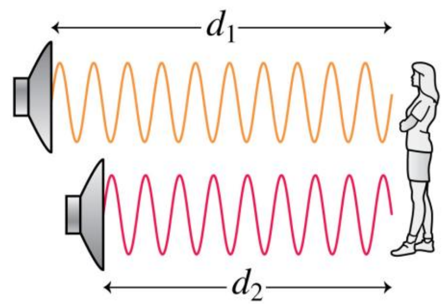
$d_1 = 6.0$ m
$d_2 = 5.0$ m
$v = 340$ m/s

Find

f

The path-length difference matches the constructive-interference condition $\Delta d = m\lambda$ with $m = 2$. We expect constructive interference, which is what we get—the sound is loud.

Example 16.10 Interference of sound from two speakers (cont.)



Known
$d_1 = 6.0$ m
$d_2 = 5.0$ m
$v = 340$ m/s
Find
f

As the frequency is increased, the wavelength decreases and the ratio $\Delta d/\lambda$ increases. The ratio starts at 2.0. The first time destructive interference occurs is when the ratio reaches 2½, which matches the destructive-interference condition $\Delta d = (m + \frac{1}{2})\lambda$ with $m = 2$. So destructive interference first occurs when the wavelength is decreased to

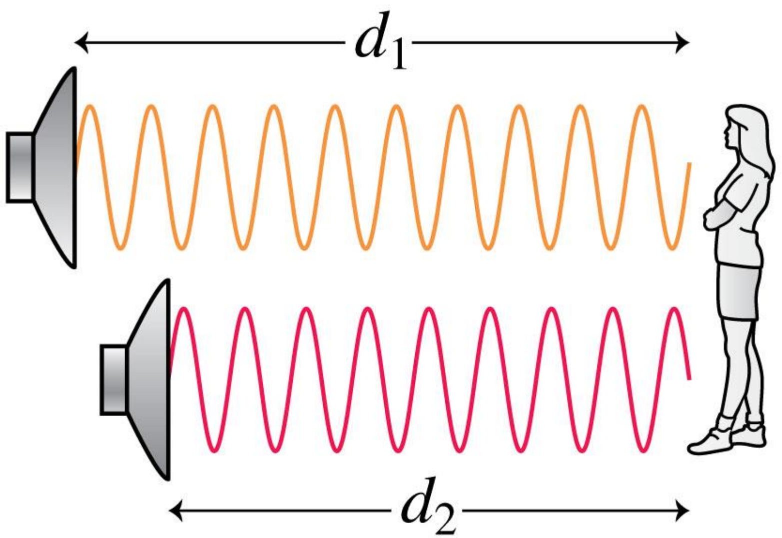
$$\lambda = \frac{\Delta d}{2.5} = \frac{1.0}{2.5} = 0.40 \text{ m}$$

This corresponds to a frequency of

$$f = \frac{340 \text{ m/s}}{0.40 \text{ m}} = 850 \text{ Hz}$$

Example 16.10 Interference of sound from two speakers (cont.)

ASSESS 850 Hz is an increase of 170 Hz from the original 680 Hz, an increase of one-fourth of the original frequency. This makes sense: Originally, 2 cycles of the wave "fit" in the 1.0 m path-length difference; now, 2.5 cycles "fit," an increase of one-fourth of the original.



Known

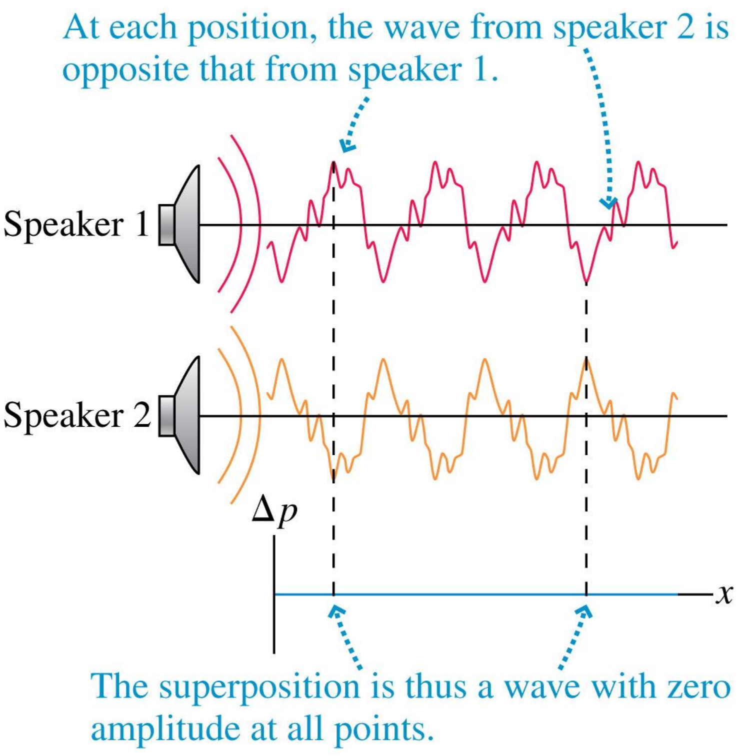
$d_1 = 6.0$ m
$d_2 = 5.0$ m
$v = 340$ m/s

Find

f

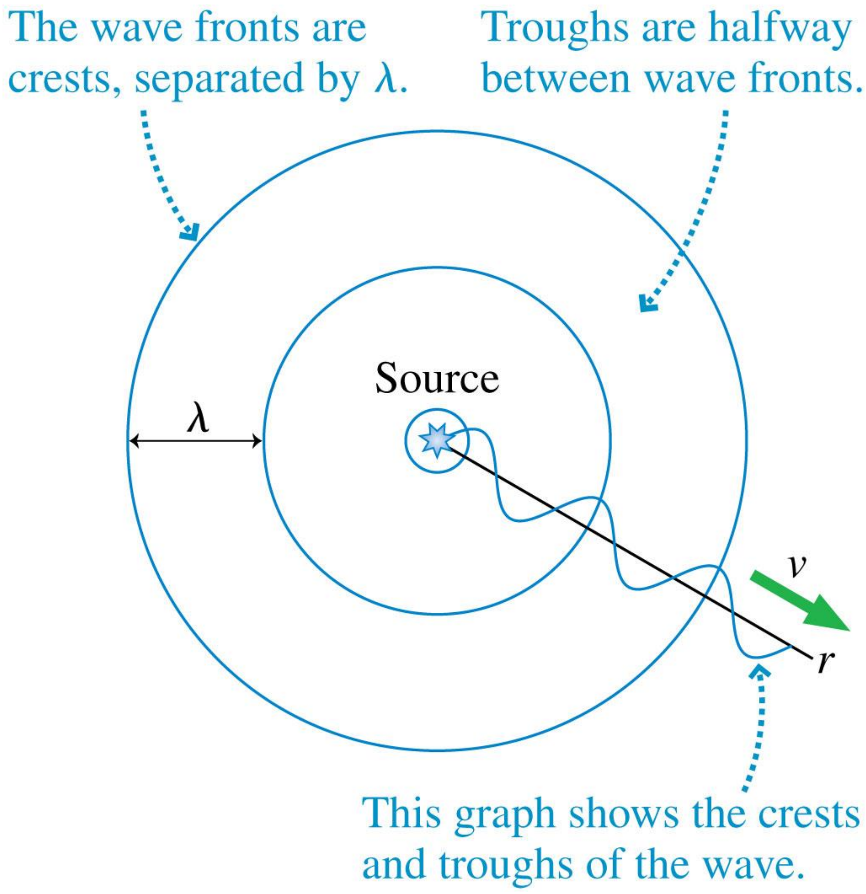
Interference Along a Line

- If two loudspeakers are side by side, and one emits the *exact inverse* of the other speaker's wave, then there will be destructive interference and the sound will completely cancel.
- Headphones with *active noise reduction* measure the ambient sound and produce an inverted version to add to it, lowering the overall intensity of the sound.



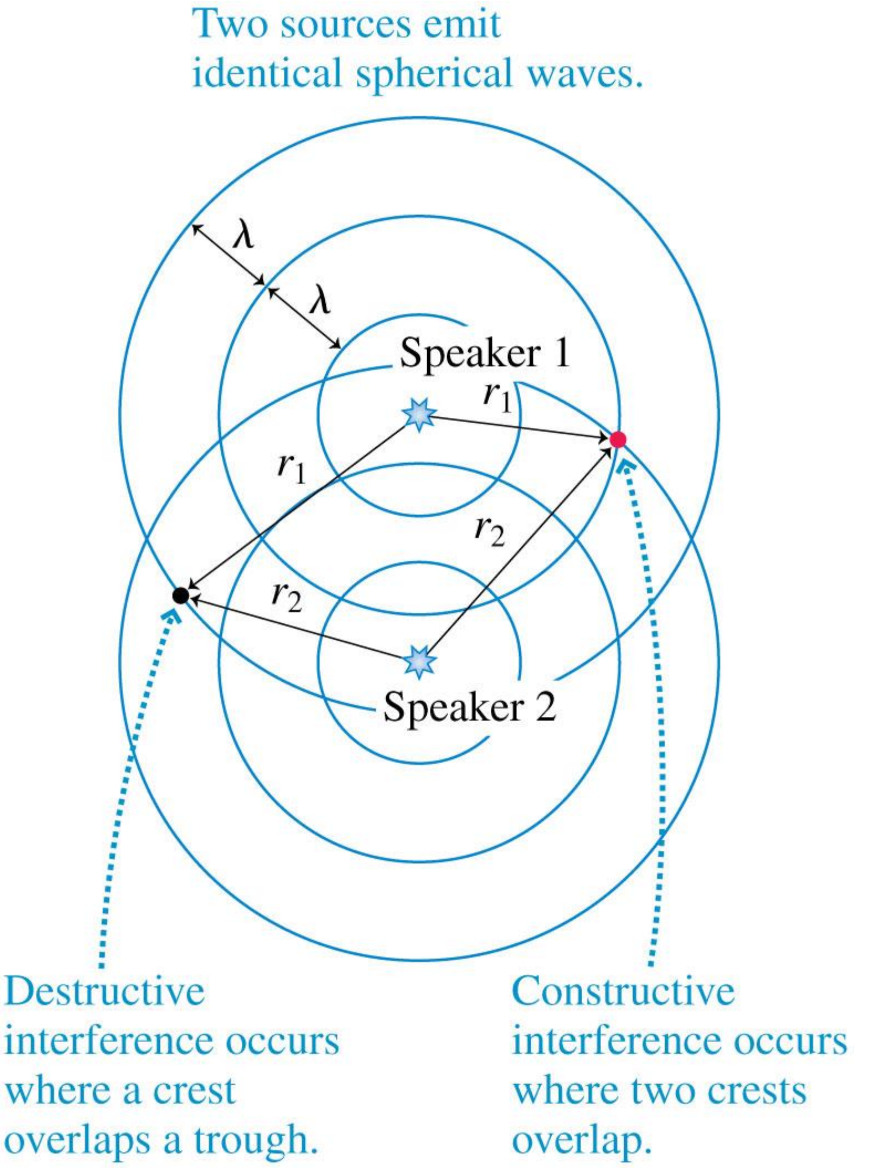
Interference of Spherical Waves

- In practice, sound waves from a speaker or light waves emitted from a lightbulb spread out as spherical waves.



Interference of Spherical Waves

- Interference occurs where the waves overlap.
- The red dot represents a point where two wave crests overlap, so the interference is constructive.
- The black dot is at a point where a crest overlaps a trough, so the wave interference is destructive.

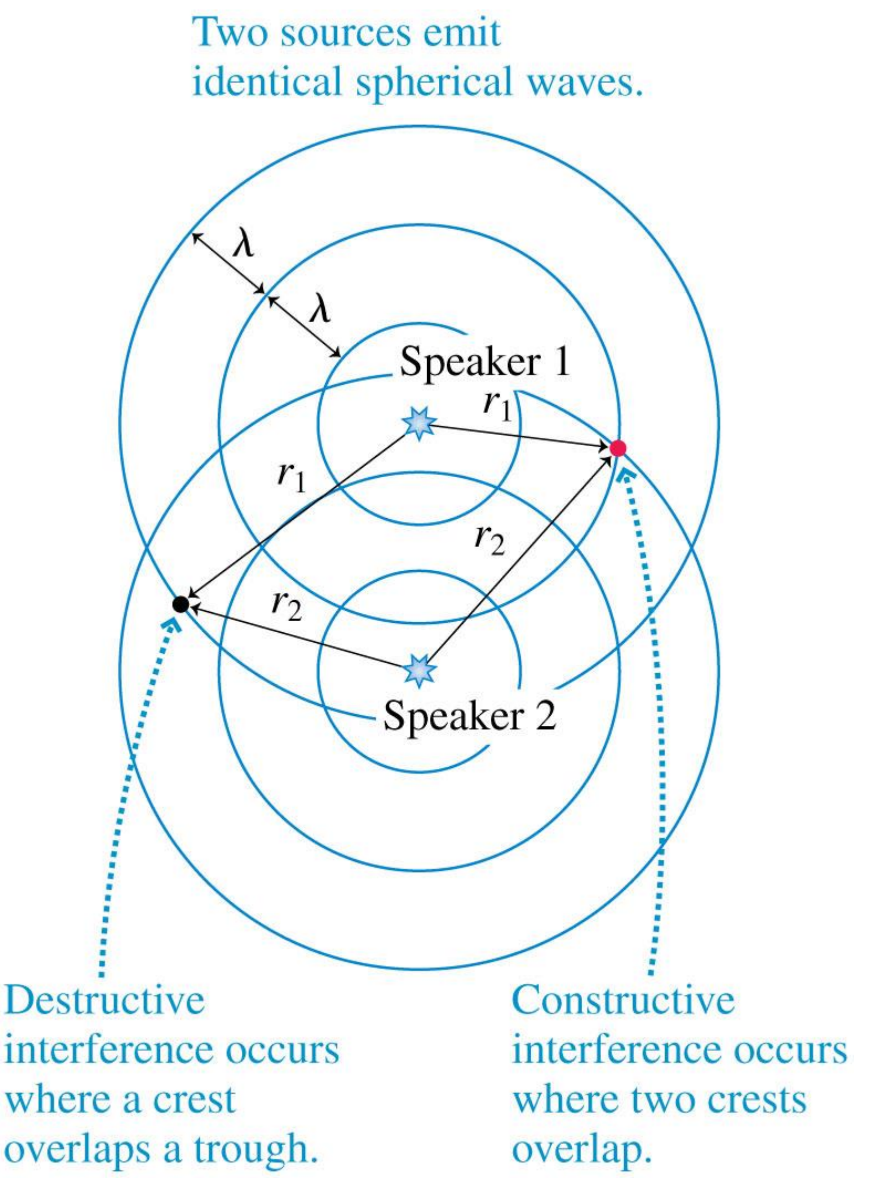


Interference of Spherical Waves

- Counting the wave fronts, we see that the red dot is three wavelengths from speaker 2 and two wavelengths from speaker 1. The path-length difference is

$$\Delta r = r_2 - r_1 = \lambda$$

- The path-length of the black dot is $\Delta r = \frac{1}{2}\lambda$.



Interference of Spherical Waves

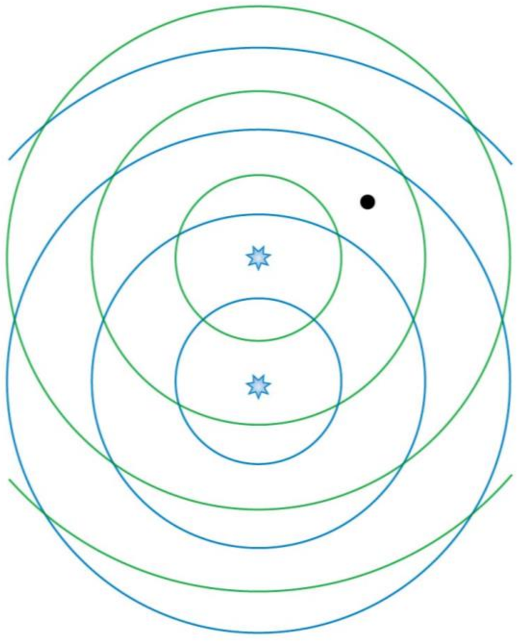
- The general rule for identifying whether constructive or destructive interference occurs is the same for spherical waves as it is for waves traveling along a line.
- Constructive interference occurs when

$$\Delta r = m\lambda \qquad m = 0, 1, 2, 3, \ldots$$

- Destructive interference occurs when

$$\Delta r = \left(m + \frac{1}{2}\right)\lambda \qquad m = 0, 1, 2, 3, \ldots$$

QuickCheck 16.16



Two in-phase sources emit sound waves of equal wavelength and intensity. At the position of the dot,

A. The interference is constructive.

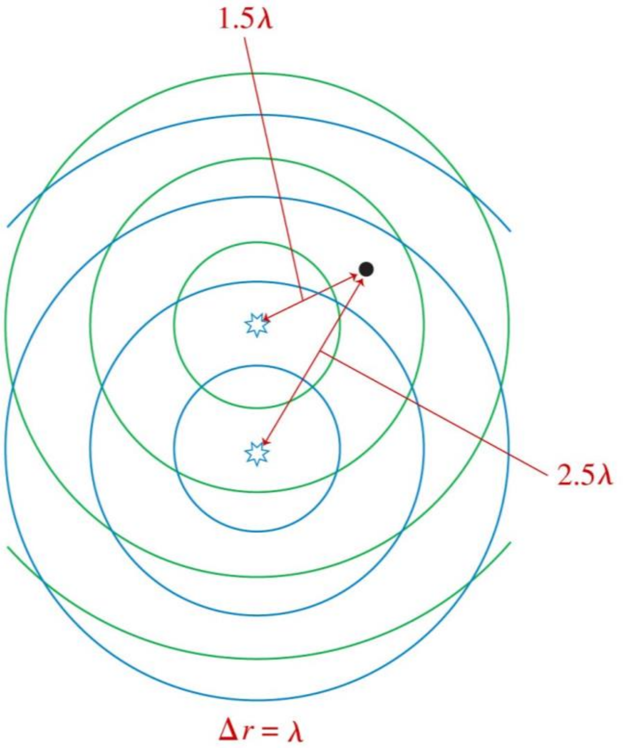
B. The interference is destructive.

C. The interference is somewhere between constructive and destructive.

D. There's not enough information to tell about the interference.

QuickCheck 16.16

Two in-phase sources emit sound waves of equal wavelength and intensity. At the position of the dot,



✔ A. The interference is constructive.

B. The interference is destructive.

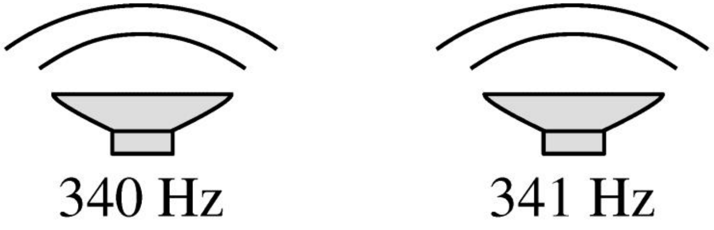
C. The interference is somewhere between constructive and destructive.

D. There’s not enough information to tell about the interference.

QuickCheck 16.17

Two speakers emit sounds of nearly equal frequency, as shown. At a point between the two speakers, the sound varies from loud to soft. How much time elapses between two successive loud moments?

A. 0.5 s
B. 1.0 s
C. 2.0 s
D. 4.0 s



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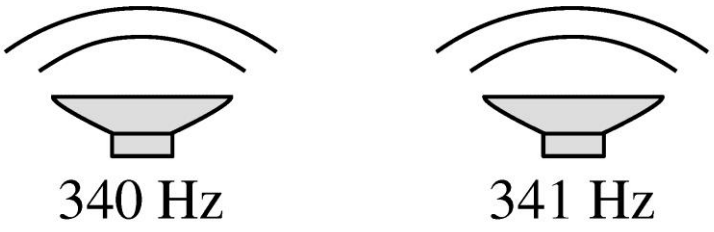


Interference of Spherical Waves

TACTICS BOX 16.1 **Identifying constructive and destructive interference**

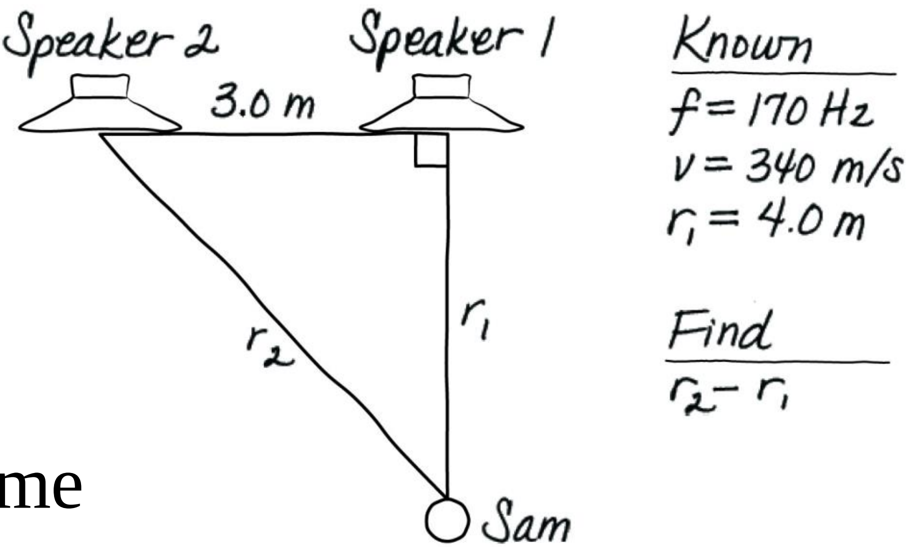
1. Identify the path length from each source to the point of interest. Compute the path-length difference $\Delta r = |r_2 - r_1|$.
2. Find the wavelength, if it is not specified.
3. If the path-length difference is a whole number of wavelengths ($\lambda, 2\lambda, 3\lambda, \ldots$), crests are aligned with crests and there is constructive interference.
4. If the path-length difference is a whole number of wavelengths plus a half wavelength $\left(1\frac{1}{2}\lambda, 2\frac{1}{2}\lambda, 3\frac{1}{2}\lambda, \ldots\right)$, crests are aligned with troughs and there is destructive interference.

Exercises 9,10

Text: p. 519

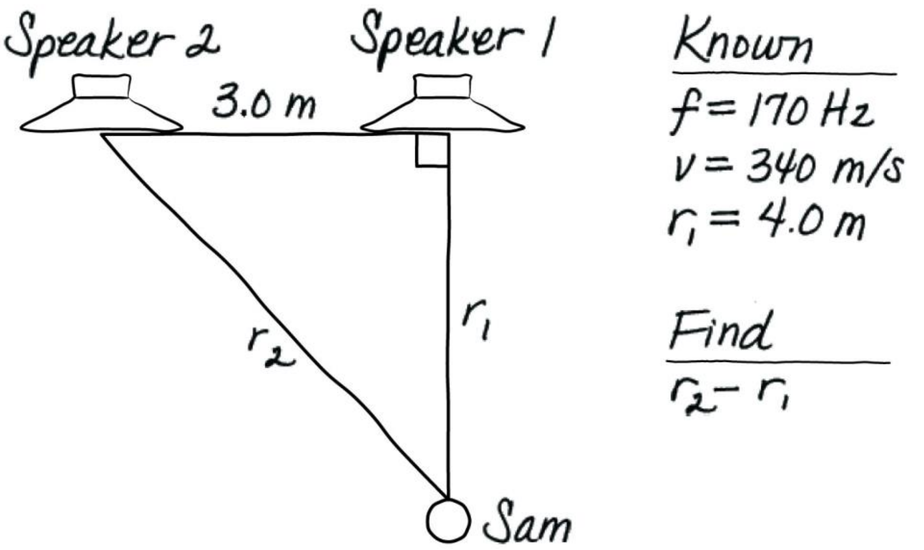
Example 16.11 Is the sound loud or quiet?

Two speakers are 3.0 m apart and play identical tones of frequency 170 Hz. Sam stands directly in front of one speaker at a distance of 4.0 m. Is this a loud spot or a quiet spot? Assume that the speed of sound in air is 340 m/s.



PREPARE FIGURE 16.31 shows a visual overview of the situation, showing the positions of and path lengths from each speaker.

Example 16.11 Is the sound loud or quiet? (cont.)



SOLVE Following the steps in Tactics Box 16.1, we first compute the path-length difference. r_1, r_2, and the distance between the speakers form a right triangle, so we can use the Pythagorean theorem to find

$$r_2 = \sqrt{(4.0\text{ m})^2 + (3.0\text{ m})^2} = 5.0\text{ m}$$

Thus the path-length difference is

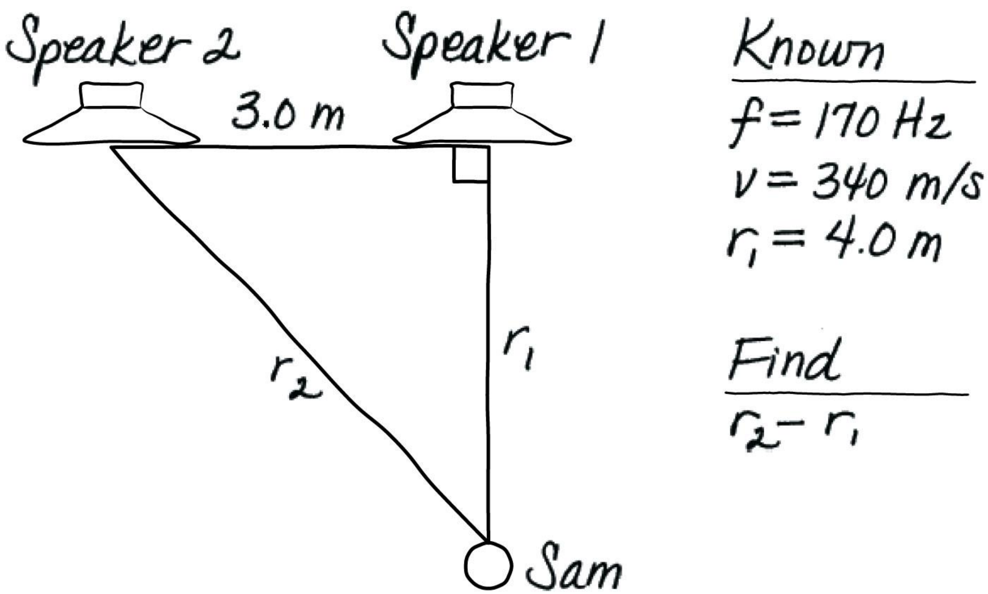
$$\Delta r = r_2 - r_1 = 1.0\text{ m}$$

Example 16.11 Is the sound loud or quiet? (cont.)

Next, we compute the wavelength:

$$\lambda = \frac{v}{f} = \frac{340 \text{ m/s}}{170 \text{ Hz}} = 2.0 \text{ m}$$

The path-length difference is $\frac{1}{2}\lambda$, so this is a point of destructive interference. Sam is at a quiet spot.

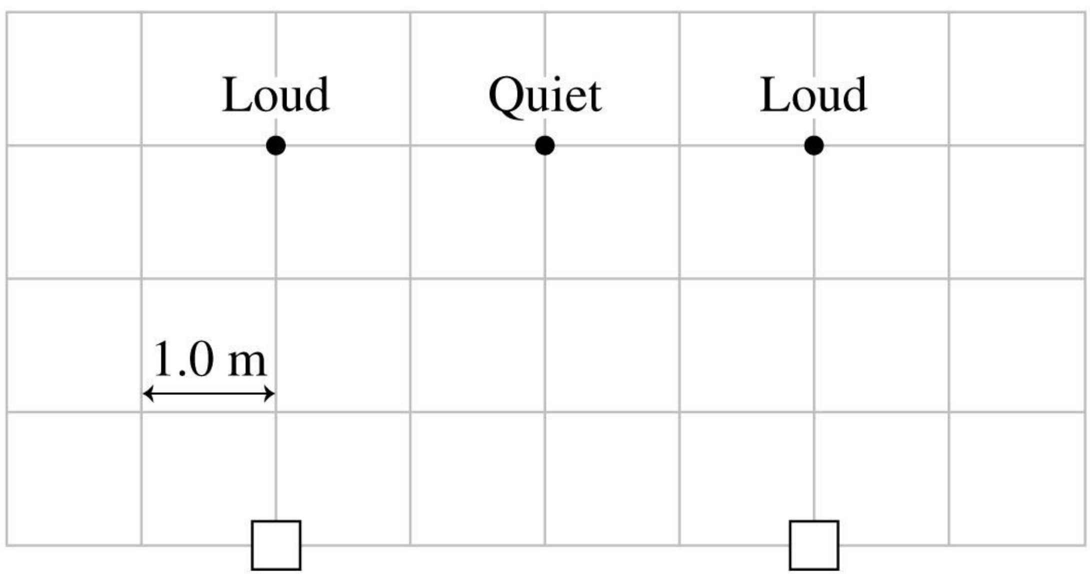


Interference of Spherical Waves

- You are regularly exposed to sound from two separate sources: stereo speakers. You don't hear a pattern of loud and soft sounds because the music is playing at a number of frequencies and the sound waves are reflected off the walls in the room.

Example Problem

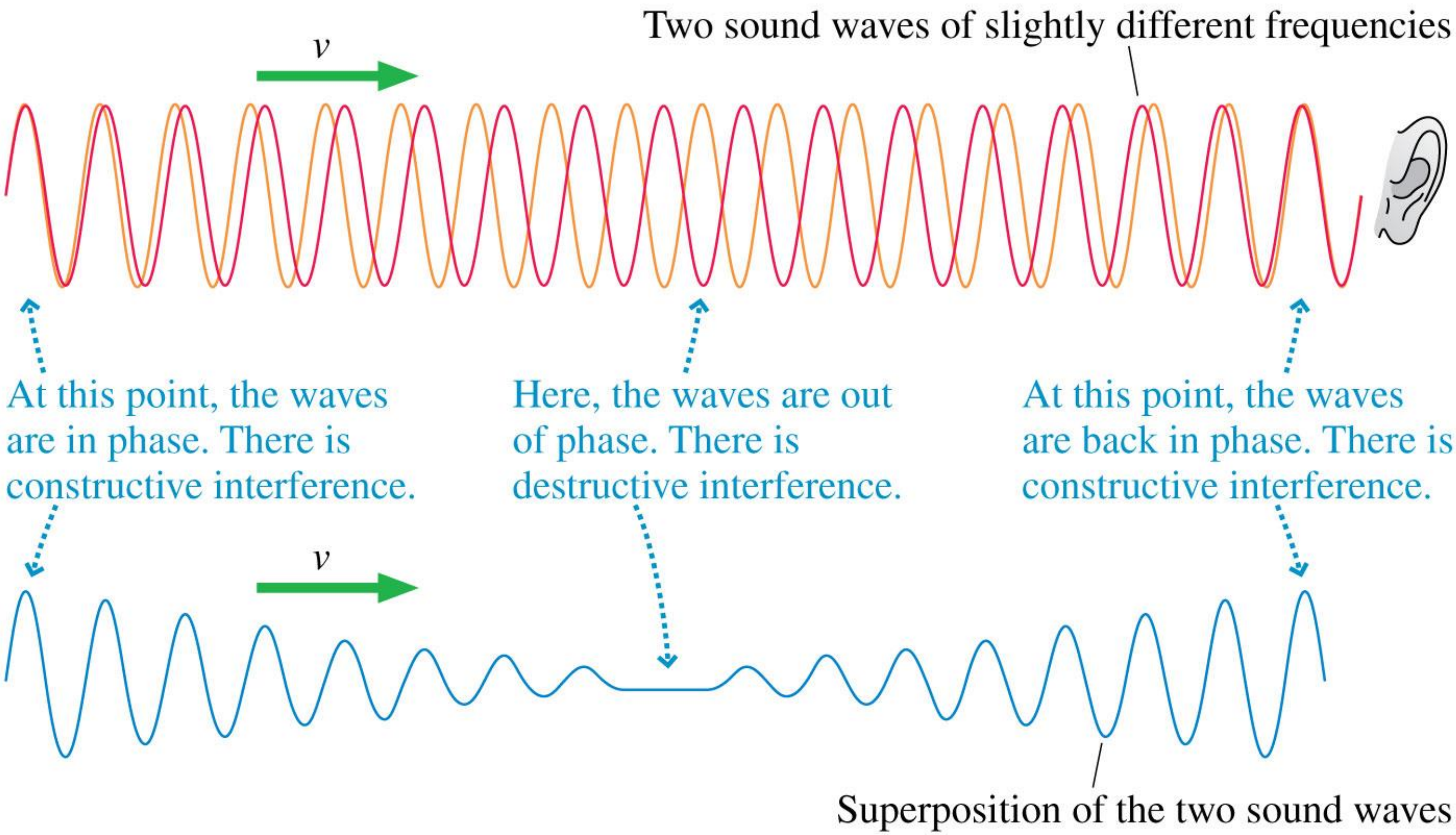
Two speakers emit identical sinusoidal waves. The speakers are placed 4.0 m apart. A listener moving along a line in front of the two speakers finds loud and quiet spots as shown in the following figure. The grid lines are spaced at 1.0 m. What is the frequency of the sound from the two speakers?



Section 16.7 Beats

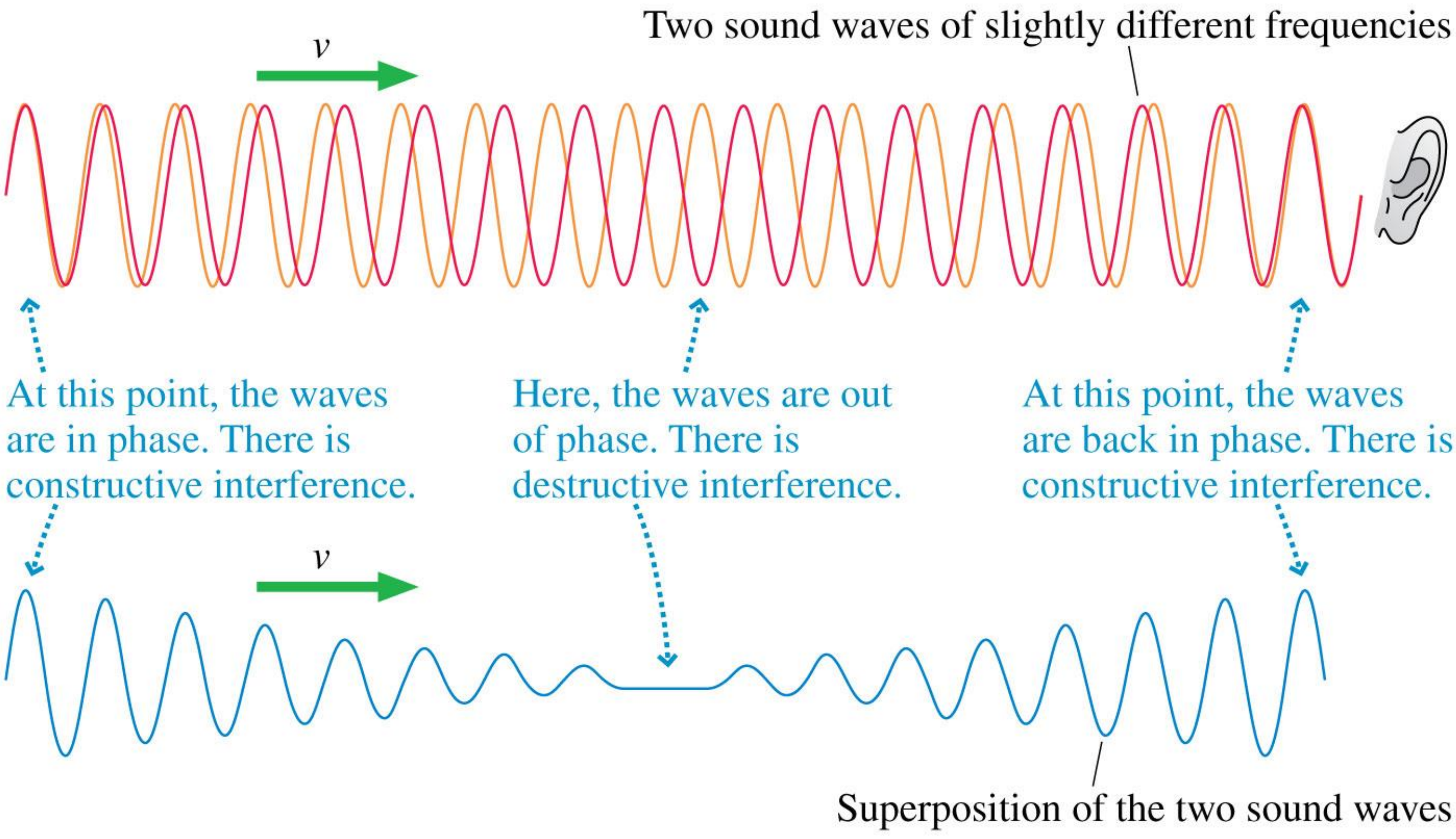
Beats

- The superposition of two waves with slightly different frequencies can create a wave whose amplitude shows a periodic variation.



Beats

- The ear hears a single tone that is *modulated*. The distinctive sound pattern is called **beats**.



Beats

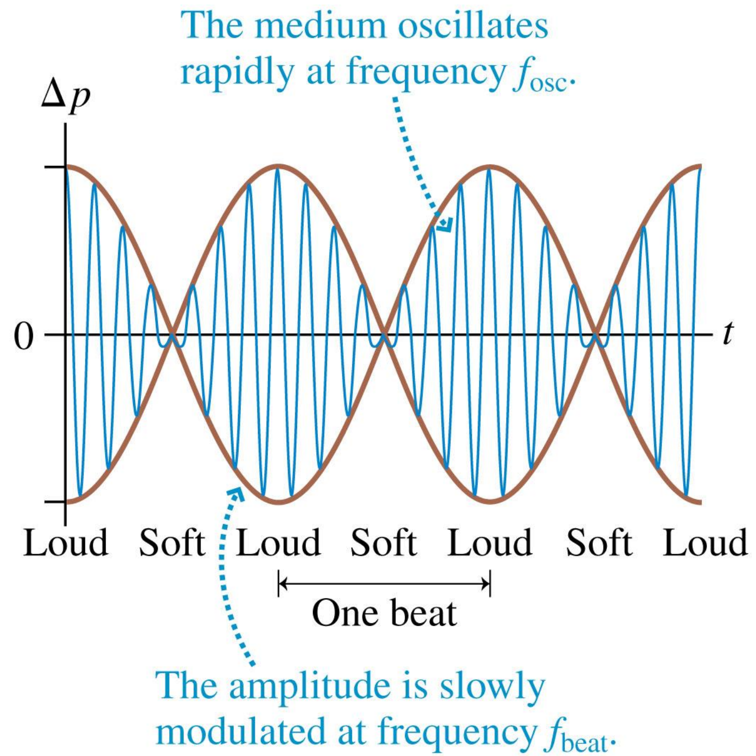
- The air oscillates against your eardrum at frequency

$$f_{osc} = \frac{1}{2}(f_1 + f_2)$$

- The *beat frequency* is the *difference* between two frequencies that differ slightly:

$$f_{beat} = |f_1 - f_2|$$

- f_{osc} determines the pitch, f_{beat} determines the frequency of the modulations.



QuickCheck 16.18

You hear 2 beats per second when two sound sources, both at rest, play simultaneously. The beats disappear if source 2 moves toward you while source 1 remains at rest. The frequency of source 1 is 500 Hz. The frequency of source 2 is

A. 496 Hz
B. 498 Hz
C. 500 Hz
D. 502 Hz
E. 504 Hz

QuickCheck 16.18

You hear 2 beats per second when two sound sources, both at rest, play simultaneously. The beats disappear if source 2 moves toward you while source 1 remains at rest. The frequency of source 1 is 500 Hz. The frequency of source 2 is

A. 496 Hz

✔ B. 498 Hz

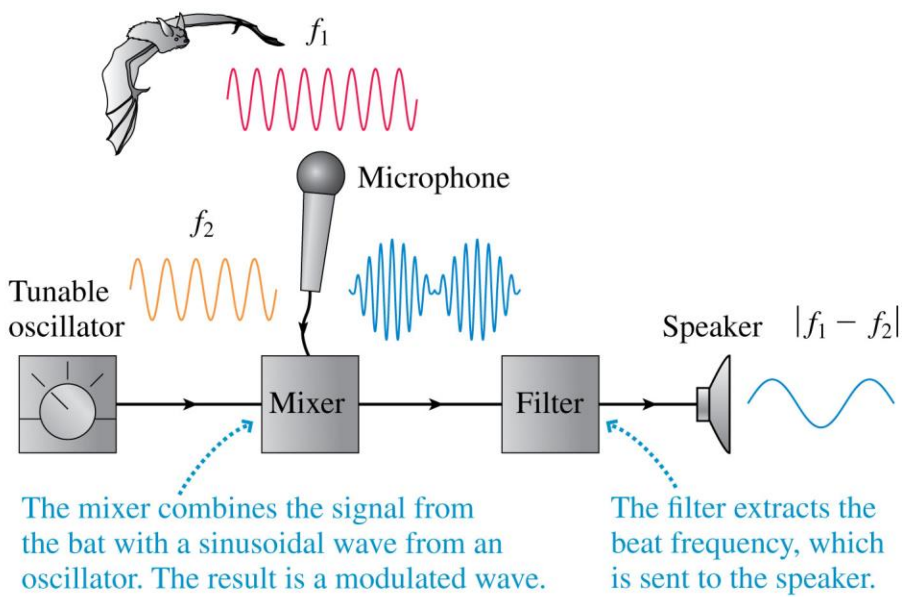
C. 500 Hz

D. 502 Hz

E. 504 Hz

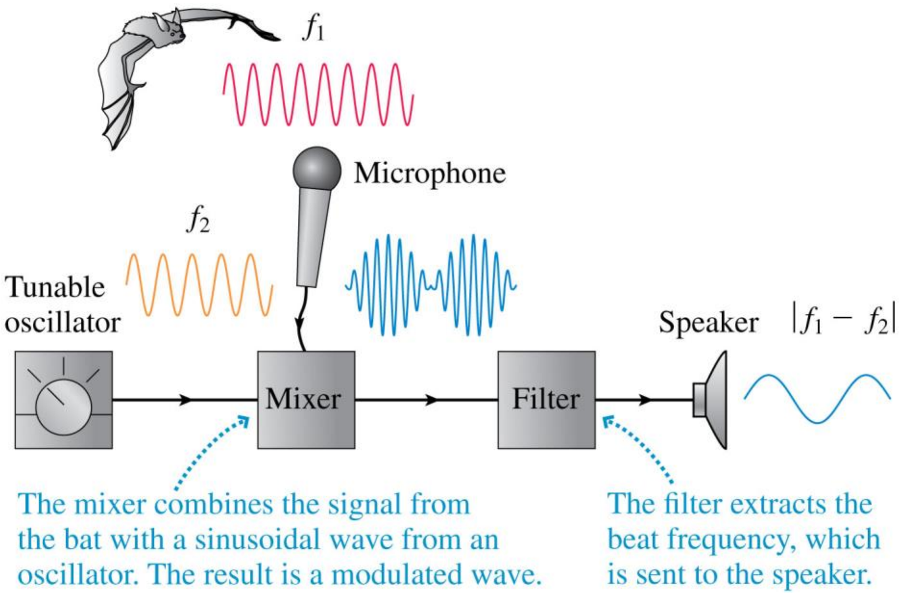
Example 16.12 Detecting bats using beats

The little brown bat is a common bat species in North America. It emits echolocation pulses at a frequency of 40 kHz, well above the range of human hearing. To allow observers to “hear” these bats, the bat detector shown in FIGURE 16.34 combines the bat’s sound wave at frequency f1 with a wave of frequency f_2 from a tunable oscillator.



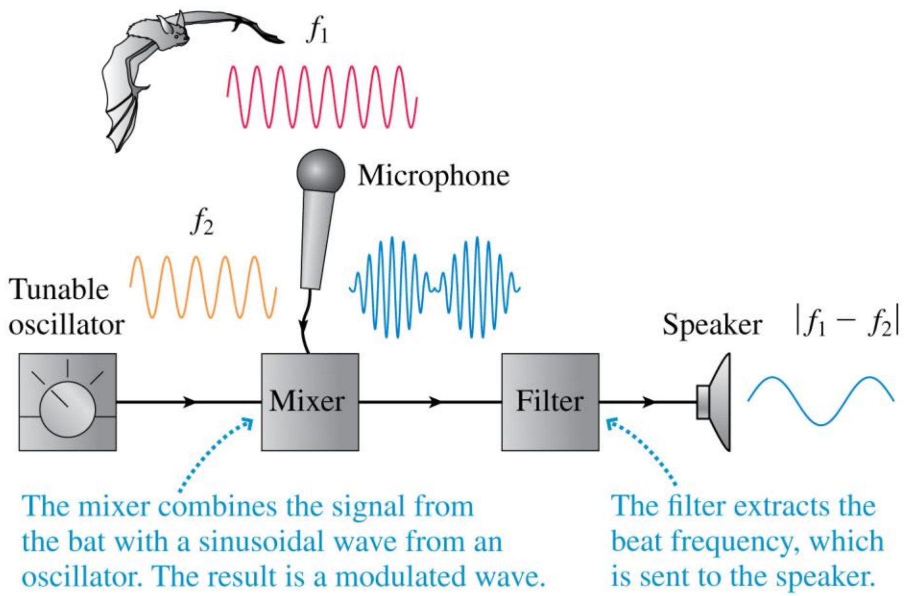
Example 16.12 Detecting bats using beats

The resulting beat frequency is isolated with a filter, then amplified and sent to a loudspeaker. To what frequency should the tunable oscillator be set to produce an audible beat frequency of 3 kHz?



Example 16.12 Detecting bats using beats

SOLVE The beat frequency is $f_{\text{beat}} = |f_1 - f_2|$, so the oscillator frequency and the bat frequency need to differ by 3 kHz. An oscillator frequency of either 37 kHz or 43 kHz will work nicely.



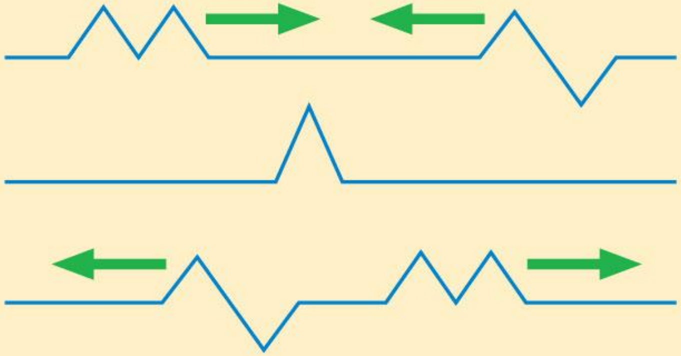
Example Problem

A typical police radar sends out microwaves at 10.5 GHz. The unit combines the wave reflected from a car with the original signal and determines the beat frequency. This beat frequency is converted into a speed. If a car is moving at 20 m/s toward the detector, what will be the measured beat frequency?

Summary: General Principles

Principle of Superposition

The displacement of a medium when more than one wave is present is the sum of the displacements due to each individual wave.



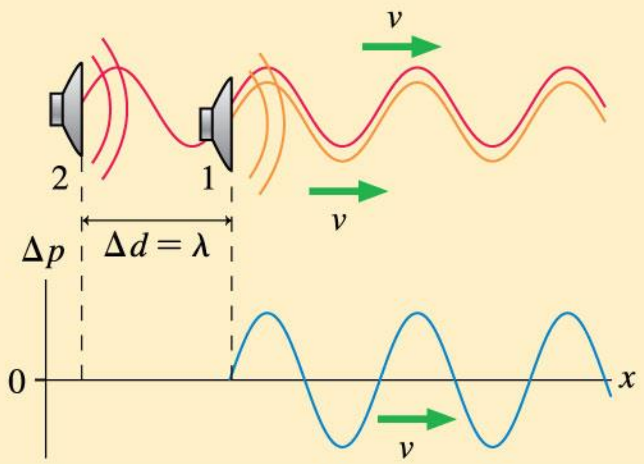
Text: p. 523

Summary: General Principles

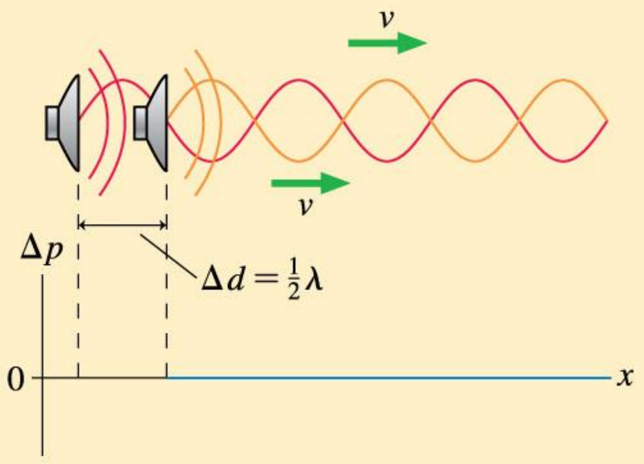
Interference

In general, the superposition of two or more waves into a single wave is called interference.

Constructive interference occurs when crests are aligned with crests and troughs with troughs. We say the waves are in phase. It occurs when the path-length difference Δd is a whole number of wavelengths.



Destructive interference occurs when crests are aligned with troughs. We say the waves are out of phase. It occurs when the path-length difference Δd is a whole number of wavelengths plus half a wavelength.



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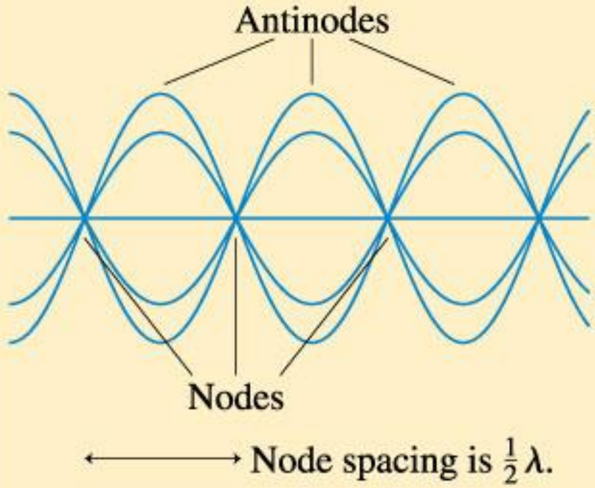
Summary: Important Concepts

Standing Waves

Two identical traveling waves moving in opposite directions create a standing wave.

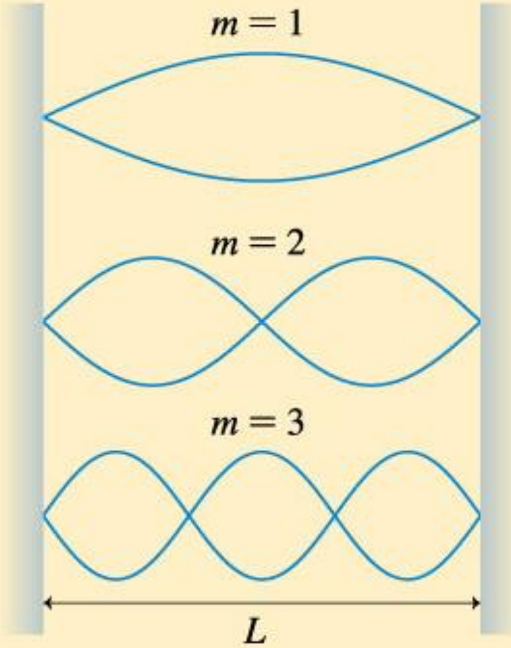


The boundary conditions determine which standing-wave frequencies and wavelengths are allowed. The allowed standing waves are **modes** of the system.

Text: p. 523

Summary: Important Concepts

A **standing wave on a string** has a node at each end. Possible modes:



$$\lambda_m = \frac{2L}{m} \qquad f_m = m\left(\frac{v}{2L}\right) = mf_1$$

$$m = 1, 2, 3, \ldots$$

Text: p. 523

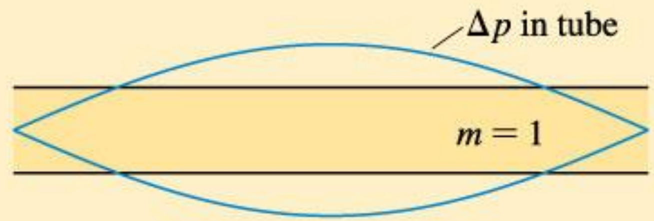
Summary: Important Concepts

A **standing sound wave in a tube** can have different boundary conditions: open-open, closed-closed, or open-closed.

Open-open

$$f_m = m\left(\frac{v}{2L}\right)$$

$m = 1, 2, 3, \ldots$



Closed-closed

$$f_m = m\left(\frac{v}{2L}\right)$$

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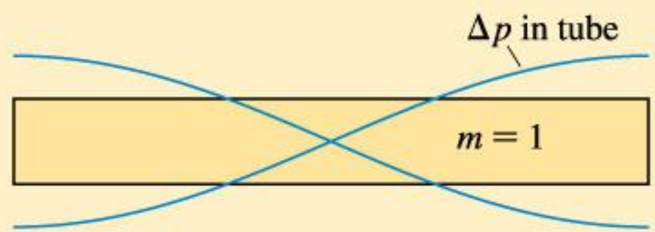

Open-closed

$$f_m = m\left(\frac{v}{4L}\right)$$

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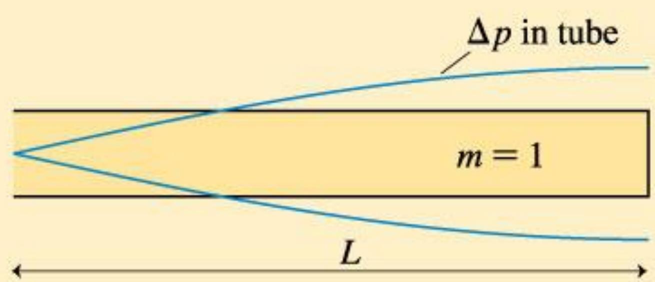
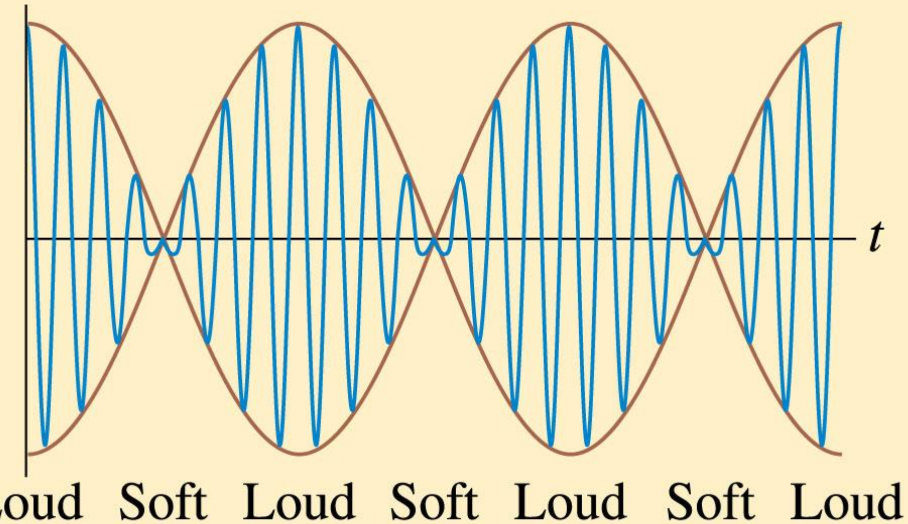


Text: p. 523

Summary: Applications

Beats (loud-soft-loud-soft modulations of intensity) are produced when two waves of slightly different frequencies are superimposed.



$$f_{beat} = |f_1 - f_2|$$

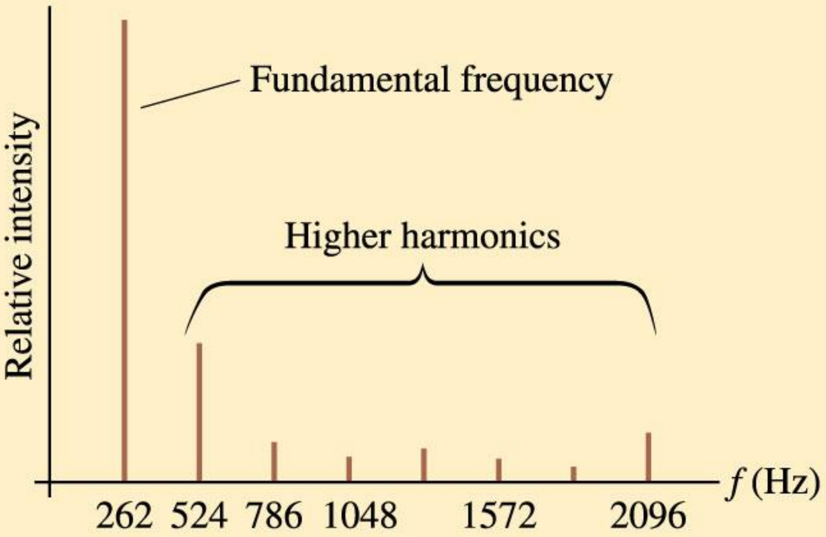
Text: p. 523

Summary: Applications

Standing waves are multiples of a **fundamental frequency,** the frequency of the lowest mode. The higher modes are the higher **harmonics.**

For sound, the fundamental frequency determines the perceived **pitch;** the higher harmonics determine the **tone quality.**

Our vocal cords create a range of harmonics. The mix of higher harmonics is changed by our vocal tract to create different vowel sounds.



Text: p. 523

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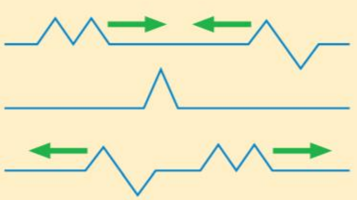

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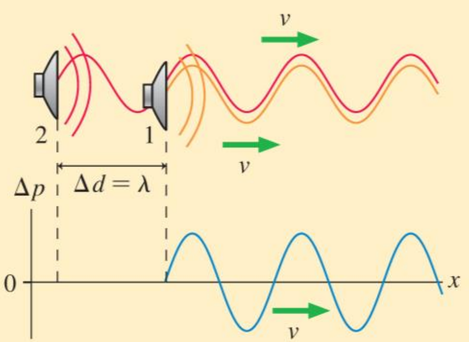

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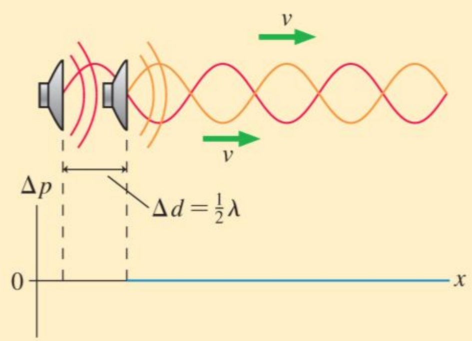

Text: p. 523

Summary

IMPORTANT CONCEPTS

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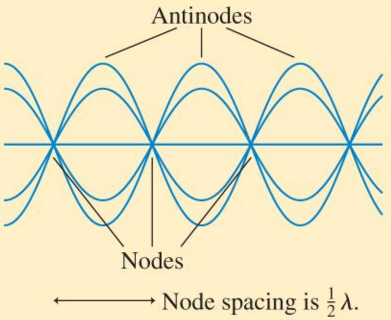

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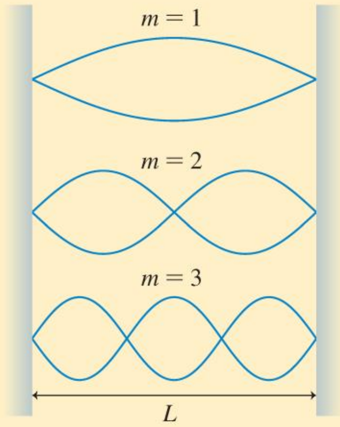

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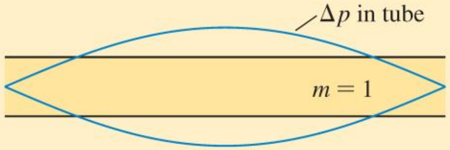

Closed-closed

$$f_m = m\left(\frac{v}{2L}\right)$$

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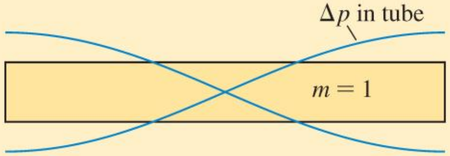

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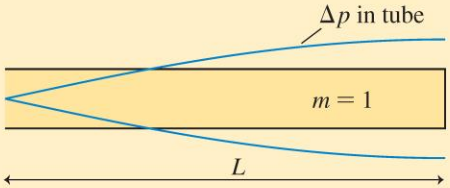

Text: p. 523

Summary

APPLICATIONS

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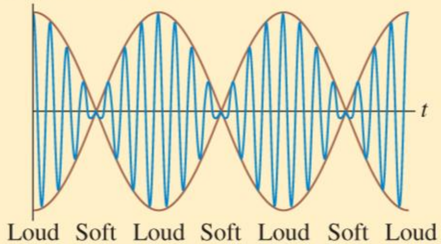

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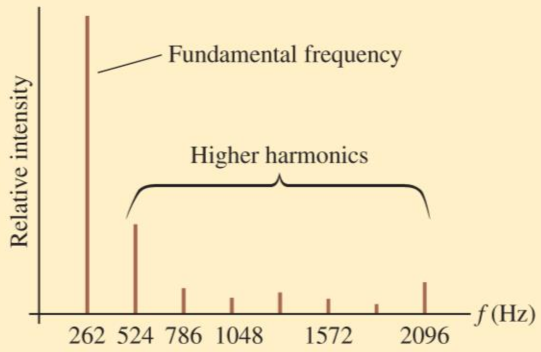

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