

Physics 2A

Chapters 15: Traveling Waves and Sound and 16: Superposition and Standing Waves

“We are what we believe we are.” – Benjamin Cardozo

“We would accomplish many more things if we did not think of them as impossible”
C. Malesherbez

“The only limit to our realization of tomorrow will be our doubts of today. Let us move forward with strong and active faith.” – Franklin Delano Roosevelt

Reading: pages 476 – 490; 496 – 500

Outline:

- ⇒ introduction to waves (PowerPoint)
 - Mechanical waves
 - EM waves and Matter Waves
 - transverse and longitudinal waves
- ⇒ graphical description of waves
 - amplitude, wavelength, period, frequency, and wave speed
- ⇒ traveling waves
 - waves on a string
 - sound waves
- ⇒ sound and light waves (PowerPoint)
- ⇒ the Doppler effect
 - moving source, moving observer, and general case
 - shock waves

Reading: pages 507 – 516; 523 - 530

Outline:

- ⇒ the principle of superposition
 - constructive and destructive interference
 - interference of waves from two sources
- ⇒ standing waves
- ⇒ standing waves on a string
- ⇒ beats (PowerPoint)

Problem Solving

Many of the problems involving waves on a string deal with the relationships $v = \lambda f = \lambda / T$, where v is the wave speed, λ is the wavelength, f is the frequency, and T is the period. Typical problems might give you the wavelength and frequency, then ask for the wave speed, or might give you the wave speed and period, then ask for the wavelength.

Sometimes the quantities are given by describing the motion. For example, a problem might tell you that the string at one point takes a certain time to go from its equilibrium position to maximum displacement. This, of course, is one-fourth the period. In other problems, you may be asked how long it takes a particle on a string to move through a total distance. You must then recognize that a particle on the string moves through a distance $4A$ (where A is the amplitude) during a time equal to the period.

Some problems deal with the wave speed. For waves on a string, the fundamental equation is $v = \sqrt{T_s / \mu}$, where T_s is the tension in the string and μ is the linear mass density. The tension may not be given directly but, if the problem asks for the wave speed, sufficient information will be given to calculate it.

Nearly all Doppler shift problems can be solved using $f = \left(\frac{1 \pm \frac{v_o}{v}}{1 \mp \frac{v_s}{v}} \right) f_0$

where v is speed of sound, v_s is the speed of the source, v_o is the speed of the observer, f_0 is the frequency of the source, and f is the frequency detected by the observer. The upper sign in the numerator refers to a situation in which the observer is moving toward the source; the lower sign refers to a situation in which the observer is moving away from the source. The upper sign in the denominator refers to a situation in which the source is moving toward the observer; the lower sign refers to a situation in which the source is moving away from the observer.

Some problems deal with the production of beats by two sound waves with nearly the same frequency. You may be given the frequency f_1 of one of the waves and the beat frequency f_{beat} , then asked for the frequency f_2 of the other wave. Since $f_{\text{beat}} = |f_1 - f_2|$, it is given by

$f_2 = f_1 \pm f_{\text{beat}}$. You require more information to determine which sign to use in this equation.

One way to give this information is to tell you what happens to the beat frequency if f_1 is increased (or decreased). If the beat frequency increases when f_1 increases, then f_1 must be greater than f_2 and $f_2 = f_1 - f_{\text{beat}}$. If the beat frequency decreases, then f_1 must be less than f_2 and $f_2 = f_1 + f_{\text{beat}}$.

Some problems deal with standing waves on a string. If you are told the distance between successive nodes or successive antinodes, double the distance to find the wavelength. If you are told the distance between a node and a neighboring antinode, multiply it by 4 to find the wavelength.

If a standing wave is generated in a string with both ends fixed, the wave pattern must have a node at each end of the string. This means the length L of the string and the wavelength λ of the traveling waves must be related by $L = n\lambda/2$, where n is an integer.

SUMMARY

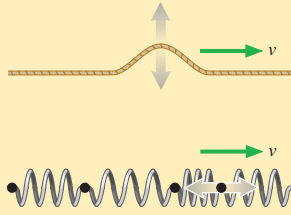
The goal of Chapter 15 has been to learn the basic properties of traveling waves.

GENERAL PRINCIPLES

The Wave Model

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

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



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

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

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

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

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

In a gas:

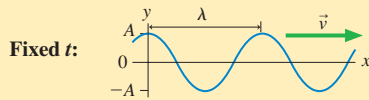
$$v_{\text{sound}} = \sqrt{\frac{\gamma RT}{M}}$$

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

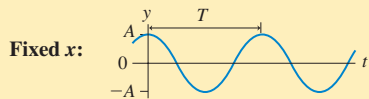
IMPORTANT CONCEPTS

Graphical representation of waves

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



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



Mathematical representation of waves

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

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

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

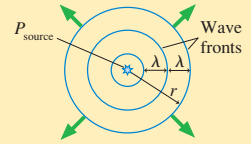
For sinusoidal and other periodic waves:

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

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

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

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



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

APPLICATIONS

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

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

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

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

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

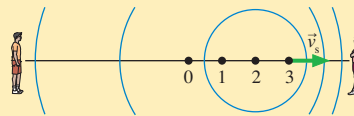
- A sound at the reference level corresponds to 0 dB.

The **Doppler effect** is a shift in frequency when there is relative motion of a wave source (frequency f_0 , wave speed v) and an observer.

Moving source, stationary observer:

Receding source:

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



Approaching source:

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

Moving observer, stationary source:

Approaching the source:

$$f_+ = \left(1 + \frac{v_o}{v}\right) f_0$$

Moving away from the source:

$$f_- = \left(1 - \frac{v_o}{v}\right) f_0$$

Reflection from a moving object:

$$\text{For } v_o \ll v, \Delta f = \pm 2f_0 \frac{v_o}{v}$$

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

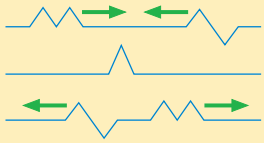
SUMMARY

The goal of Chapter 16 has been to use the idea of superposition to understand the phenomena of interference and standing waves.

GENERAL PRINCIPLES

Principle of Superposition

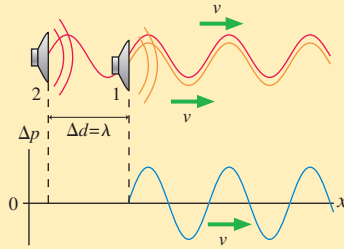
The displacement of a medium when more than one wave is present is the sum of the displacements due to each individual wave.



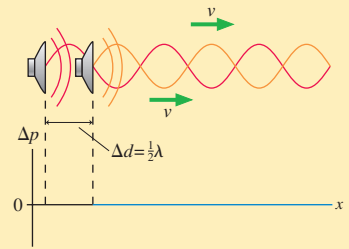
Interference

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.



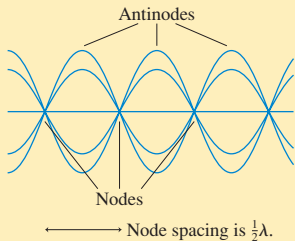
Destructive interference occurs when crests are aligned with troughs. We say the waves are out of phase. It occurs when the path-length difference Δd is a whole number of wavelengths plus half a wavelength.



IMPORTANT CONCEPTS

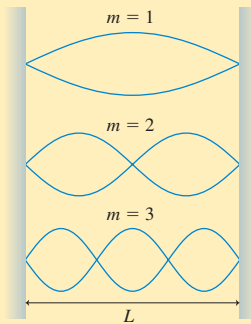
Standing Waves

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.

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



$$\lambda_m = \frac{2L}{m} \quad f_m = m \left(\frac{v}{2L} \right) = m f_1$$

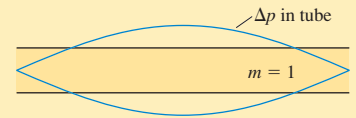
$$m = 1, 2, 3, \dots$$

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

Open-open

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

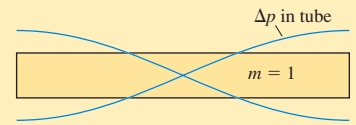
$$m = 1, 2, 3, \dots$$



Closed-closed

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

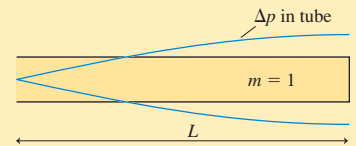
$$m = 1, 2, 3, \dots$$



Open-closed

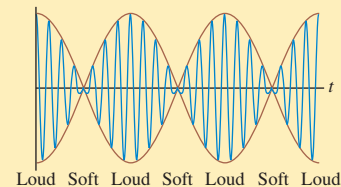
$$f_m = m \left(\frac{v}{4L} \right)$$

$$m = 1, 3, 5, \dots$$



APPLICATIONS

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

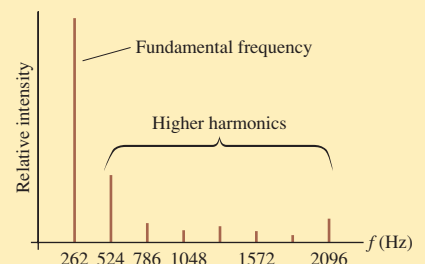


$$f_{\text{beat}} = |f_1 - f_2|$$

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.



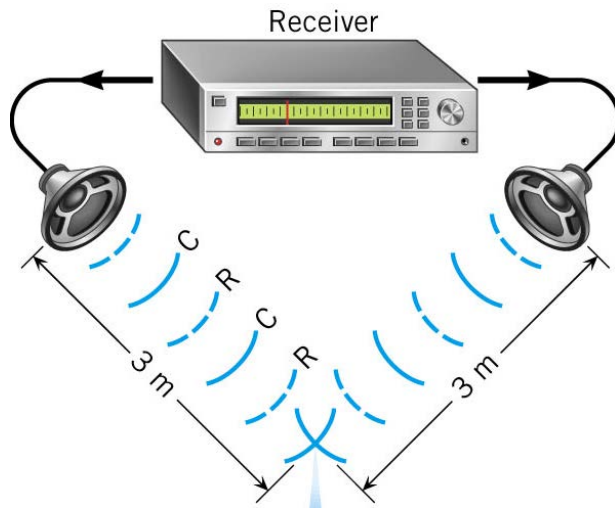
Questions and Example Problems from Chapters 15 and 16

Question 1

Two cars, one behind the other, are traveling in the same direction at the same speed. Does either driver hear the other's horn at a frequency that is different from that heard when both cars are at rest?

Question 2

Refer to the figure below. As you walk along a line that is perpendicular to the line between the speakers and passes through the overlap point, you do not observe the loudness to change from loud to faint to loud. However, as you walk along a line through the overlap point and parallel to the line between the speakers, you do observe the loudness to alternate between faint and loud. Explain why your observations are different in the two cases.



Problem 1

A person lying on an air mattress in the ocean rises and falls through one complete cycle every five seconds. The crests of the wave causing the motion are 20.0 m apart. Determine (a) the frequency and (b) the speed of the wave.

Problem 2

The linear density of the A string on a violin is 7.8×10^{-4} kg/m. A wave on the string has a frequency of 440 Hz and a wavelength of 65 cm. What is the tension in the string?

Problem 3

The middle C string on a piano is under a tension of 944 N. The period and wavelength of a wave on this string are 3.82 ms and 1.26 m, respectively. Find the linear density of the string.

Problem 4

Two submarines are underwater and approaching each other head-on. Sub A has a speed of 12 m/s and sub B has a speed of 8 m/s. Sub A sends out a 1550 Hz sonar wave that travels at a speed of 1522 m/s. (a) What is the frequency detected by sub B? (b) Part of the sonar wave is reflected from B and returns to A. What frequency does A detect for this reflected wave?

Problem 5

The security alarm on a parked car goes off and produces a frequency of 960 Hz. The speed of sound is 343 m/s. As you drive toward this parked car, pass it, and drive away, you observe the frequency to change by 95 Hz. At what speed are you driving?

Problem 6

Two loudspeakers emit sound waves along the x-axis. The sound has maximum intensity when the speakers are 20 cm apart. The sound intensity decreases as the distance between the speakers is increased, reaching zero at a separation of 30 cm. (a) What is the wavelength of the sound? (b) If the distance between the speakers continues to increase, at what separation will the sound intensity again be a maximum?

Problem 7

A pair of in-phase stereo speakers are placed next to each other, 0.60 m apart. You stand directly in front of one of the speakers, 1.0 m from the speaker. What is the lowest frequency that will produce constructive interference at your location?

Problem 8

Two out-of-tune flutes play the same note. One produces a tone that has a frequency of 262 Hz, while the other produces 266 Hz. When a tuning fork is sounded together with the 262-Hz tone, a beat frequency of 1 Hz is produced. When the same tuning fork is sounded together with the 266 Hz tone, a beat frequency of 3 Hz is produced. What is the frequency of the tuning fork?

Problem 9

A string of length 0.28 m is fixed at both ends. The string is plucked and a standing wave is set up that is vibrating at its second harmonic. The traveling waves that make up the standing waves have a speed of 140 m/s. What is the frequency of vibration?

Problem 10

On a cello, the string with the largest linear density (1.56×10^{-2} kg/m) is the C string. The string produces a fundamental frequency of 65.4 Hz and has a length of 0.800 m between the two fixed ends. Find the tension in the string.

Problem 11

The figure shows a standing wave oscillating at 100 Hz on a string. What is the wave speed?

