Chapter 16

WAVES AND SOUND

PREVIEW

A wave is a disturbance which causes a transfer of energy. Mechanical waves need a medium in which to travel, but electromagnetic waves do not. Waves can be transverse or longitudinal, depending on the direction of the vibration of the wave. Sound is a longitudinal wave. A wave is characterized by its frequency, period, wavelength, amplitude, and speed. Waves can be reflected, refracted, diffracted, and two waves in the same medium will interfere. An apparent change in frequency of a wave because of relative motion is called the Doppler effect.

QUICK REFERENCE

Important Terms

amplitude
maximum displacement from equilibrium position; the distance from the midpoint of a wave to its crest or trough.

crest of a wave
the highest point on a wave

decibel
the unit for the loudness of a sound; one-tenth of a Bel

Doppler effect
apparent change in frequency of a wave due to motion between the source of the wave and the detector of the wave

frequency
the number of vibrations of a wave per unit of time

longitudinal wave
wave in which the vibration of the medium is parallel to the direction of motion of the wave

loudness
the quality of a sound wave which is measured by its amplitude

mechanical wave
a wave which uses a material medium through which to transfer energy

period
the time for one complete cycle or revolution

periodic wave
a wave that repeats itself at regular intervals of time
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pitch
the perceived sound characteristic equivalent to frequency

rarefaction
and expansion of the medium in a longitudinal wave

transverse wave
a wave in which the vibration is perpendicular to the velocity of the wave

trough of a wave
the low point of wave motion

wavelength
the distance between successive identical parts of a wave

Equations and Symbols

\[ f = \frac{1}{T} \]
\[ v = \frac{\lambda}{T} = f\lambda \]
\[ f_o = f_r \left( \frac{1}{1 \pm \frac{v}{c}} \right) \]

where

\( f \) = frequency
\( T \) = period
\( \lambda \) = wavelength
\( v \) = speed of the wave

NOTE: Doppler equation is not required in AP Physics 1 course

DISCUSSION OF SELECTED SECTIONS

16.1 and 16.2 The Nature of Waves and Periodic Waves

A mechanical wave is a traveling disturbance in a medium which transfers energy from one place to another. A medium is the substance through which a wave moves, such as water for a water wave, or air for a sound wave. An electromagnetic wave is a vibration of an electric and magnetic field which travels through space at an extremely high speed, and does not need a medium through which to travel. Light, radio waves, and microwaves are all examples of electromagnetic waves. We will return to electromagnetic waves later.

There are two types of mechanical waves. Transverse waves vibrate in a direction which is perpendicular to the direction of motion of the wave. For example if you hold the end of a spring and vibrate your hand up and down, you create a transverse wave in the spring.
If you gather the spring up into a bunch and let it go, you create a *longitudinal wave*, in which the spring vibrates in a direction which is parallel to the direction of motion of the wave.

Sound is a common example of a longitudinal wave, since the air through which a sound wave moves is repeatedly compressed and expanded.

Since an object vibrating with simple harmonic motion can create a wave in a medium, it is not surprising that many of the terms we discussed in chapter 10 can also be applied to waves. A wave has a *period*, the time it takes for a wave to vibrate once, a *frequency*, the number of waves that pass a given point per second, and an *amplitude*, the maximum displacement of a wave, or its height. The length of one complete vibration of a wave is called the *wavelength*, and is denoted by the Greek letter lambda, \( \lambda \). The figure below illustrates these quantities.

The *crest* is the highest point on the wave and the *trough* is the lowest point on the wave. The wavelength can be measured from one crest to the next crest, or from one trough to the next trough.

The speed of a wave can be found by the equation \( v = f \lambda \), where \( v \) is the speed, \( f \) is the frequency, and \( \lambda \) is the wavelength. Since frequency is the reciprocal of period, we can also write this equation as \( v = \frac{\lambda}{T} \). The speed of all types of waves can be found using this equation.

**16.3 The Speed of a Wave on a String**

The speed of a wave passing through a tight string with tension \( F_T \) is proportional to the square root of the tension in the string. As the tension of the string is increased, the speed of the wave increases. However, when the tension in the string changes, the frequency of the wave is not affected if it is produced by an outside source such as a tuning fork or vibrating machine. Therefore when the tension and thus the speed increases, the wavelength must also increase by the equation \( v = f \lambda \).
Example 1

A string is attached to a tuning fork of frequency 256 Hz, and a wave travels along the string with a speed of 200 m/s.
(a) Determine the wavelength of the wave in the string.
(b) If the tension in the same string is increased to four times its initial value, find
   i. the speed of the wave
   ii. the wavelength of the wave.

Solution
(a) \[ \lambda = \frac{v}{f} = \frac{200 \text{ m/s}}{250 \text{ Hz}} = 0.8 \text{ m} \]
(b) i. Since \( v \propto \sqrt{F_t} \), \( 2v \propto \sqrt{4F_t} \)
    So four times the tension produces twice the speed, or 400 m/s.
   ii. \[ \lambda = \frac{v}{f} = \frac{400 \text{ m/s}}{250 \text{ Hz}} = 1.6 \text{ m} \]
We will say more about speed and tension in a string in chapter 17.

16.5 and 16.6 The Nature of Sound and The Speed of Sound

Sound is a mechanical longitudinal wave, and therefore must have a medium through which to travel. Sound generally travels at about 340 m/s in air, but travels at considerably higher speeds in more dense media such as water or steel. The characteristics of sound which are produced and how we detect and perceive these characteristics are summarized in the table below.

<table>
<thead>
<tr>
<th>Sound produced as:</th>
<th>Sound detected as:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Pitch</td>
</tr>
<tr>
<td>Amplitude</td>
<td>Loudness or volume</td>
</tr>
<tr>
<td>Harmonics</td>
<td>Quality or tone</td>
</tr>
</tbody>
</table>

The third characteristic, harmonics, is the combination of several simultaneous frequencies that give a sound its special tone. For example, we can tell the difference between a trumpet and a clarinet because our ear detects the special harmonics, even if they are playing the same pitch at the same loudness. For the same reason, we can tell the difference between two voices.
16.9 The Doppler Effect

When a sound source is moving toward you, you hear a slightly higher pitch than if the sound source is at rest relative to you. By the same token, when a sound source is moving away from you, you hear a slightly lower pitch. This phenomenon is called the Doppler effect. For example, if a train is traveling toward you while blowing its horn at a certain pitch, the waves will appear to be arriving at your ear more frequently, increasing the pitch you perceive.

If the train blows its whistle while accelerating away from you, the waves will appear to be arriving at your ear less frequently, decreasing the pitch you perceive. Remember, the Doppler effect describes the apparent change in frequency (pitch), not amplitude (loudness). Also, it doesn’t matter whether the sound source is moving or the observer is moving, only that they have relative motion between the two of them.

Of course, the frequency of the whistle is not actually changing, but you perceive it to change due to the relative motion between you and the train. The Doppler effect also occurs when a light source is moving toward or away from us. The light spectrum of a star, for example, is shifted toward the red (low frequency) end if the star is moving away from us, and toward the blue (high frequency) end of the spectrum if it were to move toward us.

The equations for calculating the apparent shift in frequency due to relative motion between the source and observer is not needed on the AP Physics 1 exam, but the concepts involved in the Doppler effect are included in the questions on the exam.
CHAPTER 16 REVIEW QUESTIONS
For each of the multiple choice questions below, choose the best answer.

The following diagram of a wave relates to questions 1 – 3.

1. The wavelength of the wave is
(A) 0.5 m
(B) 1.0 m
(C) 2.0 m
(D) 4.0 m
(E) 6.0 m

2. The amplitude of the wave is
(A) 0.5 m
(B) 1.0 m
(C) 2.0 m
(D) 4.0 m
(E) 6.0 m

3. The frequency of the wave is
(A) 2.0 Hz
(B) 3.0 Hz
(C) 1.5 Hz
(D) 0.5 Hz
(E) 1.0 Hz

4. A girl on the beach watching water waves sees 4 waves pass by in 2 seconds, each with a wavelength of 0.5 m. The speed of the waves is
(A) 0.25 m/s
(B) 0.5 m/s
(C) 1.0 m/s
(D) 2.0 m/s
(E) 4.0 m/s

5. As a wave passes from a spring to another spring with a greater tension,
(A) the speed of the wave decreases
(B) the frequency of the wave increases.
(C) the frequency of the wave decreases.
(D) the amplitude of the wave increases
(E) the speed of the wave increases.

Questions 6 – 7:
A wave source of constant frequency sends a wave through a tight string of uniform density with a speed \( v_o \) and wavelength \( \lambda_o \). The tension is then relaxed to half its initial tension.

6. The speed of the wave is now
(A) \( v_o \)
(B) \( 2v_o \)
(C) \( 4v_o \)
(D) \( \sqrt{2}v_o \)
(E) \( \frac{1}{\sqrt{2}}v_o \)

7. The wavelength of the wave is now
(A) \( \lambda_o \)
(B) \( 2\lambda_o \)
(C) \( 4\lambda_o \)
(D) \( \sqrt{2}\lambda_o \)
(E) \( \frac{1}{\sqrt{2}}\lambda_o \)

8. The Doppler effect produces apparent changes in
(A) loudness
(B) frequency
(C) amplitude
(D) velocity
(E) acceleration
9. A car’s horn emits a constant frequency as it accelerates away from a stationary listener. Which of the following quantities actually changes for the listener?
   I. frequency of the sound
   II. pitch of the sound
   III. amplitude of the sound
   IV. loudness of the sound

(A) I only
(B) I and II only
(C) III and IV only
(D) II and IV only
(E) I, II, III, and IV

**Free Response Question**

*Directions: Show all work in working the following question. The question is worth 10 points, and the suggested time for answering the question is about 10 minutes. The parts within a question may not have equal weight.*

1. (10 points)

   A tuning fork of frequency 300 Hz is activated and sends a sound wave toward a classroom wall, and the echo is detected at the location of the tuning fork 0.06 s later.

   (a) Determine the wavelength of the sound wave.
   (b) Determine the distance from the tuning fork to the wall.
The same tuning fork is mounted vertically on a ring stand as shown below. A string of length 2 m is attached to the tuning fork and a mass \( m \) is hung on the end of the string. The tuning fork is activated, and a wave passes through the string (the size of the amplitude of the wave is exaggerated for clarity). Assume that the tension in the string does not affect the frequency of vibration of the tuning fork.

(c) If the speed of the wave is 600 m/s when the mass \( m \) is hung on the end of the string, how many full wavelengths will occupy the string?

(d) If the mass \( m \) is replaced with a mass of \( 4m \), how many wavelengths (or what fraction of a wavelength) will occupy the string?

ANSWERS AND EXPLANATIONS TO CHAPTER 16 REVIEW QUESTIONS

**Multiple Choice**

1. C
   In the diagram of the wave shown, three wavelengths occupy a space of 6 m. Thus, one wavelength is 2.0 m.

2. B
   The amplitude is the distance from the base line of the wave to the crest, or half the distance from the trough to the crest, 1.0 m.

3. A
   It takes a time of 1.5 s for three waves to pass by, so it takes 0.5 s for one wave to pass by (the period). The frequency of the wave is the inverse of the period, or 2.0 Hz.

4. C
   Four waves in 2 s implies 2 waves in 1 s, or a frequency of 2 Hz. Then the speed of the wave is \( v = f\lambda = (2\text{ Hz})(0.5m) = 1.0 m/s \)
5. E
Higher tension (tightness) in the spring will allow the wave to move with a higher speed.

6. E
\[ v \propto \sqrt{F_T} \text{, so halving the tension force } F_T \text{ gives a speed of } \frac{v_o}{\sqrt{2}}. \]

7. E
Since wavelength and speed are proportional, the new tension will result in a wavelength of \( \frac{\lambda_o}{\sqrt{2}} \).

8. B
The Doppler effect describes apparent changes in frequency, although the loudness of a wave may also be changing.

9. D
The frequency and amplitude of the wave do not actually change, but the perception of these (pitch and loudness) will change according to the listener.

**Free Response Question Solution**

(a) 2 points
At room temperature, the speed of a sound wave \( v = 343 \text{ m/s} \). Thus,
\[
\lambda = \frac{v}{f} = \frac{343 \text{ m/s}}{300 \text{ Hz}} = 1.1 \text{ m}
\]

(b) 3 points
If the time for the sound wave to make a round trip is 0.06 s, then the distance from the tuning fork to the wall corresponds to 0.03 s.
\[
d = vt = (343 \text{ m/s})(0.03 \text{ s}) = 10.3 \text{ m}
\]

(c) 3 points
The wavelength of the wave in the string is
\[
\lambda = \frac{v}{f} = \frac{600 \text{ m/s}}{300 \text{ Hz}} = 2.0 \text{ m}
\]
Since the string is 2.0 m long, one wavelength will just fit in the length of the string.

(d) 2 points
Four times the mass hung on the end of the string will produce 4 times the tension in the string, doubling the speed and wavelength in the string. The new wavelength will be 4 m long, so only half the wavelength will fit into the string with 4 m hanging on it.