TOPIC

5 Waves

Vocabulary

absolute index of refraction	incident ray	reflected ray
amplitude	interference	refracted ray
angle of incidence	law of reflection	reflection
angle of reflection	longitudinal wave	refraction
angle of refraction	medium	resonance
antinode	natural frequency	Snell's law
constructive interference	node	speed
destructive interference	normal	standing wave
diffraction	period	superposition
Doppler effect	periodic wave	transverse wave
electromagnetic spectrum	phase	vacuum
electromagnetic wave	principle of superposition	wave
frequency	pulse	wave front
hertz	ray	wavelength

Introduction to Waves

A **wave** is a vibratory disturbance that propagates through a **medium** (body of matter) or field. Every wave has, as its source, a particle vibrating or oscillating about an average position. For example, a sound wave can be produced by a vibrating tuning fork and a radio wave can be generated by accelerating electrons in a transmitter.

Waves and Energy Transfer

Waves transfer energy from one place to another by repeated small vibrations of particles of a medium or by repeated small changes in the strength of a field. The source provides the initial vibrations, but there is no actual transfer of mass from the source. Only energy is transferred from the source. The propagation of mechanical waves, such as sound and water waves, requires a material medium. Electromagnetic waves, such as visible light and radio waves, can travel through a **vacuum,** which is a region of empty space.

Pulses and Periodic Waves

A wave may be classified as either a pulse or a periodic wave. A **pulse** is a single short disturbance that moves from one position to another in a field or medium. For example, a pulse produced on a stretched rope moves horizontally along the rope, as shown in Figure 5-1.

The speed of a pulse depends upon the type and properties of the medium. Pulse speed is constant if the medium is a uniform material with the same properties throughout. If the pulse reaches an interface or boundary of a new medium, part of the pulse is transmitted through the new medium, part is absorbed, and part is reflected back to the source. **Reflection** is the rebounding of a pulse or wave as it strikes a barrier.

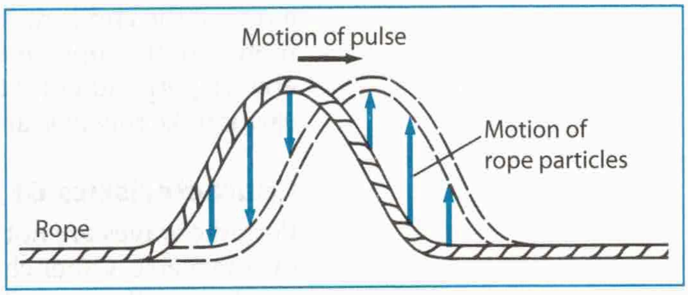


Figure 5-1. A pulse on a rope: A pulse is a single vertical disturbance transmitted horizontally at a definite speed.

Ceiling tiles, draperies, and carpeting help minimize noise levels in a room. These irregularly shaped surfaces absorb some of the energy of sound waves that strike them. The reflected sound waves have less energy than the original waves.

If the right end of the rope in Figure 5-1 was attached to a fixed unyielding body, such as a wall, the pulse would be completely reflected. None of the wave energy would be absorbed or transmitted. The reflected pulse, however, would be inverted, as shown in Figure 5-2.

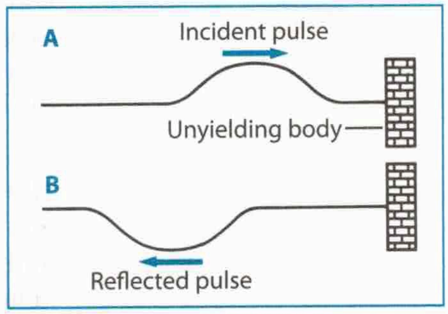


Figure 5-2. A pulse is reflected and inverted: **(A)** A wave pulse travels to the right along a rope attached to a brick wall. **(B)** When the pulse reaches the wall, it is reflected back toward the left in an inverted position.

This inversion can be explained by Newton's third law. When the pulse in Figure 5-2 arrives at the wall, the pulse exerts an upward force on the wall. Because the wall does not move, it exerts a force of equal magnitude on the rope in the opposite direction, which is downward. This reaction force inverts the pulse just before it is reflected back through the original medium.

If the initial disturbance that causes a pulse is repeated regularly, without interruption or change, a series of regular, evenly timed disturbances in the medium is produced. This series of regularly repeated disturbances of a field or medium is called a **periodic wave.**

Types of Wave Motion

A wave in which the motion of the vibratory disturbance is parallel to the direction of propagation or travel of the wave through the medium is called a **longitudinal wave.** Sound waves, compression waves in a spring, and earthquake P-waves are examples of longitudinal waves. A longitudinal wave is represented in Figure 5-3. Notice that the arrows indicating direction of motion of the wave and direction of particle motion are parallel to each other.

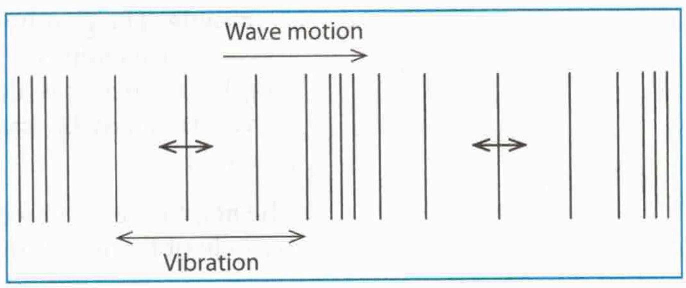


Figure 5-3. Longitudinal wave

Another type of wave, a **transverse wave,** is one in which the motion of the vibratory disturbance is perpendicular, or at right angles to the direction of travel of the wave. An easy way to remember this is that the symbol for perpendicular lines, ⊥, is the first letter in the word transverse, T, inverted. The transverse wave shown in Figure 5-4 is produced in

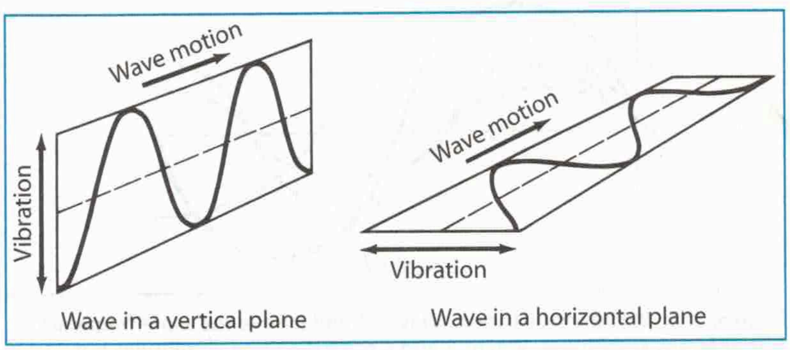


Figure 5-4. Transverse waves: These transverse waves have the same direction of travel but are in different planes.

a rope if the end is moved up and down or side to side. The direction of motion of the rope determines the plane of the wave's motion, which is always perpendicular to the rope's vibration. Electromagnetic waves and earthquake S-waves are examples of other transverse waves.

Characteristics of Periodic Waves

Periodic waves are not described solely by their type, such as longitudinal or transverse. Other characteristics distinguish an individual wave from another similar wave. Some of these characteristics are described below.

Frequency The complete series of changes at one point in a medium as a wave passes is called a cycle. The number of cycles, or complete vibrations, experienced at each point per unit time is called the **frequency,** f, of the wave. A frequency of 1 cycle per second is called 1 **hertz.** The hertz, Hz, is the derived SI unit of frequency. In fundamental units, 1 Hz equals 1/s, or s^{-1}, which can be read as *per second*.

The frequency of a sound wave determines its pitch, whereas the frequency of a light wave determines its color. The human ear can detect frequencies in the range of 20 to 20,000 hertz, and the human eye perceives frequencies of approximately 3.84×10^{14} to 7.69×10^{14} hertz.

Period The time required for one complete vibration to pass a given point in the medium is called the **period** of the wave and is denoted by T. Note that this is a capital letter. The period of a periodic wave is inversely proportional to frequency and is given by this formula.

R

$$T = \frac{1}{f}$$

The period T is in seconds and the frequency f is in hertz or per second. The second, s, is the SI unit for period.

Amplitude The graph of the displacement of a wave versus time is called the wave's waveform. The discussion that follows treats only the relatively simple sine wave, which has the shape of a sine curve. All complex waveforms may be analyzed in terms of the interactions of many different sine waves.

The **amplitude** of a mechanical wave is the maximum displacement of a particle of the medium from its rest or equilibrium position. The amplitude of a wave in a field is the maximum change in the field strength from its normal value.

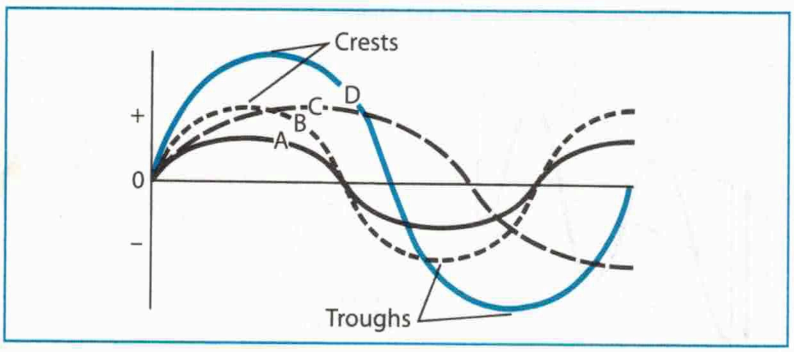


Figure 5-5. Wave amplitudes: Waves A and B have the same frequency but different amplitudes. Waves B and C have the same amplitudes but different frequencies. Wave D has the greatest amplitude of the four waves.

In a transverse wave, the position of maximum displacement of a particle of the medium in the positive direction (for example, upward) is called a crest. The position of maximum displacement in the negative direction (downward) is called a trough. The greater the amplitude of the wave, the higher the crests and the lower the troughs. Transverse waves of various amplitudes are shown in Figure 5-5.

In a longitudinal wave, the periodic displacements of the particles of the medium produce regions of maximum compression called condensations that alternate with regions of maximum expansion called rarefactions. The greater the amplitude of the wave, the greater the compression of the particles in the condensations and the greater the separation of the particles in the rarefactions. Figure 5-6 shows condensations and rarefactions in a longitudinal wave.

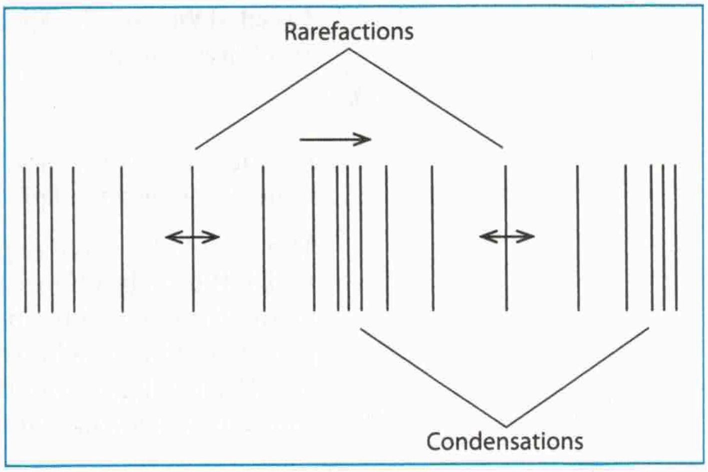


Figure 5-6. Condensations and rarefactions of a longitudinal wave

The amplitude of a wave is related to the amount of energy it transmits. The greater the amplitude of a light wave, the greater the light intensity or brightness. The greater the amplitude of a sound wave, the louder the sound. The amplitude of a sound wave is not related to its frequency or pitch.

Phase Points on successive wave cycles of a periodic wave that are displaced from their rest position by the same amount in the same direction and are moving in the same direction (away from or towards their rest positions) are said to have the same **phase,** or to be "in phase" with each other. For example, in a transverse wave, all the wave crests are in phase. In Figure 5-7 points A and E are in phase, B and F are in phase, and C and G are in phase.

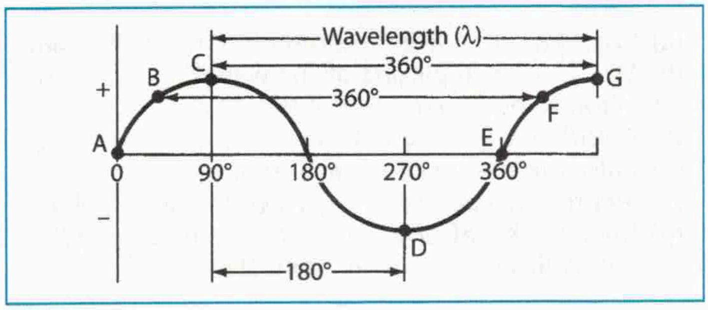


Figure 5-7. Phase relations in a wave

A simple way to determine if two points on a wave are in phase is to picture cutting out a template of the waveform between the points. If the template can be lifted, placed adjacent to one of the points, and traced without interruption to make the original sine waveform, the points are in phase.

Because there are 360° in a complete circle, one complete cycle of a periodic wave is often represented as equal to 360°. One half-cycle is then 180°. Points on a wave that are 180° apart are said to be "out of phase." In Figure 5-7, points C and D are out of phase.

Wavelength The distance between any two successive points in phase with one another in a periodic wave is called the **wavelength** of the wave. In Figure 5-7, the distance between points C and G, B and F, and A and E is one wavelength. Wavelength is represented by the symbol λ and is measured in units of length, such as meters and nanometers. If two points on a transverse wave are 180° out of phase, the distance between them is one-half wavelength or $\frac{1}{2}\lambda$.

The wavelength of a transverse wave is often measured between successive crests or troughs. The wavelength of a longitudinal wave is measured between successive condensations or rarefactions.

Speed of Waves The **speed** of a wave is equal to the product of its frequency and wavelength.

$$v = f\lambda$$

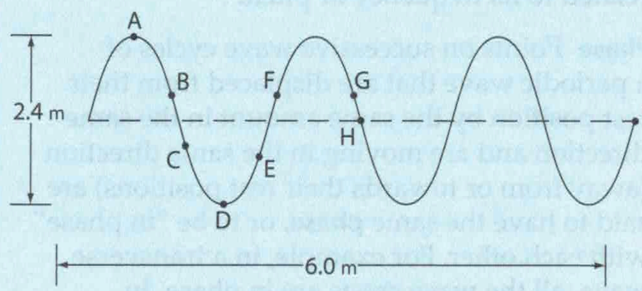
Frequency, f, is in hertz, wavelength, λ, is in meters, and speed, v, is in meters per second. This formula is valid for all waves in all media.

The speed of a wave depends upon its type and the medium through which it travels. Often at baseball games the bat is *seen* hitting the ball before the crack of the bat is *heard*. Why? Light travels at 3.00×10^8 meters per second in air, whereas sound travels only 346 meters per second in air at 25°C. The light from the bat hitting the ball reaches your eyes before the sound reaches your ears.

SAMPLE PROBLEM

The diagram shows a segment of a periodic wave in a spring traveling to the right to point I. The frequency of the wave is 2.0 hertz.

(a) What type of wave is represented in the diagram?
(b) What is the amplitude of the wave?
(c) What is the wavelength of the wave?
(d) Calculate the period of the wave.
(e) Calculate the speed of the wave.
(f) Identify two points on the wave that are in phase.
(g) Immediately after the wave moves through point I, in which direction will point H move?



SOLUTION:

(a) The particles of the medium vibrate perpendicular to the direction of wave motion. Thus, the wave is transverse.

(b) The at-rest position is represented by the horizontal dashed line. Displacement is the vertical distance from the at-rest position to the curve. Therefore, the maximum displacement is $\frac{1}{2}$ the vertical height of the diagram or 1.2 m.

(c) Three complete wavelengths are shown. Divide the given length by 3.

$$\lambda = \frac{6.0\text{ m}}{3} = 2.0\text{ m}$$

(d) Use the formula for the period $T = \frac{1}{f}$. Substitute the known values and solve.

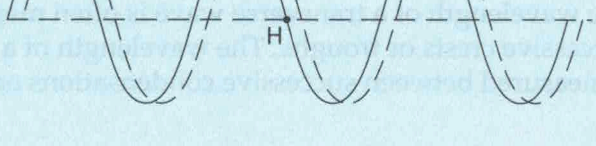
$$T = \frac{1}{f} = \frac{1}{2.0\text{ Hz}} = 0.50\text{ s}$$

(e) Write the formula for the speed of a wave $v = f\lambda$. Substitute the known values and solve.

$$v = f\lambda = (2.0\text{ Hz})(2.0\text{ m}) = 4.0\text{ m/s}$$

(f) Notice that points B and C are moving in the same direction and are the same distance from the at-rest position of the medium, but they do not have the same displacement and thus are out of phase. Points B and F have the same displacement from the at-rest position, but are moving in opposite directions, up and down, respectively, and therefore are out of phase. Points B and G are in phase because they have the same displacement and are moving in the same direction. Points B and G are separated by a distance of one wavelength.

(g) The dashed line in the diagram below shows how the entire waveform would appear in the next instant of time. Point H moves up.



Review Questions

1. A single vibratory disturbance that moves from point to point in a medium is called
   (1) a node (3) an antinode
   (2) a periodic wave (4) a pulse

2. What generally occurs when a pulse reaches a boundary between two different media?
   (1) All of the pulse is reflected.
   (2) All of the pulse is absorbed.
   (3) All of the pulse is transmitted.
   (4) Part of the pulse is reflected, part is absorbed, and part is transmitted.

3. A tuning fork vibrating in air produces sound waves. These waves are best classified as
   (1) transverse, because the air molecules are vibrating parallel to the direction of wave motion
   (2) transverse, because the air molecules are vibrating perpendicular to the direction of wave motion
   (3) longitudinal, because the air molecules are vibrating parallel to the direction of wave motion
   (4) longitudinal, because the air molecules are vibrating perpendicular to the direction of wave motion

4. When a transverse wave moves through a medium, what is the action of the particles of the medium?
   (1) They travel through the medium with the wave.
   (2) They vibrate in a direction parallel to the direction in which the wave is moving.
   (3) They vibrate in a direction perpendicular to the direction in which the wave is moving.
   (4) They remain at rest.

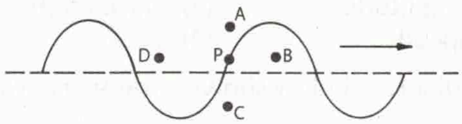
5. Compression waves in a spring are an example of
   (1) longitudinal waves
   (2) transverse waves
   (3) elliptical waves
   (4) torsional waves

6. Wave motion in a medium transfers
   (1) energy only
   (2) mass only
   (3) both energy and mass
   (4) neither energy nor mass

7. Periodic waves are produced by a wave generator at the rate of one wave every 0.50 second. What is the period of the wave?

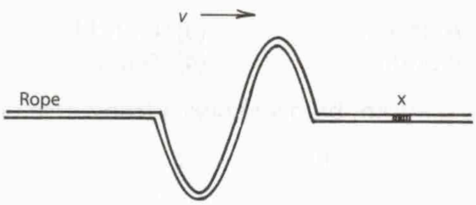
8. Which phrase best describes a periodic wave?
   (1) a single pulse traveling at constant speed
   (2) a single pulse traveling at varying speed in the same medium
   (3) a series of pulses at irregular intervals
   (4) a series of pulses at regular intervals

9. In the diagram below, the solid line represents a wave generated in a rope.



   As the wave moves to the right, point P on the rope is moving towards which position?
   (1) A (2) B (3) C (4) D

10. In the diagram below, a transverse wave is moving to the right on a rope.



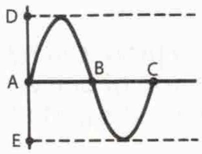
   In which direction will segment x move as the wave passes through it?
   (1) down, only
   (2) up, only
   (3) down, then up, then down
   (4) up, then down, then up

11. Which wave characteristic is defined as the number of cycles of a periodic wave occurring per unit time?

12. If the frequency of a sound wave is 440. cycles per second, the period of the wave is
   (1) 2.27×10^{-3} s (3) 1.33 s
   (2) 0.752 s (4) 3.31×10^{2} s

13. If the frequency of a sound wave is doubled, the period of the sound wave is
   (1) halved (3) unchanged
   (2) doubled (4) quadrupled

14. The diagram below represents a transverse wave.



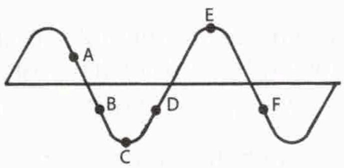
The amplitude of the wave is represented by the distance between points

(1) A and B (3) A and D
(2) A and C (4) D and E

15. If the frequency of a sound wave in air at STP remains constant, the wave's energy can be varied by changing its

(1) amplitude (3) wavelength
(2) speed (4) period

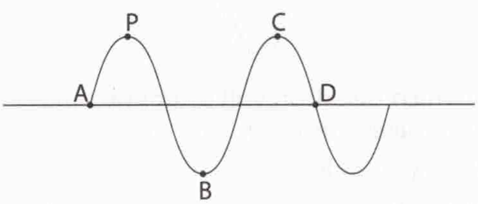
16. The diagram below shows a transverse wave.



Which two points on the wave are in phase?

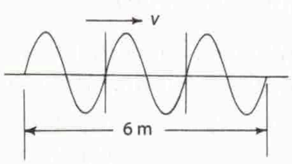
(1) A and E (3) C and E
(2) B and F (4) D and F

17. The diagram below shows a transverse wave.



Which point on the wave is 180° out of phase with point P?

18. The diagram that follows shows a train of waves moving along a string.



What is the wavelength?

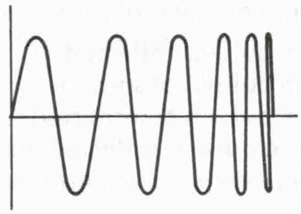
19. The wavelength of the periodic wave shown in the diagram below is 4.0 meters.

What is the distance from point B to point C?

20. An 8.0-meter long ocean wave passes the end of a dock every 5.0 seconds. Calculate the speed of the wave.

21. A sound wave travels at 340 meters per second. Determine how far from the source the wave has traveled after 0.50 second.

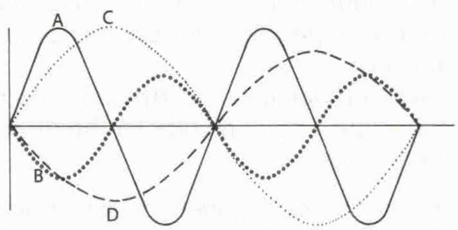
22. The diagram below represents a wave traveling in a uniform medium.



Which characteristic of the wave is constant?

(1) amplitude (3) period
(2) frequency (4) wavelength

Base your answers to questions 23 through 25 on the diagram below, which represents four transverse waves in the same medium.



23. Which two waves have the same amplitude?

24. Which two waves have the same wavelength?

25. Which two waves have the same frequency?

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26. A wave has a frequency of 2.0 hertz and a speed of 3.0 meters per second. The distance covered by the wave in 5.0 seconds is

(1) 30. m (2) 15 m (3) 7.5 m (4) 6.0 m

27. A wave traveling at 5.00×10^4 meters per second has a wavelength of 2.50×10^1 meters. What is the frequency of the wave?

(1) 5.00×10^{-4} Hz (3) 5.00×10^3 Hz
(2) 2.00×10^3 Hz (4) 1.25×10^6 Hz

28. Sound waves with constant frequency of 250 hertz are traveling through air at STP. Calculate the wavelength of the sound waves.

29. Calculate the total distance a sound wave travels in air at STP in 3.00 seconds.

30. What type of wave is sound traveling in water?