Waves

TOPIC 5

VOCABULARY

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

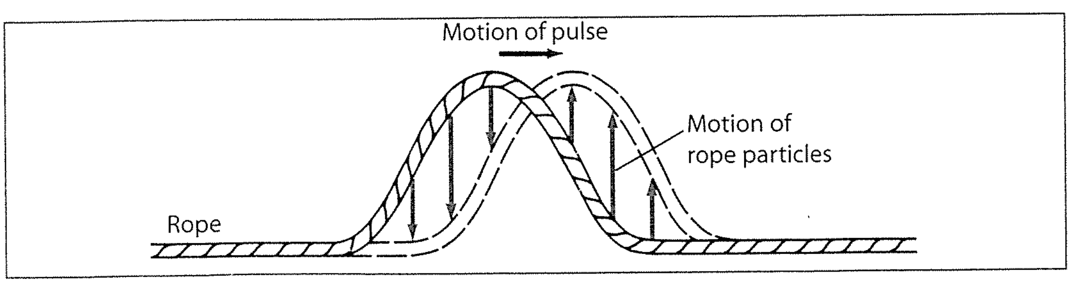


Figure 5-1. A pulse on a rope: A pulse is a single vertical disturbance transmitted horizontally at a definite speed.

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.

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.

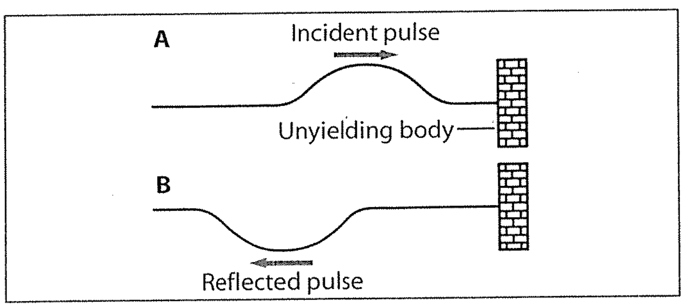


Figure 5-2. A pulse is reflected and inverted: (A) A wave pulse travels to the right along a rope attached to a brick wall. **(B)** When the pulse reaches the wall, it is reflected back toward the left in an inverted position.

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.

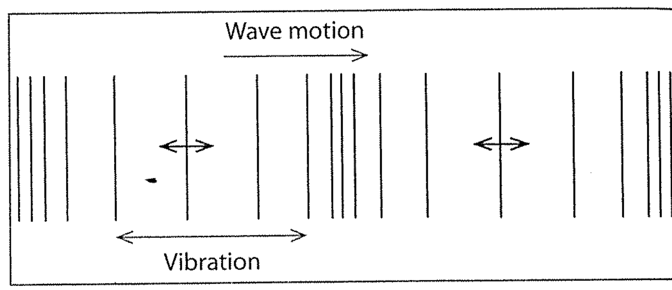


Figure 5-3. Longitudinal wave

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 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.

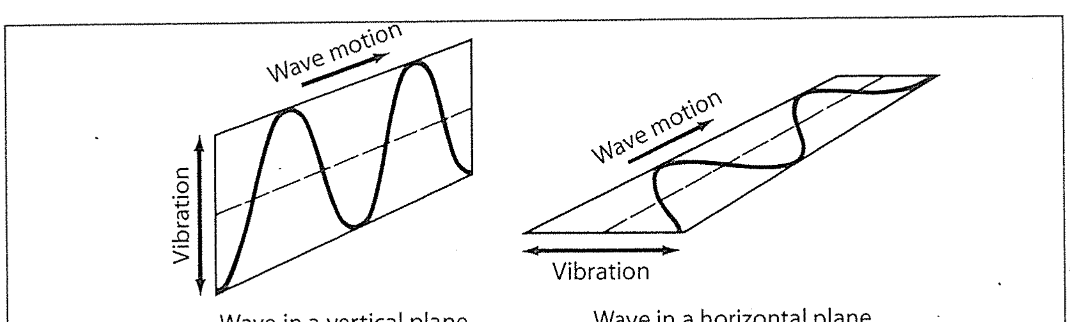


Figure 5-4. Transverse waves: These transverse waves have the same direction of travel but are in different planes.

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.

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

T is the period in seconds and f is the frequency 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.

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.

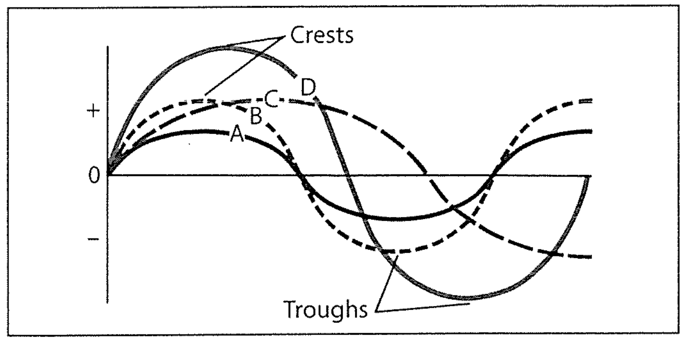


Figure 5-5. Wave amplitudes: Waves A and B have the same frequency but different amplitudes. Waves B and C have the same amplitudes but different frequencies. Wave D has the greatest amplitude of the four waves.

In a 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 on the following page shows compressions and rarefactions in 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 on the next page points A and E are in phase, B and F are in phase, and C and G are in phase.

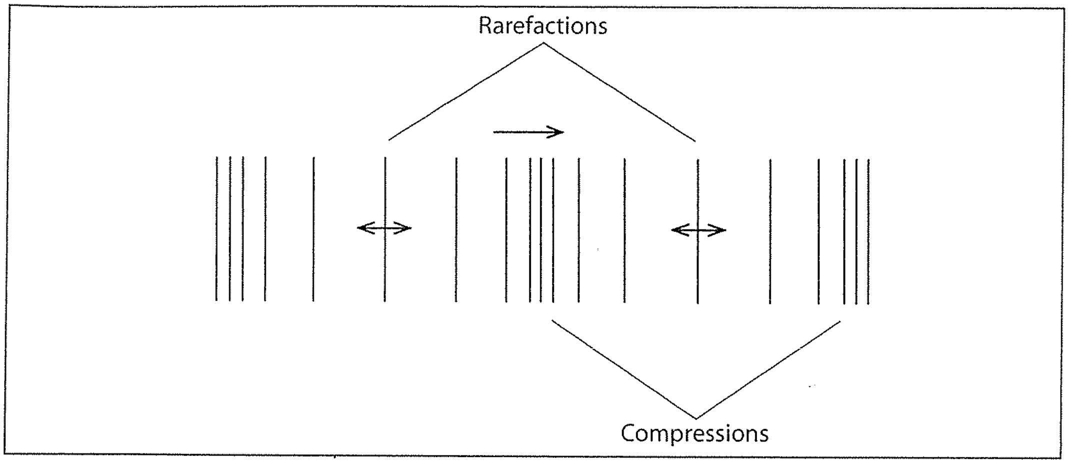


Figure 5-6. Compressions and rarefactions of a longitudinal wave

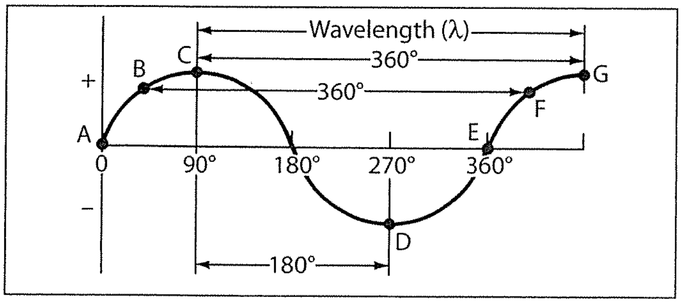


Figure 5-7. Phase relations in a wave

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 wave form, 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 compressions or rarefactions.

SPEED OF WAVES The **speed** of a wave is equal to the product of its wavelength and frequency.

$$v = f\lambda$$

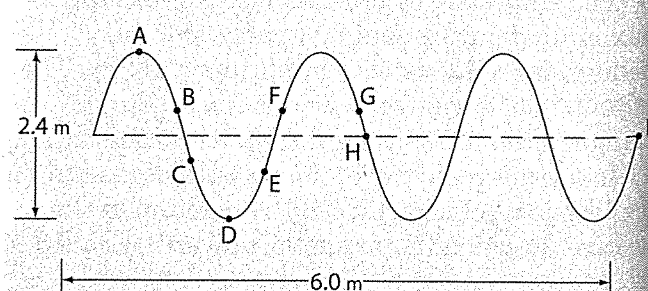
Frequency, f, is in hertz, wavelength, λ, is in meters, and speed, v, is in meters per second. This relation is valid for all waves in all media.

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 following diagram shows a segment of a periodic wave in a spring traveling to the right to point I.

(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) If the frequency of the wave is 2.0 hertz, what is the period of the wave?
(e) Determine the speed of the wave.
(f) Name two points on the wave that are in phase.
(g) Immediately after the wave moves through point I, will point H move up, down, left, or right?



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 relationship $T = \frac{1}{f}$. Substitute the known values and solve.

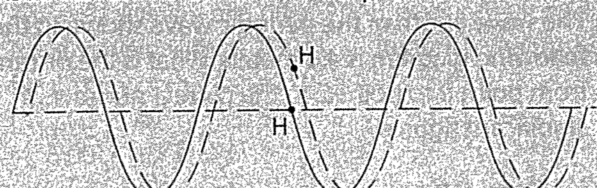
$$T = \frac{1}{f} = \frac{1}{2.0\ \text{Hz}} = 0.50\ \text{s}$$

(e) Use the relationship $v = f\lambda$. Substitute the known values and and solve.

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

(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. B and G are in phase because they have the same displacement and are moving in the same direction.

(g) The dashed line in the following diagram 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 a (1) period (2) periodic wave (3) wavelength (4) 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. Diagram A shows a glass tube containing undisturbed air molecules. Diagram B shows the same glass tube as a wave passes through it. What type of wave produced the disturbance shown in Diagram B?

Diagram A

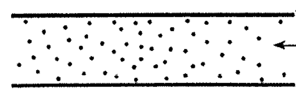
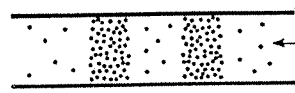


Diagram B



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.

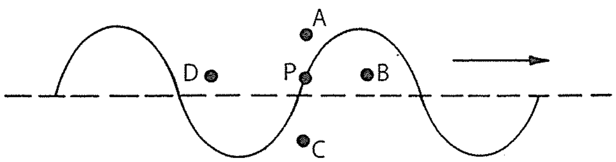
5. Compression waves in a spring are an example of (1) longitudinal waves (2) transverse waves (3) elliptical waves (4) torsional waves

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 to the correct number of significant figures?

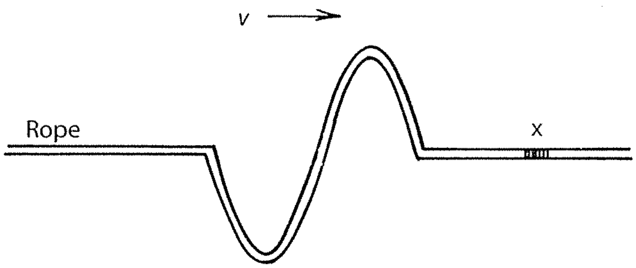
8. Which phrase best describes a periodic wave?
(1) a single pulse traveling at constant speed
(2) a single pulse traveling at varying speed in the same medium
(3) a series of pulses at irregular intervals
(4) a series of pulses at regular intervals

9. In the following diagram, 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 following diagram, a transverse wave is moving 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



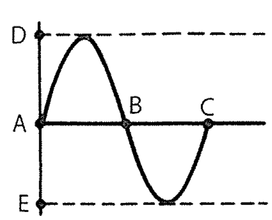
11. Which wave characteristic is defined as the number of cycles of a periodic wave occurring per unit time?

12. If the frequency of a sound wave is 440. cycles per second, its period is closest to

(1) 2.27×10^{-3} second/cycle
(2) 0.752 second/cycle
(3) 1.33 seconds/cycle
(4) 3.31×10^{2} seconds/cycle

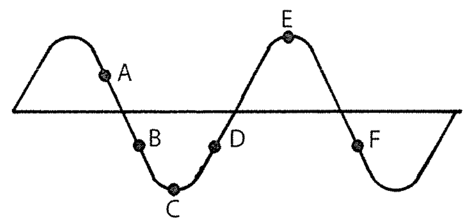
13. If the frequency of a sound wave is doubled, the period of the sound wave is (1) halved (2) doubled (3) unchanged (4) quadrupled

14. The following diagram represents a transverse wave. The amplitude of the wave is represented by the distance between points (1) A and B (2) A and C (3) A and D (4) D and E

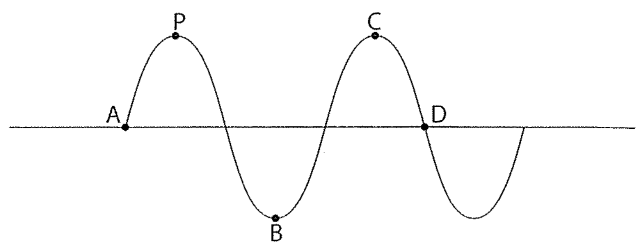


15. If the frequency of a sound wave in air at STP remains constant, the wave's energy can be varied by changing its (1) amplitude (2) speed (3) wavelength (4) period

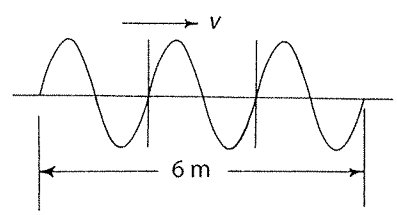
16. The following diagram shows a transverse wave. Which two points on the wave are in phase? (1) A and E (2) B and F (3) C and E (4) D and F



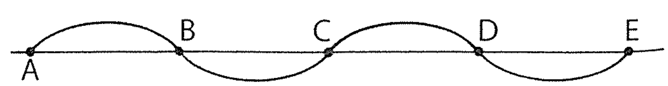
17. The following diagram shows a transverse wave. Which point on the wave is 180° out of phase with point P?



18. The diagram that follows shows a train of waves moving along a string. What is the wavelength?



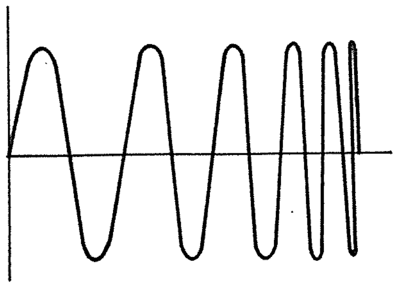
19. The wavelength of the periodic wave shown in the following diagram is 4.0 meters. What is the distance from point B to point C to the correct number of significant figures?



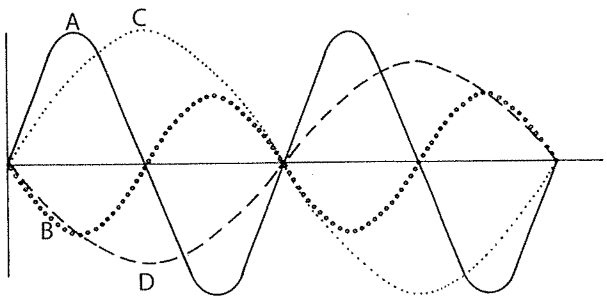
20. An 8.0-meter long ocean wave passes the end of a dock every 5.0 seconds. What is the speed of the wave?

21. A sound wave travels at 340 meters per second. After 0.50 second, how far from the source of the wave has the wave traveled?

22. The following diagram represents a wave traveling in a uniform medium. Which characteristic of the wave is constant? (1) amplitude (2) frequency (3) period (4) wavelength



Base your answers to questions 23 through 25 on the following diagram, 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?

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

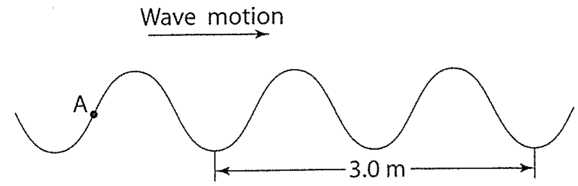
27. A wave traveling at 5.00×10^4 meters per second has a wavelength of 2.50×10^1 meters. What is the frequency of the wave? (1) 1.25×10^6 Hz (2) 2.00×10^3 Hz (3) 5.00×10^{-4} Hz (4) 5.00×10^3 Hz

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

29. What total distance will a sound wave travel in air in 3.00 seconds at STP?

Base your answers to questions 30 through 33 on the information and diagram that follow.

A periodic wave, having a frequency of 40. hertz, travels to the right in a uniform medium as shown.



30. On the diagram, draw one or more arrows to indicate the direction of motion of point A in the next instant of time.

31. On the diagram, label a point P that is in phase with point A.

32. Determine the speed of the wave.

33. Determine the period of the wave.

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

Base your answers to questions 35 and 36 on the following information.

The elapsed time between successive crests of a transverse wave passing a given point is 0.080 second.

35. Determine the period of the wave.

36. Determine the frequency of the wave.

Base your answers to questions 37 through 39 on the following information.

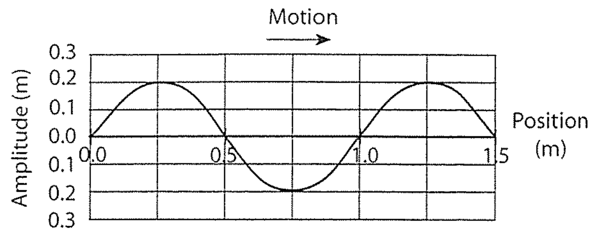
The distance from one crest of a water wave to the next crest is 4.0 meters. One crest passes an observation point every 2.5 seconds.

37. Determine the speed of the wave.

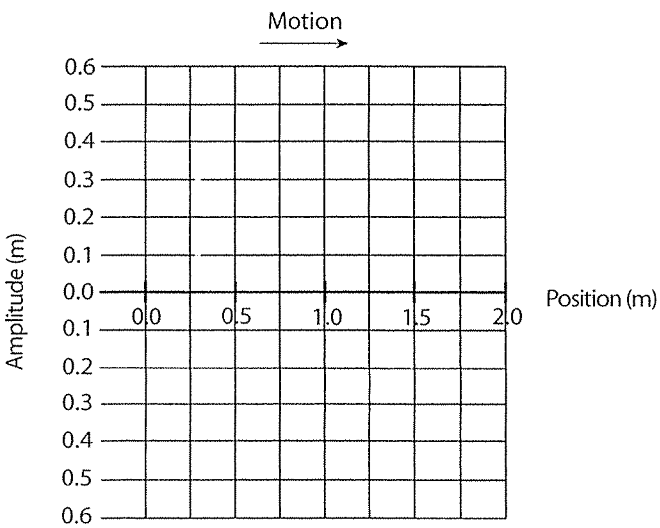
38. How much time is required for the wave to travel 50. meters?

39. How far will the wave travel in 4.0 seconds?

40. The diagram below shows a periodic wave W traveling to the right in a uniform medium.



On the grid below sketch at least one cycle of a periodic wave having twice the amplitude and half the wavelength of wave W.



41. A sound wave is produced by a musical instrument for 0.40 second. If the frequency of the wave is 370 hertz, how many complete waves are produced in that time period?

42. Write an equation that correctly relates the speed v, wavelength λ, and period T of a periodic wave.

43. A wave x meters long passes through a medium at y meters per second. The frequency of the wave could be expressed as (1) $\frac{y}{x}$ Hz (2) $\frac{x}{y}$ Hz (3) xy Hz (4) $(x + y)$ Hz

44. Which is a unit for the amplitude of a transverse wave? (1) m/s (2) s (3) Hz (4) m

45. If the frequency of a sound wave increases, the wavelength of the wave in air will (1) decrease (2) increase (3) remain the same

46. Which phrase best describes the wavelength of a sound wave in air at STP? (1) inversely proportional to its amplitude and inversely proportional to its frequency (2) inversely proportional to its amplitude and directly proportional to its frequency (3) independent of its amplitude and inversely proportional to its frequency (4) independent of its amplitude and directly proportional to its frequency

47. A water wave travels a distance of 10.0 meters in 5.0 seconds. What can be determined from this information? (1) the speed of the wave only (2) the period of the wave only (3) the speed and frequency of the wave (4) the period and frequency of the wave

Periodic Wave Phenomena

By observing two types of mechanical waves, transverse and longitudinal, you can discover some characteristics of waves and the behavior of waves under various conditions. Some of these characteristics and behaviors are discussed below.

Wave Fronts

When water drips from a leaky faucet into a water-filled sink, waves spread, or radiate, in concentric circles along the surface of the water from the point where the drips strike the surface. In a three-dimensional medium such as air, waves radiate in concentric spheres from a vibrating point. All points on a wave that are in phase comprise a wave front. A **wave front** is the locus of all adjacent points on a wave that are in phase. For example, in the waves in the sink, all of the points on one of the crests constitute a wave front. Two successive crests are separated by a distance of one wavelength and, therefore, are in phase.

Doppler Effect

When a source and an observer (receiver) of waves are moving relative to each other, the observed frequency is different from the frequency of the vibrating source. This change in observed or apparent frequency due to relative motion of source and observer is called the **Doppler effect.**

If the source is approaching the observer, or if the observer is approaching the source, the frequency appears to increase. If the source is receding from the observer or the observer is receding from the source, the frequency appears to decrease. Because the speed of the waves in the medium is not affected by the Doppler effect, it can be seen from the equation $v = f\lambda$ that the change in apparent wavelength is inversely proportional to the change in apparent frequency.

The wave front diagrams in Figure 5-8 illustrate the changes in apparent frequency and wavelength caused by the Doppler effect. In Figure 5-8A, the source is stationary, and the four successive wave fronts (1, 2, 3, and 4) are equally spaced circles in all directions. The observed wavelength and frequency are the same for all stationary observers. In Figure 5-8B, the source is moving from right to left. Each successive wave front has a different center. To a stationary observer at the left, the wavelengths appear shorter and the frequency higher; to a stationary observer at the right, the effect is the opposite.

The Doppler effect can cause changes in the apparent pitch of a sound wave because the ear perceives a sound wave of higher frequency as a sound of higher pitch. Thus the pitch of an approaching sound source is higher than its pitch when the source is stationary, and the pitch drops lower as the source passes the observer and begins to recede.

Visible light waves are subject to a similar effect. The human eye perceives light waves of different frequencies as differences in color. Light waves of the lowest frequency (longest wavelength) that the eye can detect are seen as red, while those of highest frequency (shortest wavelength) are seen as blue-violet. Other colors are distributed between these extremes in the visible spectrum. Because of the Doppler effect, the apparent color of an approaching light source is shifted toward the blue-violet end of the spectrum, while that of a receding source is shifted toward the red end. If the light source is a mixture of many frequencies, such as the light from a star, its light appears slightly bluer if it is approaching an observer, or slightly redder if it is receding, than it would appear if it were not moving relative to the observer.

APPLICATIONS OF THE DOPPLER EFFECT

The Doppler effect has practical applications in weather forecasting and police work. For example, the speed of a car can be determined by a computerized radar system. If a car is at rest and a beam of radio waves is directed at the car from a stationary source, the incident and reflected waves have the same frequency. If the car is moving toward the source of the radar, however, the reflected waves have a higher frequency than the waves emitted by the source. The greater the car's speed toward the radar source, the greater the Doppler shift in frequency. In a similar way, if the car is moving away from the source of radar, the frequency of the reflected waves decreases by an amount that depends upon the speed of the car. Thus, equipped with a "radar gun," a law-enforcement officer can detect speed-limit violators "coming or going."

Interference

Superposition occurs when two or more waves travel through the same medium simultaneously. The **principle of superposition** states that the resultant displacement at any point is the algebraic sum of the displacements of the individual waves. The effect of the superposition is called **interference,** which may be constructive or destructive. Although any number of waves may superpose, the discussion that follows is restricted to two waves.

Constructive interference occurs when the wave displacements of two in-phase waves in the same medium are in the same direction. The algebraic sum of the displacements is an amplitude greater than that of either of the original waves. Maximum constructive interference occurs when the waves

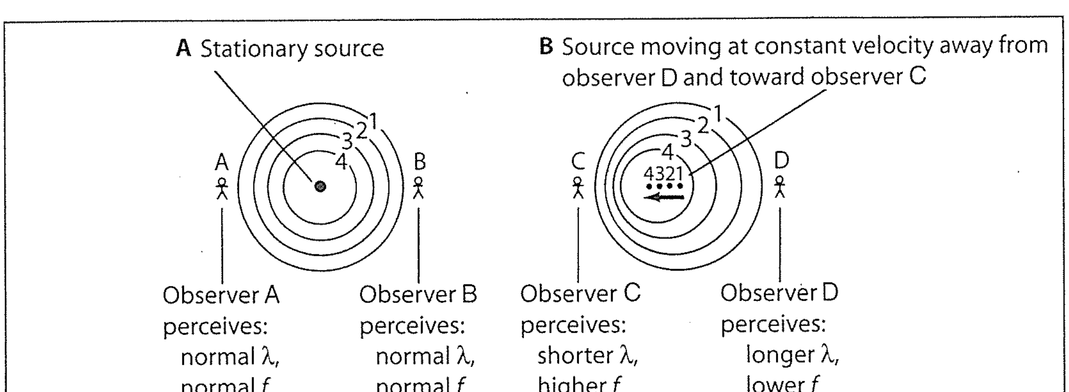


Figure 5-8. The Doppler effect: (A) When the source is stationary, the wave fronts are equally spaced in all directions. **(B)** When the source is moving, the wave fronts are closer together in the direction in which the source is moving.

are in phase and crest superposes on crest. Thus, maximum constructive interference occurs when the phase difference is equal to 0°, as shown in Figure 5-9A. The point of maximum displacement of a medium when two waves are interacting is called an **antinode.**

When two waves of equal frequency and amplitude whose phase difference is 180° or $\frac{1}{2}\lambda$ meet at a point (for example, crest to trough), there is maximum **destructive interference,** as shown in Figure 5-9B. Maximum destructive interference results in the formation of **nodes** (points or lines), which are regions of zero displacement of the medium. Intermediate degrees of interference occur between the regions of maximum constructive interference and maximum destructive interference.

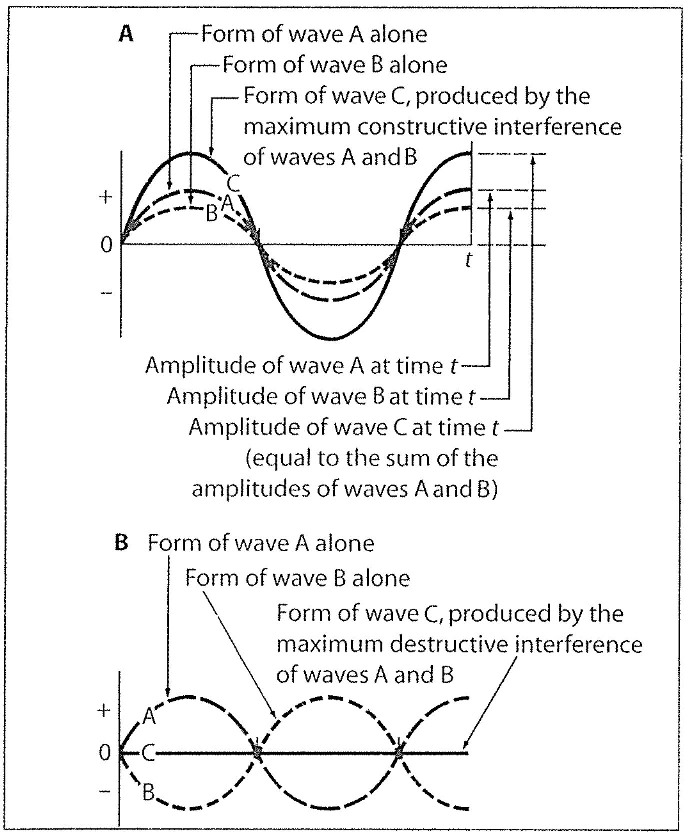


Figure 5-9. Constructive and Destructive Interference: **(A)** Waves A and B have the same frequency and a phase difference of 0°. As a result, they show maximum constructive interference, producing wave C. Note that the amplitudes of A and B always add up to the amplitude of C at every instant of time. This is demonstrated for the time *t* at the extreme right of the graph. **(B)** Waves A and B have the same frequency and the same amplitude, but a phase difference of 180°. As a result, they show maximum destructive interference. Notice that waves A and B cancel each other.

Beats are produced by the interference of two notes of slightly different frequencies that are heard simultaneously.

TWO SOURCES IN PHASE IN THE SAME MEDIUM When two in-phase point sources generate waves in the same medium, a symmetrical interference pattern results because of maximum constructive and destructive interference. Figure 5-10A shows two identical point sources, S_1 and S_2, producing wave crests (solid lines) and wave troughs (dashed lines) that interfere. The path difference from any point of constructive interference to the sources, S_1 and S_2, is an even number of half-wavelengths. For example, along antinodal line P_1P_4, the difference in path length from any point on the line to S_1 and S_2 is 0λ. In Figure 5-10B, point A is on an antinodal line because distance AS_1 differs from distance AS_2 by two half-wavelengths. On the other hand, point B is on a nodal line because distance BS_1 differs from distance BS_2 by an odd number of half-wavelengths. Nodal lines occur midway between antinodal lines.

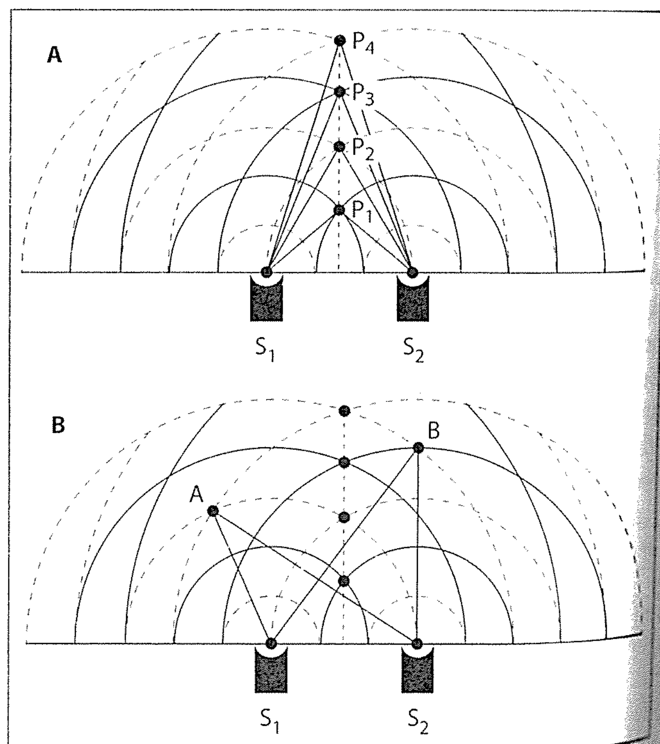


Figure 5-10. Interference of waves produced by two identical point sources: **(A)** Along antinodal line P_1P_4, the difference in path length from any point to S_1 and S_2 is 0λ. **(B)** Point A is an antinode because the distance AS_1 differs from the distance AS_2 by an even number of half-wavelengths. Point B is a node because the distance BS_1 differs from the distance BS_2 by an odd number of half-wavelengths.

Standing Waves

When two waves having the same amplitude and frequency travel in opposite directions through a medium, a standing wave is formed. A **standing wave** is a pattern of wave crests and troughs that remains stationary in a medium. The nodes and antinodes are stationary and the wave appears to stand still. Standing waves are easily produced in a stretched string that is fixed at both ends. Wave trains traveling along the string are reflected at the ends and travel back with the same frequency and amplitude. Figure 5-11 illustrates several possible standing waves in a string. Note that a node appears at each end of the string. The distance between two successive nodes is equal to $\frac{1}{2}\lambda$.

Resonance

Every elastic body has a particular frequency called its **natural frequency** at which it will vibrate if disturbed. When a periodic force is applied to an elastic body, it absorbs energy and the amplitude of its vibration increases. The vibration of a body at its natural frequency because of the action of a vibrating source of the same frequency is called **resonance.** For example, a nonvibrating tuning fork, having a natural frequency of 512 hertz, will resonate when a vibrating tuning fork with a natural frequency of 512 hertz is brought near it. Furthermore, it is possible for an opera singer to shatter a glass by maintaining a note with a frequency equal to the natural frequency of the glass. The transfer of energy by resonance increases the amplitude of vibrations in the glass until its structural strength is exceeded. Probably the most dramatic example of resonance was the collapse of the Tacoma Narrows Bridge in the state of Washington in 1940. High winds set up standing waves in the bridge in addition to vibrations in a torsional (twisting) mode. Resonance increased the amplitude of vibrations until the bridge collapsed.

Diffraction

The spreading of waves into the region behind a barrier in the wave's path is called **diffraction.** Parallel water wave fronts incident on a small opening are diffracted to form concentric semicircular fronts. These semicircular fronts have the same wavelength as the incident wave if the medium is uniform throughout, as shown in Figure 5-12A. If the opening through which the wave is diffracted is much larger than one wavelength of the incident wave, diffraction effects are small, as shown in Figure 5-12B.

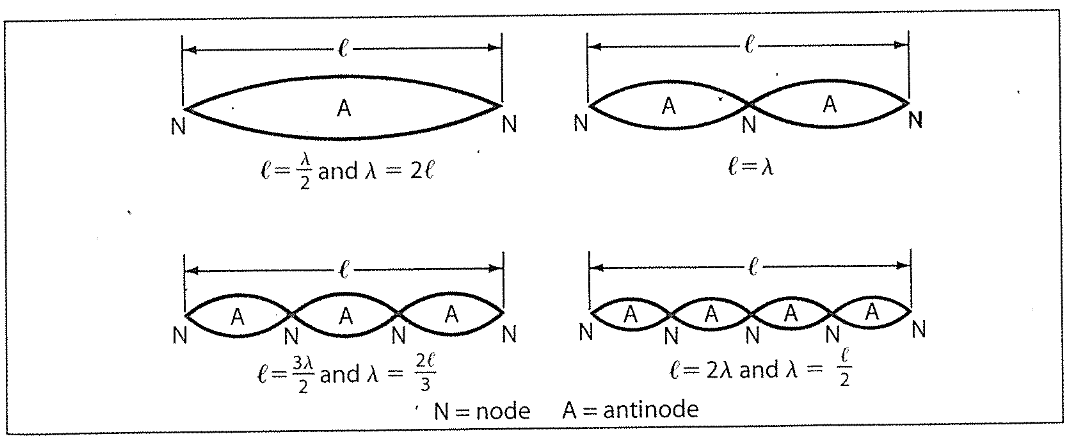


Figure 5-11. Standing waves of different wavelengths along a string

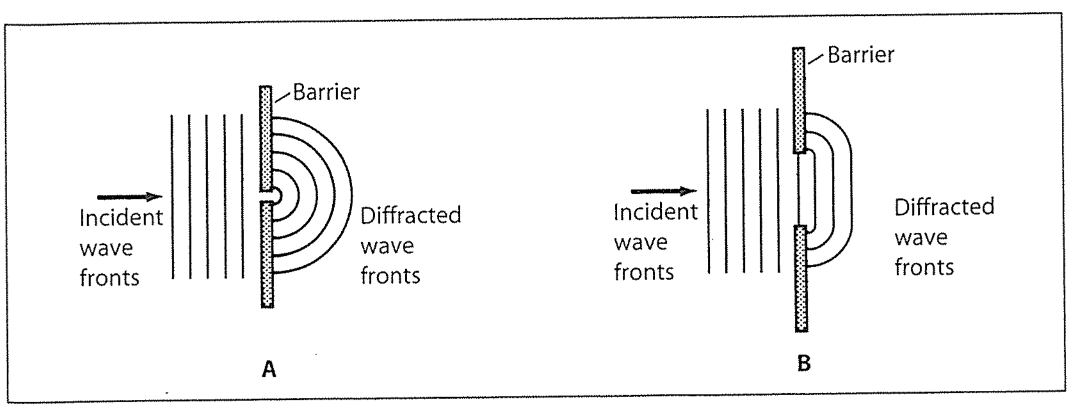
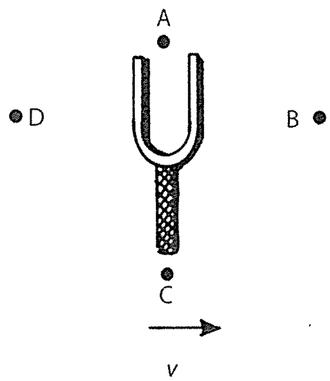


Figure 5-12. Diffraction of parallel wave fronts by different openings in a barrier

Review Questions

48. What term describes the variations in the observed frequency of a sound wave when there is relative motion between the source and the receiver?

49. The vibrating tuning fork shown in the diagram that follows produces a constant frequency. The tuning fork is being moved to the right at constant speed, and observers are located at points A, B, C, and D. Which observer hears the lowest frequency?



50. The driver of a car hears the siren of an ambulance that is moving away from her. If the actual frequency of the siren is 2000. hertz, the frequency heard by the driver may be (1) 1900. Hz (2) 2000. Hz (3) 2100. Hz (4) 4000. Hz

51. A police officer's stationary radar device indicates that the frequency of the radar wave reflected from an automobile is less than the frequency emitted by the radar device. This indicates that the automobile is (1) moving toward the police officer (2) moving away from the police officer (3) not moving

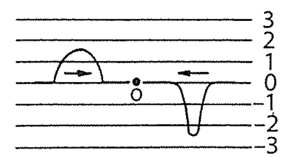
52. A stationary person makes observations of the periodic waves produced by a moving source. When the wave source recedes from the observer, he observes an apparent increase in the wave's (1) speed (2) frequency (3) wavelength (4) amplitude

53. Light from a distant star displays a Doppler red shift. This shift is best explained by assuming the star is (1) decreasing in temperature (2) increasing in temperature (3) moving toward Earth (4) moving away from Earth

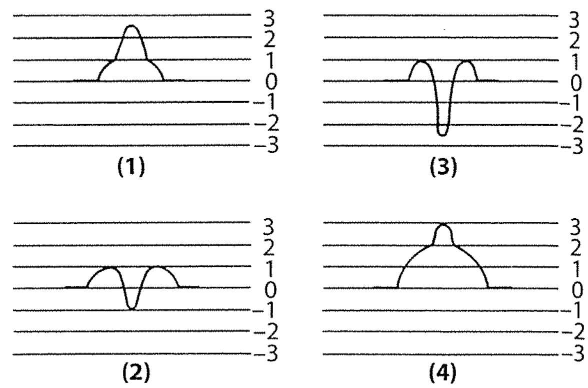
54. Maximum constructive interference occurs when the phase difference between the interfering waves is (1) 0° (2) 45° (3) 90° (4) 180°

55. By how many degrees should two waves be out of phase to produce maximum destructive interference?

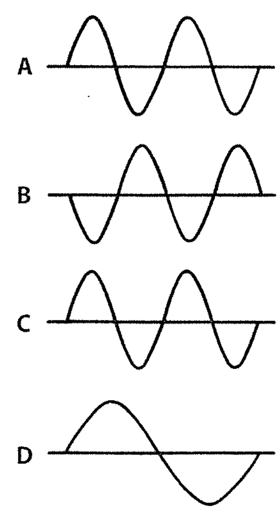
56. The diagram below shows a rope with two pulses moving along it in the directions shown.



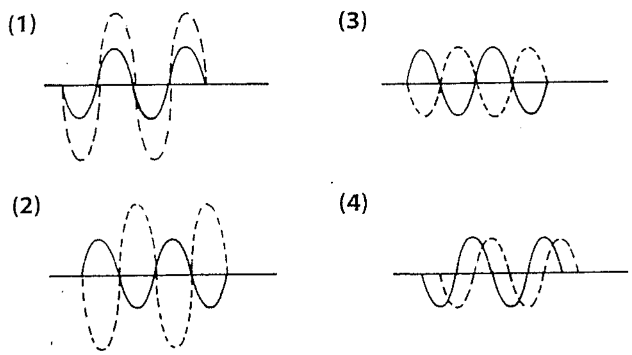
What is the resultant wave pattern at the instant when the maximum displacement of both pulses is at point O on the rope?



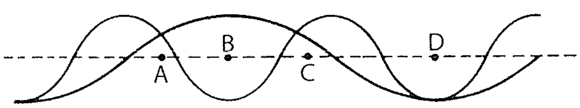
57. The following diagram shows four waves that pass simultaneously through a region. Which two waves will produce maximum constructive interference if they are combined? (1) A and B (2) A and C (3) B and C (4) C and D



58. Which pair of waves will produce a resultant wave with the smallest amplitude?



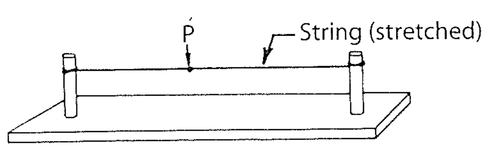
59. The following diagram represents two waves traveling simultaneously in the same medium. At which of the given points will maximum constructive interference occur?



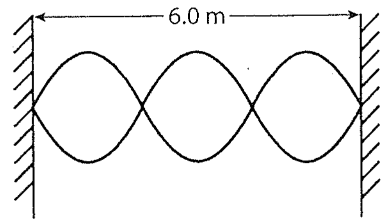
60. Standing waves are produced by two waves traveling in opposite directions in the same medium. The two waves must have (1) the same amplitude and the same frequency (2) the same amplitude and different frequencies (3) different amplitudes and the same frequency (4) different amplitudes and different frequencies

61. In order for standing waves to form in a medium, two waves must (1) have the same frequency (2) have different amplitudes (3) have different wavelengths (4) travel in the same direction

62. When the stretched string of the apparatus represented in the following diagram is made to vibrate, point P does not move. Point P is most probably the location of (1) a node (2) an antinode (3) maximum amplitude (4) maximum pulse



Base your answers to questions 63 and 64 on the following diagram, which shows a standing wave in a rope.

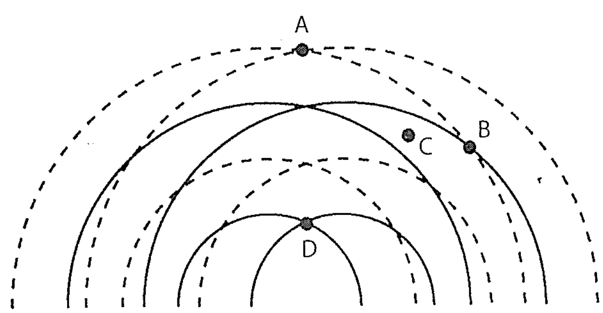


63. How many nodes are represented?

64. If the rope is 6.0 meters long, what is the wavelength of the standing wave?

65. Two waves traveling in the same medium interfere to produce a standing wave. What is the phase difference in degrees between the two waves at a node?

66. Two wave sources operating in phase in the same medium produce the circular wave patterns shown in the diagram that follows. The solid lines represent wave crests and the dashed lines represent wave troughs. Which point is at a position of maximum destructive interference?

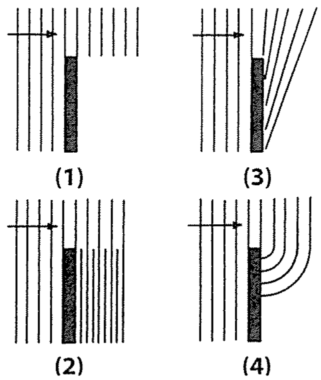


67. An opera singer's voice is able to break a thin crystal glass if a note sung and the glass have the same natural (1) speed (2) frequency (3) amplitude (4) wavelength

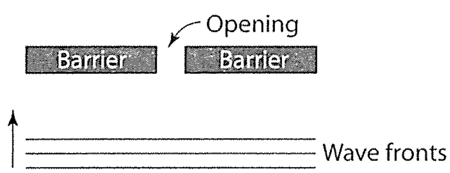
68. When an opera singer hits a high-pitch note, a glass on the opposite side of the opera hall shatters. Which statement best explains this phenomenon? (1) The amplitude of the note increases before it reaches the glass. (2) The singer and the glass are separated by an integral number of wavelengths. (3) The frequency of the note and the natural frequency of the glass are equal. (4) The sound produced by the singer slows down as it travels from the air into the glass.

69. A wave spreads into the region behind a barrier. What is this phenomenon called?

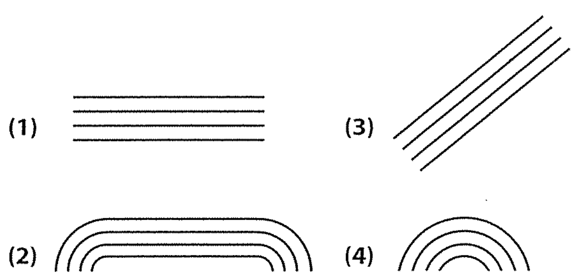
70. Which diagram best illustrates diffraction of waves incident on a barrier?



71. The diagram that follows represents straight wave fronts approaching a narrow opening in a barrier.



Which diagram best represents the shape of the waves after passing through the opening?



Light

The human eye can perceive only an extremely small fraction of the electromagnetic spectrum. That portion of the spectrum, which allows us to see, is called light and covers the range of wavelengths from approximately 3.90×10^{-7} to 7.81×10^{-7} meter. (The electromagnetic spectrum will be discussed in detail later in this topic.) Obviously, these wavelengths are too small to measure with a ruler as you might measure the wavelength of a transverse wave on a rope or a water wave in a shallow tank.

Speed of Light

Measurements of the speed of light to more than two or three significant figures could not be made until about 100 years ago. To three significant figures, the speed of light in a vacuum or air is 3.00×10^8 meters per second. Measurements of the speed of light are now recorded to nine significant figures. This more accurate data reveals that the speed of light in air is slightly less than it is in a vacuum. The speed of light in a vacuum is represented by the symbol *c*, an important physical constant.

The speed of light in a vacuum is the upper limit for the speed of any material body. No object can travel faster than *c*. The speed of light in a material medium is always less than *c*. The equation $v = f\lambda$ applies to light waves. Therefore, $c = f\lambda$, where f is the frequency of a light wave and λ is its wavelength in a vacuum.

Ray Diagrams

Because it is not possible to see individual wave fronts in a light wave, a ray is used to indicate the direction of wave travel. A **ray** is a straight line that is drawn at right angles to a wave front and points in the direction of wave travel. Ray diagrams show only the direction of wave travel, not the actual waves. An **incident ray** is a ray that originates in a medium and is incident on a boundary or an interface of that medium with another medium. A **reflected ray** is a ray that has rebounded from a boundary or interface. A **refracted ray** is a ray that results from an incident ray entering a second medium obliquely. Figure 5-13 on the following page shows these rays as well as the wave fronts whose motion they represent.

Incident, reflected, and refracted rays form corresponding angles measured from a line called the normal. The **normal** is a line drawn perpendicular to the barrier or to the interface between two media at the point where the incident ray strikes. In ray diagrams, all the rays and the normal lie in a single plane.