The Language of Physics

Wave
A wave is a propagation of a disturbance through a medium (p. 321).

Longitudinal wave
A wave in which the particles of the medium oscillate in simple harmonic motion parallel to the direction of the wave propagation (p. 321).

Transverse wave
A wave in which the particles of the medium execute simple harmonic motion in a direction perpendicular to its direction of propagation (p. 321).

Displacement
The distance that a particle of the medium is displaced from its equilibrium position as the wave passes by (p. 322).

Amplitude
The maximum value of the displacement (p. 322).

Wavelength
The distance, in the direction of propagation, in which the wave repeats itself (p. 323).

Period
The time it takes for one complete wave to pass a particular point. Hence, it is the time for a wave to repeat itself (p. 323).

Frequency
The number of waves passing a particular point per second (p. 323).

Reflection of a wave at a boundary
If a wave on a string traveling to the right is reflected from a nonfixed end, the reflected wave moves to the left with the same size and shape as the incident wave. If a wave on a string is traveling to the right and is reflected from a fixed end, the reflected wave is the same size and shape but is now inverted (p. 331).

Reflection and transmission of a wave at the boundary of two different media
(1) *Boundary between a less dense medium and a more dense medium.* The boundary acts as a fixed end and the reflected wave is inverted. The transmitted wave slows down on entering the more dense medium and the wavelength of the transmitted wave is less than the wavelength of the incident wave (p. 333).
(2) *Boundary between a more dense medium and a less dense medium.* The boundary acts as a nonfixed end and the reflected wave is not inverted, but is rather right side up. The transmitted wave speeds up on entering the less dense medium and the wavelength of the transmitted wave is greater than the wavelength of the incident wave (p. 335).

Principle of superposition
Whenever two or more wave disturbances pass a particular point in a medium, the resultant displacement of the point of the medium is the sum of the displacements of each individual wave disturbance (p. 336).

Phase angle
The measure of how far one wave is displaced in the direction of propagation from another wave (p. 337).

Constructive interference
When two interfering waves are in phase with each other (phase angle = 0) the amplitude of the combined wave is a maximum (p. 338).

Destructive interference
When two interfering waves are 180° out of phase with each other the amplitude of the combined wave is zero (p. 338).

Node
The point where the amplitude of a standing wave is zero (p. 341).

Antinode
The point where the amplitude of a standing wave is a maximum (p. 341).

Standing wave on a string
For a string fixed at both ends, a wave train is sent down the string. The wave is reflected from the fixed ends. Hence, there are two wave trains on the string, one traveling to the right and one traveling to the left. The resultant wave is the superposition of the two traveling waves. It is called a standing wave or a stationary wave because the resultant standing wave does not travel at all. The node of the standing wave remains a node for all times. Thus, the string can not move up and down at that point, and can not transmit any energy past that point. Because the string is fixed at both ends, only certain wavelengths and frequencies are possible. When the string vibrates at these specified wavelengths, the string is said to be vibrating at one of its normal modes of vibration, and the string is vibrating at one of its natural frequencies (p. 342).

Fundamental frequency
The lowest of the natural frequencies of a vibrating system (p. 343).

Resonance
When a force is applied, whose frequency is equal to the natural frequency of the system, the system vibrates at maximum amplitude (p. 344).

Sound wave
A sound wave is a longitudinal wave that can be propagated in a solid, liquid, or gas (p. 346).

Overtone
An overtone is a frequency higher than the fundamental frequency (p. 348).

Harmonic
A harmonic is an overtone that is a multiple of the fundamental frequency. Hence, the nth harmonic is n times the fundamental frequency, or first harmonic (p. 348).

Doppler effect
The change in the wavelength and hence the frequency of a sound caused by the relative motion between the source and the observer. When a moving source approaches a stationary observer the observed frequency is higher than the emitted frequency of the source. When a moving source recedes from a stationary observer, the observed frequency is lower than the emitted frequency of the source (p. 350).

Intensity of a wave
The energy of a wave that passes a unit area in a unit time (p. 357).

Summary of Important Equations

Frequency of a wave
$$f = \frac{1}{T} \quad (12.1)$$

Fundamental equation of wave propagation
$$v = \lambda f \quad (12.3)$$

Wave number
$$k = \frac{2\pi}{\lambda} \quad (12.9)$$

Equation of a wave traveling to the right
$$y = A\sin(kx - \omega t) \quad (12.13)$$

Equation of a wave traveling to the left
$$y = A\sin(kx + \omega t) \quad (12.26)$$

Angular frequency
$$\omega = 2\pi f \quad (12.12)$$

Angular frequency
$$\omega = kv \quad (12.14)$$

Velocity of transverse wave on a string
$$v = \sqrt{\frac{T}{m/l}} \quad (12.30)$$

Change in wavelength in second medium
$$\lambda_2 = \frac{v_2}{v_1}\lambda_1 \quad (12.34)$$

Principle of superposition
$$y = y_1 + y_2 + y_3 + \ldots \quad (12.35)$$

Equation of wave displaced to the right by phase angle ϕ
$$y = A\sin(kx - \omega t - \phi) \quad (12.38)$$

Interference of two waves out of phase by angle ϕ
$$y = 2A\cos\left(\frac{\phi}{2}\right)\sin\left(kx - \omega t - \frac{\phi}{2}\right) \quad (12.50)$$

The equation of the displacement of a standing wave on a string
$$y = 2A\sin\left(\frac{n\pi x}{L}\right)\cos(\omega t) \quad (12.61)$$

Location of nodes of standing wave
$$x = \frac{n\lambda}{2} \quad (12.56)$$

Location of antinodes
$$x = (2n - 1)\frac{\lambda}{4} \quad (12.57)$$

Possible wavelengths on vibrating string
$$\lambda = \frac{2L}{n} \quad (12.62)$$

Frequency of vibrating string
$$f = \frac{n}{2L}\sqrt{\frac{T}{m/l}} \quad (12.64)$$

Frequency of higher modes of vibration
$$f_n = nf_1 \quad (12.67)$$

Speed of sound in a solid
$$v = \sqrt{\frac{Y}{\rho}} \quad (12.68)$$

Speed of sound in a fluid
$$v = \sqrt{\frac{B}{\rho}} \quad (12.69)$$

Speed of sound in a gas
$$v = \sqrt{\frac{\gamma p}{\rho}} \quad (12.70)$$

Doppler frequency shift
$$f_o = \frac{v \pm v_o}{v \mp v_s} f_s \quad (12.91)$$

Energy transmitted by wave
$$E_{\text{transmitted}} = 2\pi^2 m f^2 R^2 \quad (12.95)$$

Intensity of a wave
$$I = 2\pi^2 \rho v f^2 R^2 \quad (12.99)$$

Intensity of a sound wave in decibels
$$\beta = 10\log\left(\frac{I}{I_0}\right) \quad (12H.1)$$

Questions for Chapter 12

1. Discuss the relation between simple harmonic motion and wave motion. Is it possible to create waves in a medium where the particles do not execute simple harmonic motion?
2. State the differences between transverse waves and longitudinal waves.
3. Describe how sound is made and heard by a human.
4. Discuss the statement "When a person is young enough to hear all the frequencies of a good stereo system, he can not afford to buy it. And when he can afford to buy it, he can not hear all the frequencies."
5. Discuss the statement that a wave is periodic in both space and time.
6. Why are there four different strings on a violin? Describe what a violin player does when she "tunes" the violin.
7. Discuss what happens to a pulse that is reflected from a fixed end and a free end.

†8. A wave is reflected from, and transmitted through, a more dense medium. What criteria would you use to estimate how much energy is reflected and how much is transmitted?

9. If the wavelength of a wave decreases as it enters a medium, what does this tell you about the medium?
10. When does the superposition principle fail in the analysis of combined wave motions?
11. Discuss what is meant by a standing wave and give some examples.
12. Discuss the difference between overtones and harmonics for a vibrating string, an open organ pipe, and a closed organ pipe.

†13. Discuss the possible uses of ultrasound in medicine.

†14. Discuss the Doppler effect on sound waves. Could the Doppler effect be applied to light waves? What would be the medium for the propagation?

†15. How could the Doppler effect be used to determine if the universe is expanding or contracting?

16. If two sounds of very nearly the same frequency are played together, the two waves will interfere with each other. The slight difference in frequency will cause an alternate rising and lowering of the intensity of the combined sound. This phenomenon is called beats. How can this technique be used to tune a piano?

Problems for Chapter 12

12.1 Introduction

1. Find the period of a sound wave of (a) 20.0 Hz and (b) 20,000 Hz.
2. A sound wave has a wavelength of 2.25×10^{-2} m and a frequency of 15,000 Hz. Find its speed.
3. Find the wavelength of a sound wave of 60.0 Hz at 20.0 °C.

12.2 Mathematical Representation of a Wave

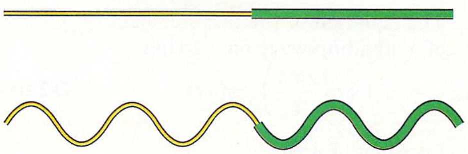
4. At a time $t = 0$, a certain wave is given by $y = 10 \sin 5x$. Find the (a) amplitude of the wave and (b) its wavelength.
5. You want to generate a wave that has a wavelength of 20.0 cm and moves with a speed of 80.0 m/s. Find (a) the frequency of such a wave, (b) its wave number, and (c) its angular frequency.
6. A particular wave is given by $y = (8.50\text{ m})\sin[(0.800\text{ m}^{-1})x - (5.40\text{ rad/s})t]$. Find (a) the amplitude of the wave, (b) the wave number, (c) the wavelength, (d) the angular frequency, (e) the frequency, (f) the period, (g) the velocity of the wave, and (h) the displacement of the wave at $x = 5.87$ m and $t = 2.59$ s.
7. A certain wave has a wavelength of 25.0 cm, a frequency of 230 Hz, and an amplitude of 1.85 cm. Find (a) the wave number k and (b) the angular frequency ω. (c) Write the equation for this wave in the standard form $y = A \sin(kx - \omega t)$.

12.3 The Speed of a Transverse Wave on a String

8. A 60.0-cm guitar string has a mass of 1.40 g. If it is to play the note A at a frequency of 440 Hz, what must the tension be in the string? Assume that the wavelength of the note is twice the length of the string.
9. A 1.50-m length of wire with a mass of 0.035 kg is stretched between two points. Find the necessary tension in the wire such that the wave may travel from one end to another in a time of 0.0900 s.
10. A guitar string that has a mass per unit length of 2.33×10^{-3} kg/m is tightened to a tension of 655 N. What frequency will be heard if the string is 60.0 cm long? Is this a standard note or is it sharp or flat? (Remember that the wavelength of the note played is twice the length of the string.)

12.4 Reflection of a Wave at a Boundary

11. One end of a 100-cm wire of 3.45 g is welded to a 90.0-cm wire of 9.43 g. (a) If a wave moves along the first wire at a speed of 528 m/s, find its speed along the second wire. (b) If the wavelength on the first wire is 1.76 cm, find the wavelength of the wave on the second wire.



12. The first end of a combined string has a linear mass density of 4.20×10^{-3} kg/m, whereas the second end has a mass density of 10.5 kg/m. (a) If a 60.0-cm wave is to be sent along the first string at a speed of 8.56 m/s, what must the tension in the string be? (b) What is the wavelength of the reflected and transmitted wave?
13. The first end of a combined string has a linear mass density of 8.00 kg/m, whereas the second string has a density of 2.00 kg/m. If the speed of the wave in the first string is 10.0 m/s, find (a) the speed of the wave in the second string and (b) the tension in the string. (c) If a wave of length 60.0 cm is observed in the first string, find the wavelength and frequency of the wave in the second string.
14. The first end of a combined string has a linear mass density of 6.00 kg/m, whereas the second string has a density of 2.55 kg/m. The tension in the string is 350 N. If a vibration with a frequency of 20 vibrations is imparted to the first string, find the frequency, velocity, and wavelength of (a) the incident wave, (b) the reflected wave, and (c) the transmitted wave.

12.5 The Principle of Superposition

15. The following two waves interfere with each other:

$$y_1 = (10.8\text{ m})\sin[(0.654\text{ m}^{-1})x - (2.45\text{ rad/s})t]$$
$$y_2 = (6.73\text{ m})\sin[(0.893\text{ m}^{-1})x - (6.82\text{ rad/s})t]$$

Find the resultant displacement when $x = 0.782$ m and $t = 5.42$ s.

16. The following two waves combine:

$$y_1 = (10.8\text{ m})\sin[(0.654\text{ m}^{-1})x - (2.45\text{ rad/s})t]$$
$$y_2 = (10.8\text{ m})\sin[(0.654\text{ m}^{-1})x - (2.45\text{ rad/s})t - 0.834\text{ rad}]$$

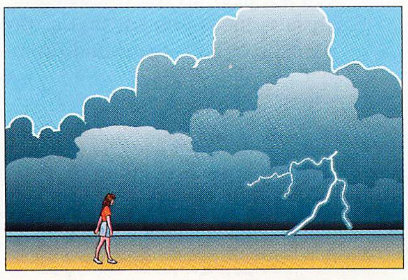
(a) Find the equation of the resultant wave. (b) Find the displacement of the resultant wave when $x = 0.895$ m and $t = 6.94$ s.

12.6 Standing Waves—The Vibrating String

17. The E string of a violin is vibrating at a fundamental frequency of 659 Hz. Find the wavelength and frequency of the third, fifth, and seventh harmonics. Let the length of the string be 60.0 cm.
18. A steel wire that is 1.45 m long and has a mass of 45 g is placed under a tension of 865 N. What is the frequency of its fifth harmonic?
19. A violin string plays a note at 440 Hz. What would the frequency of the wave on the string be if the tension in the string is (a) increased by 20.0% and (b) decreased by 20.0%?
20. A note is played on a guitar string 60.0 cm long at a frequency of 432 Hz. By how much should the string be shortened by pressing on it to play a note of 440 Hz?
21. A cello string, 75.0 cm long with a linear mass density of 7.25×10^{-3} kg/m, is to produce a fundamental frequency of 440 Hz. (a) What must be the tension in the string? (b) Find the frequency of the next three higher harmonics. (c) Find the wavelength of the fundamental and the next three higher harmonics.

12.7 Sound Waves

22. A sound wave in air has a velocity of 335 m/s. Find the temperature of the air.
23. A lightning flash is observed and 12 s later the associated thunder is heard. How far away is the lightning if the air temperature is 15.0 °C?



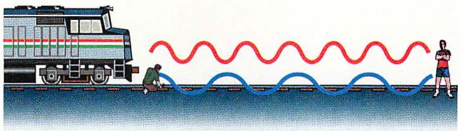
24. A soldier sees the flash from a cannon that is fired in the distance and 10 s later he hears the roar of the cannon. If the air temperature is 33 °C, how far away is the cannon?
25. A sound wave is sent to the bottom of the ocean by a ship in order to determine the depth of the ocean at that point. The sound wave returns to the boat in a time of 1.45 s. Find the depth of the ocean at this point. Use the bulk modulus of water to be 2.30×10^9 N/m^2 and the density of seawater to be 1.03×10^3 kg/m^3.
26. Find the speed of sound in aluminum, copper, and lead.
27. You are trying to design three pipes for a closed organ pipe system that will give the following notes with their corresponding fundamental frequencies, C = 261.7 Hz, D = 293.7 Hz, E = 329.7 Hz. Find the length of each pipe. Assume that the speed of sound in air is 343 m/s.
28. Repeat problem 27 for an open organ pipe.

12.8 The Doppler Effect

29. A train is moving at a speed of 90.0 m/s and emits a whistle of frequency 400.0 Hz. If the speed of sound is 343 m/s, find the frequency observed by an observer who is at rest (a) in advance of the moving source and (b) behind the moving source.
30. A stationary police car turns on a siren at a frequency of 300 Hz. If the speed of sound in air is 343 m/s find the observed frequency if (a) the observer is approaching the police car at 35.0 m/s and (b) the observer is receding from the police car at 35.0 m/s.
31. A police car traveling at 90.0 m/s, turns on a siren at a frequency of 350 Hz as it tries to overtake a gangster's car moving away from the police car at a speed of 85 m/s. If the speed of sound in air is 343 m/s find the frequency heard by the gangster.
32. Two trains are approaching each other, each at a speed of 100 m/s. They each emit a whistle at a frequency of 225 Hz. If the speed of sound in air is 343 m/s, find the frequency that each train engineer hears.
33. A train moving east at a velocity of 20 m/s emits a whistle at a frequency of 348 Hz. Another train, farther up the track and moving east at a velocity of 30 m/s, hears the whistle from the first train. If the speed of sound in air is 343 m/s, what is the frequency of the sound heard by the second train engineer?

Additional Problems

34. One end of a violin string is connected to an electrical vibrator of 120 Hz, whereas the other end passes over a pulley and supports a mass of 10.0 kg, as shown in figure 12.17. The string is 60.0 cm long and has a mass of 12.5 g. What is the wavelength and speed of the wave produced?
†35. Three pipes, the first of lead, the second of brass, and the third of aluminum, each 10.0 m long, are welded together. If the first pipe is struck with a hammer at its end, how long will it take for the sound to pass through the pipes?
†36. A sound wave of 200 Hz in a steel pipe is transmitted into water and then into air. Find the wavelength of the sound in each medium.
†37. A railroad worker hits a steel track with a hammer. The sound wave through the steel track reaches an observer and 3.00 s later the sound wave through the air also reaches the observer. If the air temperature is 22.0 °C, how far away is the worker?



38. A tuning fork of 512 Hz is set into vibration above a long vertical tube containing water. A standing wave is observed as a resonance between the original wave and the reflected wave. If the speed of sound in air is 343 m/s, how far below the top of the tube is the water level?
39. The intensity of an ordinary conversation is about 3×10^{-6} W/m^2. Find the intensity level of the sound.
40. An indoor rock concert has an intensity level of 70 dB. Find the intensity of the sound.
41. The intensity level of a 500 Hz sound from a television program is about 40 dB. If the speed of sound is 343 m/s, find the amplitude of the sound wave.
†42. The speed of high-performance aircraft is sometimes given in terms of Mach numbers, where a Mach number is the ratio of the speed of the aircraft to the speed of sound at that level. Thus, a plane traveling at a speed of 343 m/s at sea level where the temperature is 20.0 °C would be traveling at Mach 1. If the temperature of the atmosphere increased to 30.0 °C, and the aircraft is still moving at 343 m/s, what is its Mach number?

Interactive Tutorials

43. A tuning fork of frequency $f = 512$ Hz is set into vibration above a long vertical cylinder filled with water. As the water in the tube is lowered, resonance occurs between the initial wave traveling down the cylinder and the second wave that is reflected from the water surface below. Calculate (a) the wavelength λ of the sound wave in air and (b) the three resonance positions as measured from the top of the tube. The velocity of sound in air is $v = 343$ m/s.
44. The superposition of any two waves. Given the following two waves:

$$y_1 = A_1 \sin(k_1 x - \omega_1 t)$$
$$y_2 = A_2 \sin(k_2 x - \omega_2 t - \phi)$$

For each wave find (a) the wavelength λ, (b) the frequency f, (c) the period T, and (d) the velocity v. Since each wave is periodic in both space and time, (e) for the value $x = 2.00$ m plot each wave and the sum of the two waves as a function of time t. (f) For the time $t = 0.500$ s, plot each wave and the sum of the two waves as a function of the distance x. For the initial conditions take $A_1 = 3.50$ m, $k_1 = 0.55$ m^{-1}, $\omega_1 = 4.25$ rad/s, $A_2 = 4.85$ m, $k_2 = 0.85$ m^{-1}, $\omega_2 = 2.58$ rad/s, and $\phi = 0$. Then consider all the special cases listed in the tutorial itself.
45. A 60.0-cm string with a mass of 1.40 g is to produce a fundamental frequency of 440 Hz. Find (a) the tension in the string, (b) the frequency of the next four higher harmonics, and (c) the wavelength of the fundamental and the next four higher harmonics.
46. General purpose Doppler Effect Calculator. The Doppler Effect Calculator will calculate the observed frequency of a sound wave for the motion of the source or the observer, whether either or both are approaching or receding.