Wave Information

4a. *Students know* waves carry energy from one place to another.

Waves may transport energy through a vacuum or through matter. Light waves, for example, transport energy in both fashions, but sound waves and most other waves occur only in matter. However, even waves propagating through matter transport energy without any net movement of the matter, thus differing from other means of energy transport, such as convection, a waterfall, or even a thrown object.

4. b. *Students know* how to identify transverse and longitudinal waves in mechanical media, such as springs and ropes, and on the earth (seismic waves).

Waves that propagate in mechanical media are either longitudinal or transverse waves. The disturbance in longitudinal waves is parallel to the direction of propagation and causes compression and expansion (rarefaction) in the medium carrying the wave. The disturbance in transverse waves is perpendicular to the direction of propagation of the wave. Examples of longitudinal waves are sound waves and P-type earthquake waves. In transverse waves a conducting medium, or a test particle inserted in the wave, moves perpendicular to the direction in which the wave propagates. Examples of transverse waves are S-type earthquake waves and electromagnetic (or light) waves.

4. c. *Students know* how to solve problems involving wavelength, frequency, and wave speed.

All waves have a velocity **v** (propagation speed and direction), a property that represents the rate at which the wave travels. Only periodic, sustained waves can be easily characterized through the properties of wavelength and frequency. However, most real waves are *composite,* meaning they can be understood as the sum of a few or of many waveforms, each with an amplitude, a wavelength, and a frequency.

Wavelength λ is the distance between any two repeating points on a periodic wave (e.g., between two successive crests or troughs in a transverse wave or between adjacent compressions or expansions [rarefactions] in a longitudinal wave). Wavelength is measured in units of length.

Frequency f is the number of wavelengths that pass any point in space per second. A wave will make any particle it encounters move in regular cycles, and frequency is also the number of such cycles made per second and is often abbreviated as cycles per second. The unit of frequency is the inverse second (s^{-1})(1/s) $\frac{1}{s}$, a unit also called the hertz (Hz).

Periodic wave characteristics are related to each other. For example,

$v = f\lambda$.

4. d. *Students know* sound is a longitudinal wave whose speed depends on the properties of the medium in which it propagates.

Sound waves, sometimes called *acoustic waves,* are typically produced when a vibrating object is in contact with an elastic medium, which may be a solid, a liquid, or a gas. A sound wave is longitudinal, consisting of regions of high and low pressure (and therefore of compression and rarefaction) that propagate away from the source. (Note that sound cannot travel through a vacuum.) In perceiving sound, the human eardrum vibrates in response to the pattern of high and low pressure. This vibration is translated into a signal transmitted by the nervous system to the brain and interpreted by the brain as the familiar sensation of sound. Microphones similarly translate vibrations into electrical current. Sound speakers reverse the process and change electrical signals into vibrational motion, recreating sound waves.

Wave Information

An acoustic wave attenuates, or reduces in amplitude, with distance because the energy in the wave is typically spread over a spherical shell of ever-increasing area and because interparticle friction in the medium gradually transforms the wave's energy into heat. The speed of sound varies from one medium to another, depending primarily on the density and elastic properties of the medium. The speed of sound is typically greater in solid and liquid media than it is in gases.

4. e. ***Students know*** radio waves, light, and X-rays are different wavelength bands in the spectrum of electromagnetic waves whose speed in a vacuum is approximately 3×10^8 m/s (186,000 miles/second).

Electromagnetic waves consist of changing electric and magnetic fields. Because these fields are always perpendicular to the direction in which a wave moves, an electromagnetic wave is a transverse wave. The electric and magnetic fields are also always perpendicular to each other. Concepts of electric and magnetic fields are introduced in Standard Set 5, "Electric and Magnetic Phenomena," in this section. The range of wavelengths for electromagnetic waves is very large, from less than nanometers (nm) for X-rays to more than kilometers for radio waves. The human eye senses only the narrow range of the electromagnetic spectrum from 400 nm to 700 nm. This range generates the sensation of the rainbow of colors from violet through the respective colors to red. In a vacuum all electromagnetic waves travel at the same speed of 3×10^8 m/s (or 186,000 miles per second). In a medium the speed of an electromagnetic wave depends on the medium's properties and on the frequency of the wave. The ratio of the speed of a wave of a given frequency in a vacuum to its speed in a medium is called that medium's *index of refraction.* For visible light in water, this number is approximately 1.33.

4. f. ***Students know*** how to identify the characteristic properties of waves: interference (beats), diffraction, refraction, Doppler effect, and polarization.

A characteristic and unique property of waves is that two or more can occupy the same region of space at the same time. At a particular instant, the crest of one wave can overlap the crest of another, giving a larger displacement of the medium from its condition of equilibrium *(constructive interference);* or the crest of one wave can overlap the trough of another, giving a smaller displacement *(destructive interference).* The effect of two or more waves on a test particle is that the net force on the particle is the algebraic sum of the forces exerted by the various waves acting at that point.

If two overlapping waves traveling in opposite directions have the same frequency, the result is a standing wave. There is a persistent pattern of having no displacement in some places, called *nulls* or *nodes,* and large, oscillating displacements in others, called *maxima* or *antinodes.* If two overlapping waves have nearly the same frequency, a node will slowly change to a maximum and back to a node, and a maximum will slowly change to a node and back to a maximum. For sound waves this periodic change leads to audible, periodic changes from loud to soft, known as *beats.*

Diffraction describes the constructive and destructive patterns of waves created at the edges of objects. Diffraction can cause waves to bend around an obstacle or to spread as they pass through an aperture. The nature of the diffraction patterns of a wave interacting with an object depends on the ratio of the size of the obstacle to the wavelength. If this ratio is large, the shadows are nearly sharp; if it is small, the shadows may be fuzzy or not appear at all. Therefore, a hand can block a ray of light, whose average wavelength is about 500 nm, but cannot block an audible sound, whose average wavelength is about 100 cm. The bending

Wave Information

of water waves around a post and the diffraction of light waves when passing through a slit in a screen are examples of diffraction patterns.

Refraction describes a change in the direction of a wave that occurs when the wave encounters a boundary between one medium and another provided that the media have either different wave velocities or indexes of refraction and provided that the wave arrives at some angle to the boundary other than perpendicular. At a sharp boundary, the change in direction is abrupt; however, if the transition from one medium to another is gradual, so that the velocity of the wave changes slowly, then the change in the wave's direction is also gradual. Therefore, a ray of light that passes obliquely from air to water changes its direction at the water's surface, but a ray that travels through air that has a temperature gradient will follow a bent path. A ray of light passing through a saturated solution of sugar (sucrose) and water, which has an index of refraction of 1.49, will not change direction appreciably on entering a colorless, transparent piece of quartz submersed in the solution because the quartz has an almost identical index of 1.51. The match in indexes makes the quartz nearly invisible in the sugar-water solution.

Another interesting phenomenon, the *Doppler effect,* accounts for the shift in the frequency of a wave when a wave source and an observer are in motion relative to each other compared with when they are at relative rest. This effect is most easily understood when the source is at rest in some medium and the observer is approaching the source at constant speed. The interval in time between each successive wave crest is shorter than it would be if the observer were at rest, and so the frequency observed is larger. The general rule, for observers moving at velocities much less than the velocity of the wave in its medium, is that the change in frequency depends only on the velocity of the observer relative to the source. Therefore, the shriek of an ambulance siren has a higher pitch when the source approaches and a lower pitch when the source recedes. For an observer following the ambulance at the same speed, the siren would sound normal. Similar shifts are observed for visible light.

Polarization is a property of light and of other transverse waves. *Transverse waves* are those in which the displacement of a test particle is always perpendicular to the direction in which the wave travels. When that displacement is always parallel to a particular direction, the wave is said to be *(linearly) polarized.* A ray of light emitted from a hot object, like a lamp filament or the sun, is unpolarized; such a ray consists of many component waves overlapped so that there is no special direction perpendicular to the ray in which a test particle is favored to move. The components of an unpolarized ray can be sorted to select such a special direction and so make one or more polarized rays. An unpolarized ray that is partly reflected and partly transmitted by an angled sheet of glass is split into rays that are polarized; an unpolarized ray can become polarized by going through a material that allows only waves corresponding to one special direction to pass through. Polarized sunglasses and stretched cellophane wrap are examples of polarizing materials.