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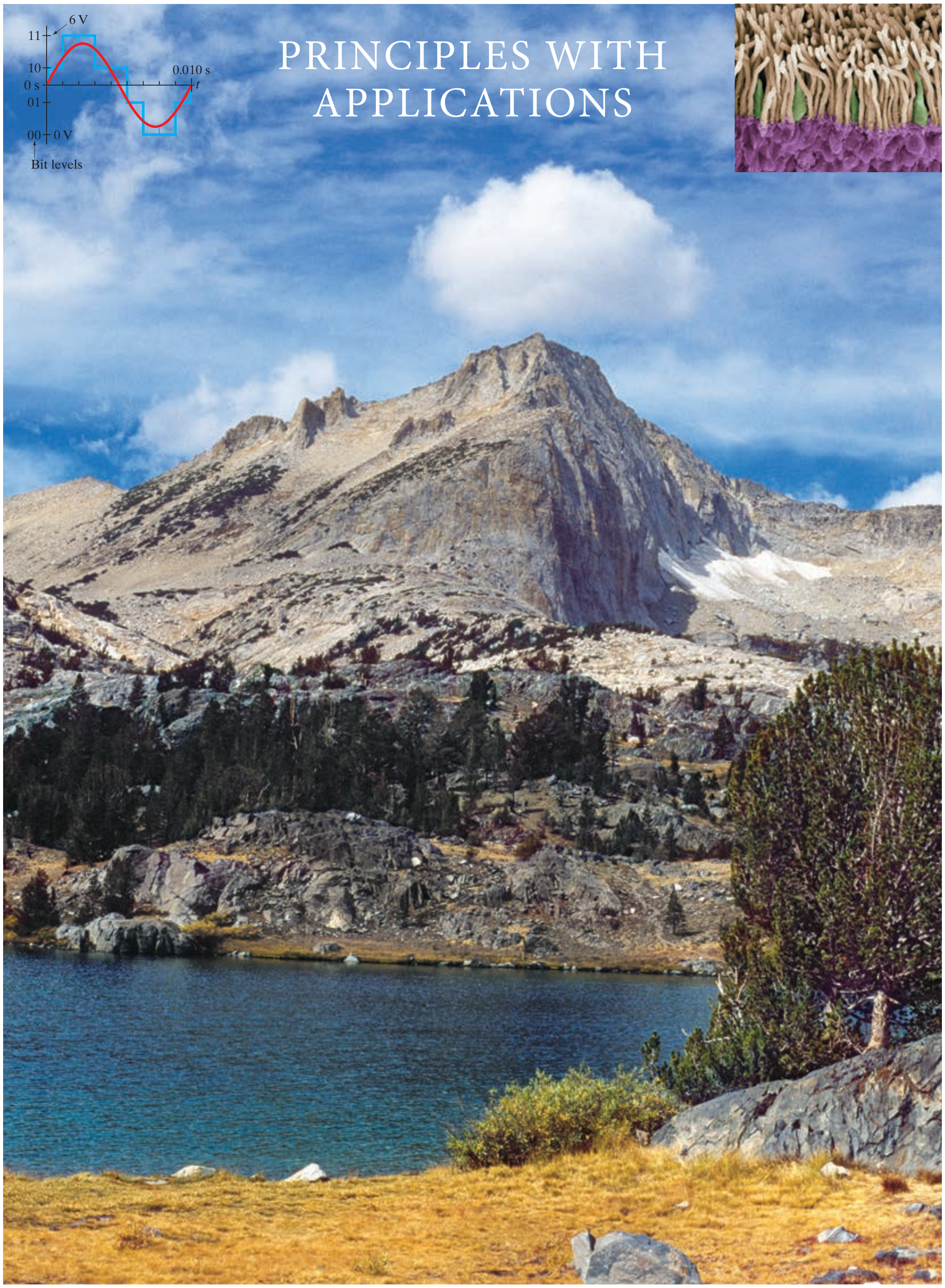

DOUGLAS C.

GIANCOLI

SEVENTH EDITION

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PRINCIPLES WITH APPLICATIONS

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EXAMPLE 11–9 **Measuring g.** A geologist uses a simple pendulum that has a length of 37.10 cm and a frequency of 0.8190 Hz at a particular location on the Earth. What is the acceleration due to gravity at this location?

APPROACH We can use the length ℓ and frequency f of the pendulum in Eq. 11–11b, which contains our unknown, g.

SOLUTION We solve Eq. 11–11b for g and obtain

$$g = (2\pi f)^2\ell = (2\pi)^2\left(0.8190\ \mathrm{s}^{-1}\right)^2(0.3710\ \mathrm{m}) = 9.824\ \mathrm{m/s^2}.$$

11–5 Damped Harmonic Motion

The amplitude of any real oscillating spring or swinging pendulum slowly decreases in time until the oscillations stop altogether. Figure 11–14 shows a typical graph of the displacement as a function of time. This is called **damped harmonic motion**. The damping† is generally due to the resistance of air and to internal friction within the oscillating system. The energy that is dissipated to thermal energy results in a decreased amplitude of oscillation.

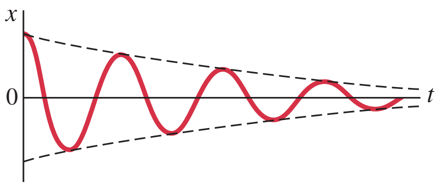
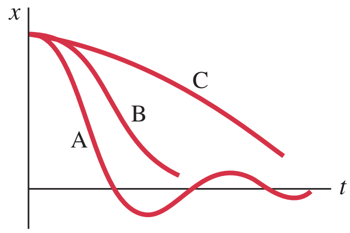


FIGURE 11–14 Damped harmonic motion.

Since natural oscillating systems are damped in general, why do we even talk about (undamped) simple harmonic motion? The answer is that SHM is much easier to deal with mathematically. And if the damping is not large, the oscillations can be thought of as simple harmonic motion on which the damping is superposed, as represented by the dashed curves in Fig. 11–14. Although damping does alter the frequency of vibration, the effect can be small if the damping is small; then Eqs. 11–6 can still be useful approximations.

Sometimes the damping is so large, however, that the motion no longer resembles simple harmonic motion. Three common cases of *heavily damped* systems are shown in Fig. 11–15. Curve A represents an **underdamped** situation, in which the system makes several oscillations before coming to rest; it corresponds to a more heavily damped version of Fig. 11–14. Curve C represents the **overdamped** situation, when the damping is so large that there is no oscillation and the system takes a long time to come to rest (equilibrium). Curve B represents **critical damping**: in this case the displacement reaches zero in the shortest time. These terms all derive from the use of practical damped systems such as door-closing mechanisms and **shock absorbers** in a car (Fig. 11–16), which are usually designed to give critical damping. But as they wear out, underdamping occurs: the door of a room slams and a car bounces up and down several times when it hits a bump.

FIGURE 11–15 Graphs that represent (A) underdamped, (B) critically damped, and (C) overdamped oscillatory motion.



In many systems, the oscillatory motion is what counts, as in clocks and musical instruments, and damping may need to be minimized. In other systems, oscillations are the problem, such as a car's springs, so a proper amount of damping (i.e., critical) is desired. Well-designed damping is needed for all kinds of applications. Large buildings, especially in California, are now built (or retrofitted) with huge dampers to reduce possible earthquake damage (Fig. 11–17).

PHYSICS APPLIED
Shock absorbers and building dampers

†To "damp" means to diminish, restrain, or extinguish, as to "dampen one's spirits."

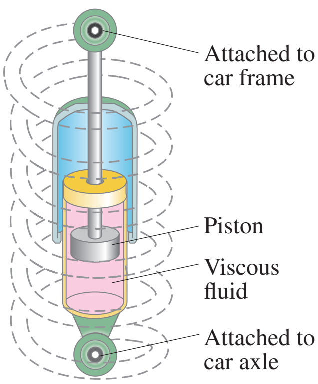


FIGURE 11–16 Automobile spring and shock absorber provide damping so that a car won't bounce up and down so much.

FIGURE 11–17 These huge dampers placed in a building look a lot like huge automobile shock absorbers, and they serve a similar purpose—to reduce the amplitude and the acceleration of movement when the shock of an earthquake hits.

11–6 Forced Oscillations; Resonance

When an oscillating system is set into motion, it oscillates at its natural frequency (Eqs. 11–6b and 11–11b). However, a system may have an external force applied to it that has its own particular frequency. Then we have a **forced oscillation**.

For example, we might pull the mass on the spring of Fig. 11–1 back and forth at an externally applied frequency f. The mass then oscillates at the external frequency f of the external force, even if this frequency is different from the **natural frequency** of the spring, which we will now denote by f_0, where (see Eq. 11–6b)

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}.$$

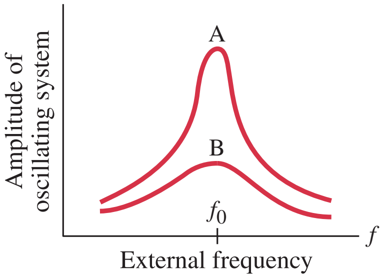


FIGURE 11–18 Amplitude as a function of driving frequency f, showing resonance for lightly damped (A) and heavily damped (B) systems.

For a forced oscillation with only light damping, the amplitude of oscillation is found to depend on the difference between f and f_0, and is a maximum when the frequency of the external force equals the natural frequency of the system—that is, when $f = f_0$. The amplitude is plotted in Fig. 11–18 as a function of the external frequency f. Curve A represents light damping and curve B heavy damping. When the external driving frequency f is near the natural frequency, $f \approx f_0$, the amplitude can become large if the damping is small. This effect of increased amplitude at $f = f_0$ is known as **resonance**. The natural oscillation frequency f_0 of a system is also called its **resonant frequency**.

PHYSICS APPLIED
Child on a swing

A simple illustration of resonance is pushing a child on a swing. A swing, like any pendulum, has a natural frequency of oscillation. If you push on the swing at a random frequency, the swing bounces around and reaches no great amplitude. But if you push with a frequency equal to the natural frequency of the swing, the amplitude increases greatly. At resonance, relatively little effort is required to obtain and maintain a large amplitude.

PHYSICS APPLIED
Shattering glass via resonance

The great tenor Enrico Caruso was said to be able to shatter a crystal goblet by singing a note of just the right frequency at full voice. This is an example of resonance, for the sound waves emitted by the voice act as a forced oscillation on the glass. At resonance, the resulting oscillation of the goblet may be large enough in amplitude that the glass exceeds its elastic limit and breaks (Fig. 11–19).

FIGURE 11–19 This goblet breaks as it vibrates in resonance to a trumpet call.

PHYSICS APPLIED
Resonant collapse

Since material objects are, in general, elastic, resonance is an important phenomenon in a variety of situations. It is particularly important in construction, although the effects are not always foreseen. For example, it has been reported that a railway bridge collapsed because a nick in one of the wheels of a crossing train set up a resonant oscillation in the bridge. Marching soldiers break step when crossing a bridge to avoid the possibility that their rhythmic march might match a resonant frequency of the bridge. The famous collapse of the Tacoma Narrows Bridge (Fig. 11–20a) in 1940 occurred as a result of strong gusting winds driving the span into large-amplitude oscillatory motion. Bridges and tall buildings are now designed with more inherent damping. The Oakland freeway collapse in the 1989 California earthquake (Fig. 11–20b) involved resonant oscillation of a section built on mudfill that readily transmitted that frequency.

Resonance can be very useful, too, and we will meet important examples later, such as in musical instruments and tuning a radio. We will also see that vibrating objects often have not one, but many resonant frequencies.

FIGURE 11–20 (a) Large-amplitude oscillations of the Tacoma Narrows Bridge, due to gusty winds, led to its collapse (November 7, 1940). (b) Collapse of a freeway in California, due to the 1989 earthquake.

(a)


(b)

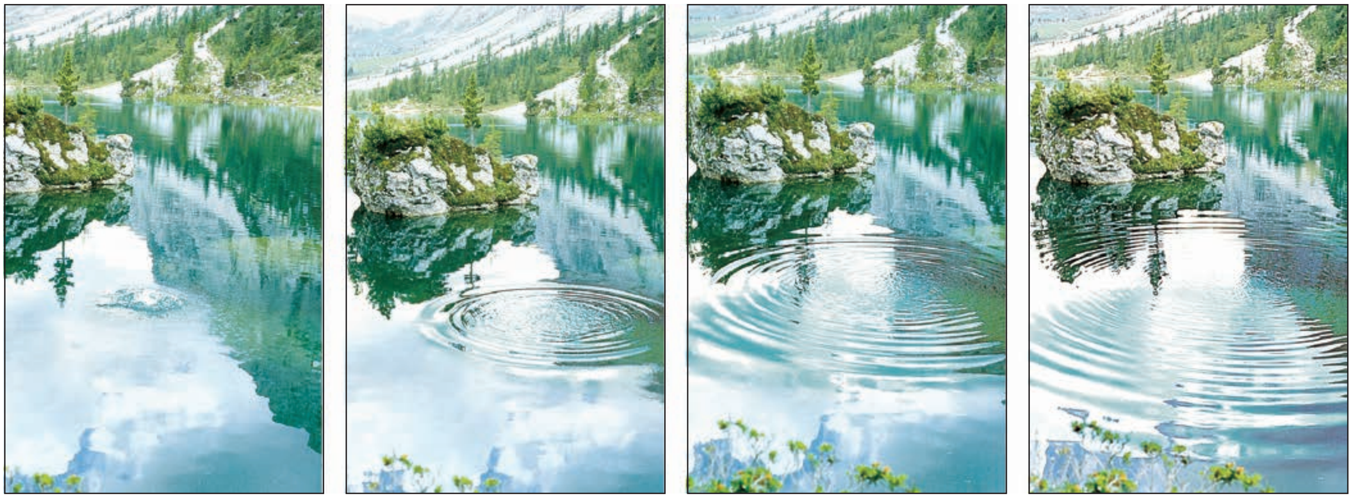



FIGURE 11–21 Water waves spreading outward from a source. In this case the source is a small spot of water oscillating up and down briefly where a rock hit (left photo).

11–7 Wave Motion

When you throw a stone into a lake or pool of water, circular waves form and move outward, Fig. 11–21. Waves will also travel along a rope that is stretched out straight on a table if you vibrate one end back and forth as shown in Fig. 11–22. Water waves and waves on a rope or cord are two common examples of **mechanical waves**, which propagate as oscillations of matter. We will discuss other kinds of waves in later Chapters, including electromagnetic waves and light.

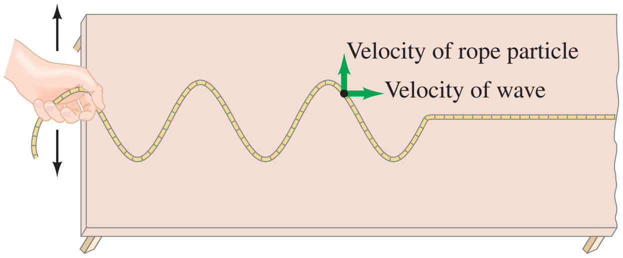


FIGURE 11–22 Wave traveling on a rope or cord. The wave travels to the right along the rope. Particles of the rope oscillate back and forth on the tabletop.

If you have ever watched ocean waves moving toward shore before they break, you may have wondered if the waves were carrying water from far out at sea onto the beach. They don't.[†] Water waves move with a recognizable velocity. But each particle (or molecule) of the water itself merely oscillates about an equilibrium point. This is clearly demonstrated by observing leaves on a pond as waves move by. The leaves (or a cork) are not carried forward by the waves, but oscillate more or less up and down about an equilibrium point because this is the motion of the water itself.

CONCEPTUAL EXAMPLE 11–10 **Wave vs. particle velocity.** Is the velocity of a wave moving along a rope the same as the velocity of a particle of the rope? See Fig. 11–22.

RESPONSE No. The two velocities are different, both in magnitude and direction. The wave on the rope of Fig. 11–22 moves to the right along the tabletop, but each piece of the rope only vibrates to and fro, perpendicular to the traveling wave. (The rope clearly does not travel in the direction that the wave on it does.)

Waves can move over large distances, but the medium (the water or the rope) itself has only a limited movement, oscillating about an equilibrium point as in simple harmonic motion. Thus, although a wave is not itself matter, the wave pattern can travel in matter. A wave consists of oscillations that move without carrying matter with them.

[†] Do not be confused by the "breaking" of ocean waves, which occurs when a wave interacts with the ground in shallow water and hence is no longer a simple wave.

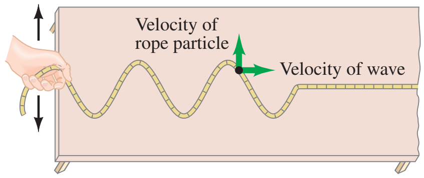
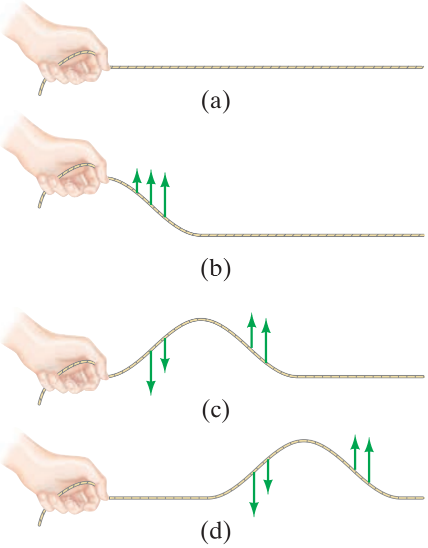


FIGURE 11–22 (Repeated.) Wave traveling on a rope or cord. The wave travels to the right along the rope. Particles of the rope oscillate back and forth on the tabletop.

Waves carry energy from one place to another. Energy is given to a water wave, for example, by a rock thrown into the water, or by wind far out at sea. The energy is transported by waves to the shore. The oscillating hand in Fig. 11–22 transfers energy to the rope, and that energy is transported down the rope and can be transferred to an object at the other end. All forms of traveling waves transport energy.

EXERCISE G Return to Chapter-Opening Question 2, page 292, and answer it again now. Try to explain why you may have answered differently the first time.

FIGURE 11–23 A wave pulse is generated by a hand holding the end of a cord and moving up and down once. Motion of the wave pulse is to the right. Arrows indicate velocity of cord particles.



Let us look more closely at how a wave is formed and how it comes to "travel." We first look at a single wave bump, or **pulse**. A single pulse can be formed on a cord by a quick up-and-down motion of the hand, Fig. 11–23. The hand pulls up on one end of the cord. Because the end section is attached to adjacent sections, these also feel an upward force and they too begin to move upward. As each succeeding section of cord moves upward, the wave crest moves outward along the cord. Meanwhile, the end section of cord has been returned to its original position by the hand. As each succeeding section of cord reaches its peak position, it too is pulled back down again by tension from the adjacent section of cord. Thus the source of a traveling wave pulse is a disturbance (or vibration), and cohesive forces between adjacent sections of cord cause the pulse to travel. Waves in other media are created and propagate outward in a similar fashion. A dramatic example of a wave pulse is a tsunami or tidal wave that is created by an earthquake in the Earth's crust under the ocean. The bang you hear when a door slams is a sound wave pulse.

A **continuous** or **periodic wave**, such as that shown in Fig. 11–22, has as its source a disturbance that is continuous and oscillating; that is, the source is a *vibration* or *oscillation*. In Fig. 11–22, a hand oscillates one end of the rope. Water waves may be produced by any vibrating object at the surface, such as your hand; or the water itself is made to vibrate when wind blows across it or a rock is thrown into it. A vibrating tuning fork or drum membrane gives rise to sound waves in air. We will see later that oscillating electric charges give rise to light waves. Indeed, almost any vibrating object sends out waves.

The source of any wave, then, is a vibration. And it is a *vibration* that propagates outward and thus constitutes the wave. If the source vibrates sinusoidally in SHM, then the wave itself—if the medium is elastic—will have a sinusoidal shape both in space and in time. (1) In space: if you take a picture of the wave in space at a given instant of time, the wave will have the shape of a sine or cosine as a function of position. (2) In time: if you look at the motion of the medium at one place over a long period of time—for example, if you look between two closely spaced posts of a pier or out of a ship's porthole as water waves pass by—the up-and-down motion of that small segment of water will be simple harmonic motion. The water moves up and down sinusoidally in time.

Some of the important quantities used to describe a periodic sinusoidal wave are shown in Fig. 11–24. The high points on a wave are called *crests*; the low points, *troughs*. The **amplitude**, A, is the maximum height of a crest, or depth of a trough, relative to the normal (or equilibrium) level. The total swing from a crest to a trough is $2A$ (twice the amplitude). The distance between two successive crests is the **wavelength**, λ (the Greek letter lambda). The wavelength is also equal to the distance between *any* two successive identical points on the wave. The **frequency**, f, is the number of crests—or complete cycles—that pass a given point per unit time. The **period**, T, equals $1/f$ and is the time elapsed between two successive crests passing by the same point in space.

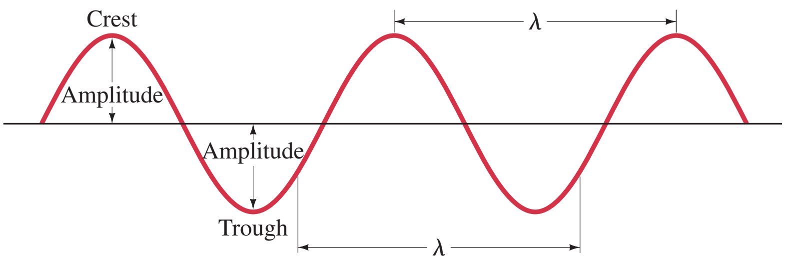


FIGURE 11–24 Characteristics of a single-frequency continuous wave moving through space.

The **wave speed**, v, is the speed at which wave crests (or any other fixed point on the wave shape) move forward. The wave speed must be distinguished from the speed of a particle of the medium itself as we saw in Example 11–10.

A wave crest travels a distance of one wavelength, λ, in a time equal to one period, T. Thus the wave speed is $v = \lambda/T$. Then, since $1/T = f$,

$$v = \lambda f. \tag{11–12}$$

For example, suppose a wave has a wavelength of 5 m and a frequency of 3 Hz. Since three crests pass a given point per second, and the crests are 5 m apart, the first crest (or any other part of the wave) must travel a distance of 15 m during the 1 s. So the wave speed is 15 m/s.

EXERCISE H You notice a water wave pass by the end of a pier, with about 0.5 s between crests. Therefore (*a*) the frequency is 0.5 Hz; (*b*) the velocity is 0.5 m/s; (*c*) the wavelength is 0.5 m; (*d*) the period is 0.5 s.

11–8 Types of Waves and Their Speeds: Transverse and Longitudinal

When a wave travels down a cord—say, from left to right as in Fig. 11–22—the particles of the cord vibrate back and forth in a direction transverse (that is, perpendicular) to the motion of the wave itself. Such a wave is called a **transverse wave** (Fig. 11–25a). There exists another type of wave known as a **longitudinal wave**. In a longitudinal wave, the vibration of the particles of the medium is *along* the direction of the wave's motion. Longitudinal waves are readily formed on a stretched spring or Slinky by alternately compressing and expanding one end. This is shown in Fig. 11–25b, and can be compared to the transverse wave in Fig. 11–25a. A series of compressions and expansions travel along the spring. The *compressions* are those areas where the coils are momentarily close together. *Expansions* (sometimes called *rarefactions*) are regions where the coils are momentarily far apart. Compressions and expansions correspond to the crests and troughs of a transverse wave.

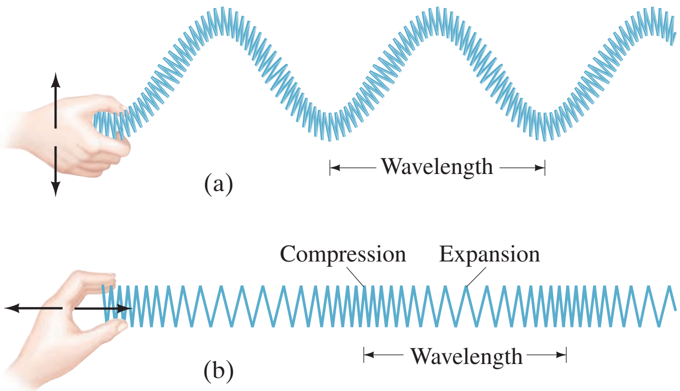


FIGURE 11–25 (a) Transverse wave; (b) longitudinal wave.

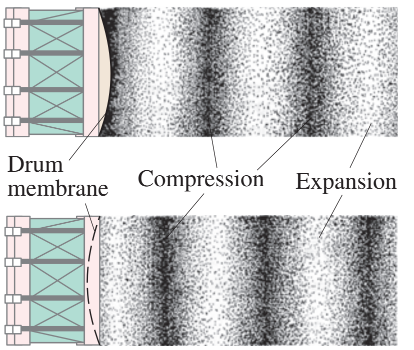


FIGURE 11–26 Production of a sound wave, which is longitudinal, shown at two moments in time about a half period $\left(\frac{1}{2}T\right)$ apart.

An important example of a longitudinal wave is a sound wave in air. A vibrating drumhead, for instance, alternately compresses and expands the air in contact with it, producing a longitudinal wave that travels outward in the air, as shown in Fig. 11–26.

As in the case of transverse waves, each section of the medium in which a longitudinal wave passes oscillates over a very small distance, whereas the wave itself can travel large distances. Wavelength, frequency, and wave speed all have meaning for a longitudinal wave. The wavelength is the distance between successive compressions (or between successive expansions), and frequency is the number of compressions that pass a given point per second. The wave speed is the speed with which each compression appears to move; it is equal to the product of wavelength and frequency, $v = \lambda f$ (Eq. 11–12).

A longitudinal wave can be represented graphically by plotting the density of air molecules (or coils of a Slinky) versus position at a given instant, as shown in Fig. 11–27. Such a graphical representation makes it easy to illustrate what is happening. Note that the graph looks much like a transverse wave.

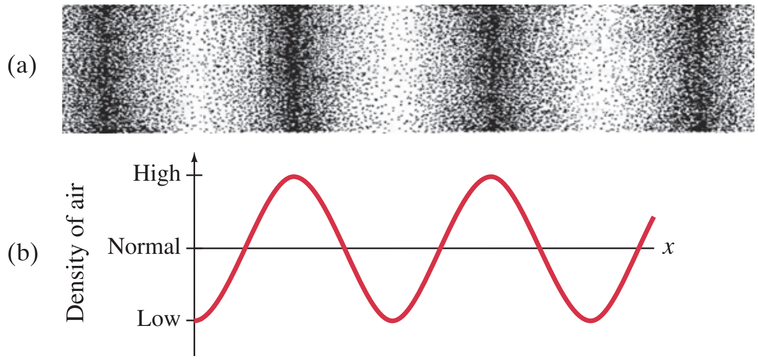


FIGURE 11–27 (a) A longitudinal wave in air, with (b) its graphical representation at a particular instant in time.

Speed of Transverse Waves

The speed of a wave depends on the properties of the medium in which it travels. The speed of a transverse wave on a stretched string or cord, for example, depends on the tension in the cord, F_T, and on the mass per unit length of the cord, μ (the Greek letter mu). If m is the mass of a length ℓ of wire, $\mu = m/\ell$. For waves of small amplitude, the wave speed is

$$v = \sqrt{\frac{F_T}{\mu}}. \qquad \left[\begin{array}{l}\text{transverse wave}\\ \text{on a cord}\end{array}\right] \qquad \textbf{(11–13)}$$

This formula makes sense qualitatively on the basis of Newtonian mechanics. That is, we do expect the tension to be in the numerator and the mass per unit length in the denominator. Why? Because when the tension is greater, we expect the speed to be greater since each segment of cord is in tighter contact with its neighbor. Also, the greater the mass per unit length, the more inertia the cord has and the more slowly the wave would be expected to propagate.

EXAMPLE 11–11 **Wave along a wire.** A wave whose wavelength is 0.30 m is traveling down a 300-m-long wire whose total mass is 15 kg. If the wire is under a tension of 1000 N, what are the speed and frequency of this wave?

APPROACH We assume the velocity of this wave on a wire is given by Eq. 11–13. We get the frequency from Eq. 11–12, $f = v/\lambda$.

SOLUTION From Eq. 11–13, the velocity is

$$v = \sqrt{\frac{1000\text{ N}}{(15\text{ kg})/(300\text{ m})}} = \sqrt{\frac{1000\text{ N}}{(0.050\text{ kg/m})}} = 140\text{ m/s}.$$

The frequency is

$$f = \frac{v}{\lambda} = \frac{140\text{ m/s}}{0.30\text{ m}} = 470\text{ Hz}.$$

NOTE A higher tension would increase both v and f, whereas a thicker, denser wire would reduce v and f.

Speed of Longitudinal Waves

The speed of a longitudinal wave has a form similar to that for a transverse wave on a cord (Eq. 11–13); that is,

$$v = \sqrt{\frac{\text{elastic force factor}}{\text{inertia factor}}}.$$

In particular, for a longitudinal wave traveling down a long solid rod,

$$v = \sqrt{\frac{E}{\rho}}, \qquad \left[\begin{array}{l}\text{longitudinal wave}\\ \text{in a long rod}\end{array}\right] \qquad \textbf{(11–14a)}$$

where E is the elastic modulus (Section 9–5) of the material and ρ is its density.