CHAPTER 6

Waves in Matter

Our concern until now has been with simple and complex vibrations that stayed at one place and didn't travel. Many vibrations, including those we hear, travel or propagate as waves from a vibrating source to other places. A **wave** is a disturbance traveling outward from a vibrating source. A **medium** is the substance or material through which a wave travels. A wave may carry energy from one place to another, but a wave does not carry the medium in which it travels from one place to another. We can understand this by imagining flipping a rope or dropping a rock in a pond of water. We can visualize the disturbance traveling in the medium (rope or water), but the medium itself does not travel from one place to another. Waves travel with certain speeds governed by the medium in which they travel. Periodic waves have a well-defined frequency and wavelength. In this chapter we will consider how waves travel through solids, liquids, and gases. We will consider how these waves can be represented graphically. We will also consider the relationships among frequency, wavelength, and wave speed.

6.1 Models of Matter and Wave Propagation

An **impulse** or **pulse** is a burst of energy or a disturbance of short time duration. An impulsive wave is produced when a medium is abruptly or impulsively excited such as in plucking a guitar string or striking a drumhead. A **continuous wave** is a disturbance of continuing duration. A continuous wave is produced when a medium is continuously excited such as in bowing a violin string, blowing a clarinet, speaking, and so on. Both wave types are useful for studying how waves travel in matter.

It is often useful to excite a system—room, string, drumhead—and observe how it responds to the excitation. In this manner some of the interesting features of the system can be observed. Suppose, for example, that we strike a piece of iron once with a hammer; that is, we impulsively excite the iron. If it were possible to observe the individual atoms of the iron we would notice that the impulse with which we excited the system does not remain stationary but travels outward from the point of impact. To learn how the impulse travels we must consider the atomic structure of the solid. Figure 6.1 is a two-dimensional representation of the atoms in a solid. (In an actual solid the structure would be three dimensional.) The structure is characterized by an orderly arrangement of atoms which are held in place by electrical forces, represented by springs. The electrical force law governs the forces that bind together the atoms or molecules in a solid. Each atom is composed of a positively charged nucleus surrounded by negatively charged electrons. The positively charged nuclei of different atoms repel each other, but they are attracted by the negatively charged electrons located between them and thus are also bound to each other. The electrical binding forces are analogous to springs, as shown in the diagram.

When one molecule of a solid is displaced from its normal position the forces represented by the spring tend to return it to its normal position. Suppose, for example, that one molecule is displaced to the right. The "spring" to the right of the molecule is compressed while the "spring" to the left is expanded. There are, then, two forces acting to

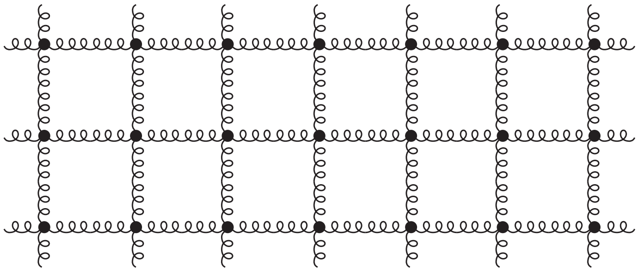

Figure 6.1 *Two-dimensional diagram of molecules in a solid. The electrical binding forces are represented by springs.*

return the molecule to its normal position: the force from the compressed "spring," which tends to push the molecule back into place, and the force from the expanded "spring," which tends to pull the molecule back into place. Each molecule has an equilibrium position and may undergo back-and-forth excursions, or oscillations, in a manner quite similar to that of a mass on a spring. When the system is disturbed by an impulse from a hammer blow, several molecules are displaced and several "springs" are correspondingly compressed and expanded. As the forces move the molecules back toward their equilibrium positions, the molecules oscillate for a short time. Because each end of a "spring" is attached to a molecule and each molecule has several "springs" attached, displacement of one molecule will soon cause more molecules, which are attached to the other ends of the "springs," to be displaced. This process will continue from each molecule to its neighbors and the impulse, in addition to causing oscillation at one point in the solid, will cause a disturbance that travels throughout the solid.

Disturbances may also propagate through liquids and gases. The propagation mechanism for liquids and gases is somewhat different than it is for solids. Figure 6.2 is a two-dimensional representation of the molecules in a gas. Again, there are electrical forces represented by the springs, but the forces are not strong enough to keep the molecules attached in an orderly arrangement. The forces act only when the molecules are very close, as in a collision. For this reason the "springs" are shown attached to only one molecule. When two molecules get sufficiently close, the "springs" cause the molecules to repel; otherwise they do not affect each other. Suppose that a piston gives an impulse to the molecules at the left in the figure and causes them to move toward the right. These molecules will collide with and push neighboring molecules to the right and in turn be stopped in the collision. The process will continue through the entire region where the gas is enclosed, so an impulse can be propagated in a gas as well as in a solid or liquid.

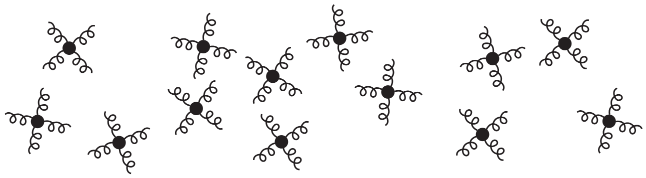

Figure 6.2 *Two-dimensional diagram of molecules in a gas. The electrical forces of repulsion are represented by springs.*

The structural models of solids and gases given here are greatly simplified to show some of the more salient properties of wave propagation and its dependence on the properties of the matter through which the wave passes. We view solids as composed of closely packed molecules bound in place, liquids as closely packed molecules that are free to slide past each other, and gases as widely separated molecules that are in a constant state of random motion and collision with one another. The strong intermolecular forces ("springs") of solids cause a solid to maintain its shape, whereas liquids and gases typically take on the shape of their containers because of the weaker intermolecular binding forces.

6.2 Wave Types

Often, a continuously recurring vibration, rather than a single impulse, disturbs a material medium. The medium is then disturbed in a continuous manner and the disturbance travels as a continuous wave. The particles which compose the medium vibrate or "wave" back and forth as the disturbance travels through the medium.

When a rope is pulled tight and flipped, a disturbance is caused which travels along the rope. The individual parts of the rope move up and down as the disturbance (wave) passes. A wave of this type, in which the particles of the medium move transverse (perpendicular) to the direction in which the wave travels, is called a **transverse wave** or **shear wave**. If the molecules at the left end of the solid represented in Figure 6.1 are "jiggled" up and down (as shown in Figure 6.3a), the disturbance travels through the solid toward the right because the molecules are bound to each other. If one molecule of a gas at the left (as in Figure 6.2) were jiggled up and down, the disturbance would not travel to the right because the molecules are not bound together. Transverse waves can propagate in solids but not in gases and liquids because gases and liquids have no restoring force which would return a displaced molecule to its former position.

However, if the left wall of a gas container is jiggled (as in Figure 6.3b), this disturbance does travel through the gas. The wall bumps the nearest molecules, exerting a force which is propagated to other molecules. The forces between molecules occur only during collisions, at which time the "springs" are momentarily compressed. The disturbance

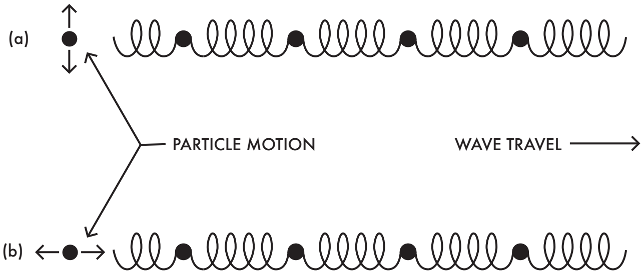

Figure 6.3 *Two wave types: (a) transverse and (b) longitudinal.*

consists of molecules shaking to and fro along the direction the disturbance propagates, and spreads because the jiggling molecules bump into their neighbors. A wave in which the particles of the medium move parallel to the direction the wave travels is called a **longitudinal wave** or **compressional wave**. If a solid is jiggled in and out on its left side this back and forth disturbance can also travel along the solid to the right. Longitudinal waves can therefore propagate in solids, liquids, and gases.

Finally, there are **surface waves**, such as those traveling on the surface of a pond or on the ocean surface. These waves involve both transverse and longitudinal motions of the liquid medium. They are possible because the surface tension of the liquid provides the restoring force necessary to transmit a transverse disturbance on the surface of the liquid.

6.3 Representation of Waves

Waves on a string are transverse displacement waves; the particles of the string move up and down as the waves travel from left to right (see Figure 6.4). Sound waves in air are longitudinal waves; the air molecules are displaced back and forth in the direction of wave travel as a sound wave passes. For convenience, however, sound waves in air are described in terms of pressure changes produced rather than the displacement of the air molecules.

When the air molecules are forced closer together than normal by the impinging disturbance, the resulting excess of air molecules produces a slight increase of pressure called a **condensation**. An increase of pressure is relative to and above normal atmospheric pressure. When the air molecules are pulled slightly farther apart than normal there is a slight decrease in pressure, called a **rarefaction**. We will refer to pressures greater than atmospheric pressure as positive (+) pressures and pressures less than atmospheric as negative (-) pressures.

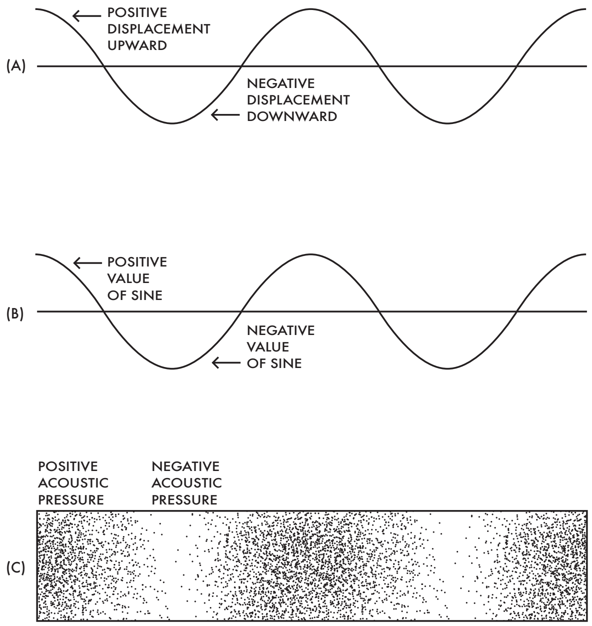

Figure 6.4 *representations of waves: (A) displacement waves on a string, (B) sinusoid used to represent either displacement waves or pressure waves, and (C) pressure waves in a tube. Darker regions show higher molecular density.*

Transverse waves on a string can be represented by sinusoids if we adopt the convention that the positive and negative portions of the sinusoid represent the upward and downward displacement of the string, respectively. Likewise, the longitudinal pressure waves in a tube of air can be represented by sinusoids if we adopt the convention that the positive part of the sinusoid represents pressure above atmospheric (+) and the negative part represents pressure below atmospheric (-). Imagine a vibrating piston, such as a loudspeaker diaphragm, mounted on the left end of a long tube filled with air, as shown in Figure 6.4C. As the piston moves in and out at a certain frequency it alternately produces condensations and rarefactions. The disturbance created by the vibrating piston then moves from left to right in the tube with a certain speed. The wavelength of the wave train thus produced is the distance from one condensation to the next. The series of condensations and rarefactions in the tube at any instant of time can be represented by a sinusoid as shown in Figure 6.4B.

Now imagine a long coiled spring through which a longitudinal wave is passing. When the spring is compressed we have an increased “pressure” (or compression) and when the spring is expanded we have a decreased “pressure” (or expansion). The spring with a set of compressions and expansions is shown in Figure 6.5. Note that the points of maximum compression and expansion of the spring do not correspond to the points of maximum displacement of the coil. For instance, at a point of maximum compression, the displacement is zero. At the center of a compression the spring moves toward the center from either side, so that the spring does not move at the center. Likewise, at the center of an expansion the spring moves outward from either side and there is no displacement. The displacement

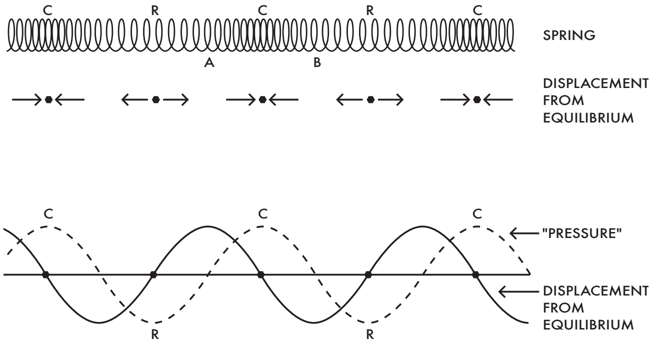

Figure 6.5 *“Pressure” and “displacement” waves in a spring illustrating the relative phases between the two.*

of the spring in the positive direction (toward the right in Figure 6.5) is at a maximum at a point halfway between a "rarefaction" and a "condensation" (such as point A in the figure). The displacement of the spring in the negative direction (toward the left in the figure) is at a maximum at a point halfway between a "condensation" and a "rarefaction" (such as point B in Figure 6.5). Note that the pressure wave is a sinusoid, but it is displaced from the corresponding displacement wave by one-quarter of a cycle. This generally holds for pressure waves—the pressure wave differs in phase from the displacement wave by one-quarter cycle.

6.4 Wave Properties

The medium through which sound waves travel is air; the medium for transverse waves on a taut string is the string itself. The wave speed at which a wave travels through a medium is determined by the physical properties of that medium. If we pluck a stretched string, we create a transverse wave which travels at a constant speed. The wave speed is increased when the string is stretched more tightly. The wave speed is decreased when the density of the string is increased. This information can be summarized by the relation

$$v=\sqrt{\frac{F}{D}} \qquad (6.1)$$

where v is the wave speed, F is the stretching force (or tension) applied to the string, and D is the string's linear density (given as mass per unit length).

The speed of sound in air is obtained from the relation

$$v=\sqrt{\frac{1.4p}{D}} \qquad (6.2)$$

where p is the atmospheric air pressure and D is the density of the gas (given as mass per unit volume). Note that this expression is similar to the equation for the string, with pressure analogous to force. A change in the temperature of the air will change both the atmospheric pressure, the density of the air, and the molecular speeds. The changes are such that as temperature increases, the speed of sound increases in direct proportion. The relation

$$v=331.4+0.6 \times temperature \qquad (6.3)$$

may be used to determine the speed of sound in air (in m/s) at any temperature expressed in degrees Celsius. At room temperature the speed of sound is approximately 343 m/s.

6.5 Wavelength

A periodic wave, in which the wave motion repeats, has a frequency which is identical to the frequency of the vibrating source producing the wave. A periodic wave also has a wavelength associated with it. Consider a vibrating string with a periodic disturbance caused by an oscillator (which moves up and down sinusoidally) attached to the left end. Figure 6.6 shows the displacement at different points along the string as a wave travels from left to right.

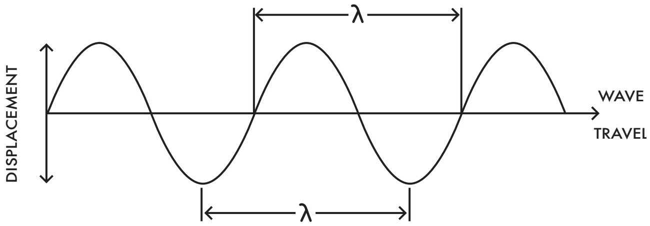

Figure 6.6 *Wave motion in a vibrating string.*

In this case we see several wavelengths along the string at one instant of time. If we were to view a single point on the string as the wave passed, we would see a sinusoidally varying displacement in time similar to Figure 4.4.

An important relationship among speed, frequency, and wavelength for a periodic wave will now be derived. The frequency of the oscillator is represented by f (the number of vibrations per second). The period of vibration (the time for one cycle of vibration) is related to the frequency by the expression T =1/f. The **wavelength**, represented by ? in Figure 6.6, is the distance any part of the wave travels during a time equal to one period. Wavelength can also be defined as the distance between nearest equivalent points on a periodic wave. The definition of wave speed is v = d/t, where d is the distance the wave travels in a time t. In a time equal to T (one period) a point on a wave will travel a distance equal to ? (one wavelength). Putting this information in the definition of speed, we obtain v = ?/T. Since 1/T = f, speed can be written:

$$v=\lambda f \qquad (6.4)$$

The speed of a wave is equal to the product of the frequency of vibration and the wavelength. Because the speed of a wave is a constant determined by the physical properties of the medium, if the frequency of the oscillator changes the wavelength also changes so that the product of frequency and wavelength is constant. For instance, if the frequency is doubled, the wavelength will be halved, and vice versa.

Sinusoids can be used to represent different aspects of vibrations and waves as can be seen by comparing Figure 4.4 and Figure 6.6. The displacement (vertical axis) of a mass-spring system as it varies in time (horizontal axis) is shown in Figure 4.4. The displacement (vertical axis) of a wave as it varies along a string (horizontal axis) is shown in Figure 6.6. This is just a “snapshot” at an instant as the wave travels long the string. If one were to observe a single point on the string, its displacement would vary in time and could be represented by a sinusoid similar to that of Figure 4.4.

6.6 *Energy in Waves*

The energy in waves comes in two forms with which we are familiar (see Chapter 3): KE associated with particle speeds and PE associated with deformations in the medium. When a force produces a transverse wave in a medium such as a string (or a membrane or a bar) the force does work on the medium which results in an increase of energy in the medium. The disturbance travels along the string, deforming and changing the speed of local sections of the string as it passes. The KE and PE associated with the disturbance travel along with the disturbance.

When a vibrating source such as a loudspeaker diaphragm pushes and pulls on the molecules in the surrounding air it does work on the molecules and so increases their energy. In some regions the velocity of the air molecules increases, and the KE density is also increased. (Refer to Chapter 3 for a discussion of energy density as energy per unit volume.) In other regions the air molecules are compressed into a smaller space resulting in an increased pressure with its associated increase in PE density. When a sound wave travels through the air any local region will experience changes in both KE density and PE density as the wave passes. The total energy density is just equal to the sum of the KE and PE densities and to the maximum of either. (This is analogous to the total energy of a simple vibrator being equal to the sum of its KE and PE or to the maximum of either.) Pressure is more easily measured than speed, so the measurement of energy density is most often in terms of PE density.

6.7 *Summary*

The oscillations of a vibrating object travel outward as waves through the surrounding medium. The properties of the medium, particularly the intermolecular forces, determine what wave types can propagate. Both transverse and longitudinal waves can travel in solids. Fluids can only carry longitudinal waves because the interactions between molecules in fluids are weaker than in solids. Both transverse and longitudinal waves can be represented by sinusoids, with the positive value of the sinusoid indicating a positive displacement or a positive pressure. The wave speed on a string is proportional to the square root of the tension-to-density ratio. The wave speed in gases is proportional to the square root of the pressure-to-density ratio. Wave speed is equal to the product of frequency and wavelength. The wave speed in a medium may be considered constant unless properties of the medium change. Waves carry potential and kinetic energy through a medium in which they travel.

References and Further Reading

French, A. P. (1971). *Vibrations and Waves, MIT Introductory Physics Series* (Norton). Chapter 7 provides a technical presentation of waves and pulses in matter.

Hall, D. E. (2002). *Musical Acoustics, 3rd ed* (Brooks/Cole). Chapter 1 provides a brief description of surface waves on water.

Rossing, T. D. and D. A. Russell (1990). "Laboratory Observation of Elastic Waves in Solids," *Am. J. Phys. 58*, 1153–1162.

Questions

6.1 Describe how an impulse travels through a solid and how the "internal" forces of a solid help to transmit the impulse. What keeps the solid from coming apart?

6.2 Describe how an impulse travels through a gas and how the “internal” forces of a gas help to transmit the impulse. What keeps the gas from coming apart?

6.3 What are several disturbances that travel in a gas? In a liquid? In a solid?

6.4 What materials (solid, liquid, gas) will transmit longitudinal waves? Why does a gas not transmit both kinds of waves?

6.5 If a transverse wave cannot be propagated through liquids, how do you explain water waves? What is the medium for these waves?

6.6 What are displacement, velocity, and acceleration for waves on a string?

6.7 What are displacement, velocity, and acceleration for waves in a gas?

6.8 When a clarinet is played, is the clarinet reed free or driven? Is the wave transverse or longitudinal? Does the wave travel in a solid or a gas?

6.9 Repeat Question 6.8 for the vocal folds and also for the vocal tract.

6.10 Repeat Question 6.8 for a piano string and for a bowed violin string.

6.11 Repeat Question 6.8 for an oboe.

6.12 Repeat Question 6.8 for a drumhead and for a chime.

Exercises

6.1 Equations 6.1 and 6.2 give wave speeds for waves in a string and waves in a gas, respectively. Explain how both give the same units of m/s or cm/s for wave speed.

6.2 A wave has a frequency of 500 Hz and a wavelength of 0.01 m. What is the speed of the wave?

6.3 Compute the wavelength of a wave with a frequency of 100 Hz and a speed of 1.0 m/s.

6.4 Given a speed of 10.0 m/s and a wavelength of 0.10 m, find the frequency.

6.5 The tension in a string is 0.1 N, and the string has a mass of 10^{-5} kg and a length of 1.0 m. What is the speed of waves in the string?

6.6 The ambient pressure in air is 10^5 Pa and the density of air is 1.3 kg/m^3. Calculate the speed of sound in these conditions.

6.7 Take the speed of sound in air to be 340 m/s. What is the wavelength in air if $f = 340$ Hz? What is the frequency when the wavelength is 0.10 m? What is the wave speed in helium if $f = 1000$ Hz and the wavelength is 0.97 m?

6.8 The velocity of sound in air is about 340 m/s. If the space between the Earth and the Moon were filled with air, how long would it take sound to travel from the Moon to the Earth (a distance of 4 ? 10^6m)?

6.9 Calculate the speed of sound at the following temperatures: (a) 70'C, (b) 32'C, (c) 12'C, (d) 0° C, and (e) 20° C.

6.10 Players bring their trombones in from the cold (0° C) outdoors and sound a note without warming up. What is the wave speed in their instruments under this condition? After warming up, the air in their instruments has a temperature of 35° C. What is the wave speed in the warmed-up condition? If they sounded a frequency of 110 Hz while cold, what frequency will they sound after warming up, assuming the wavelength is the same in both temperature conditions?

6.11 An adult male vocal tract from larynx to mouth is approximately 17 cm in length . How long does it take a sound wave to travel from larynx to mouth if the temperature is 35° C?

6.12 How long does it take a sound wave to travel from the stage to the back of a small auditorium (a distance of 20 m) if the air temperature is 25° C?

6.13 Musical instrument wavelengths remain almost the same but their frequencies change with wave speed. Frequency changes of 0.5% may be important for musical purposes. What temperature change will produce a frequency change of this amount?

6.14 A woofer in a loudspeaker system has a diameter of 40 cm. What frequency corresponds to a wavelength equal to the loudspeaker diameter? Answer the same question for a midrange diaphragm diameter of 8 cm.

6.15 Determine the range of wavelengths for audible sound if the range of frequencies is 20–20,000 Hz.

6.16 A tuning fork sounds a frequency of 440 Hz. What is the wavelength of the resulting sound in air if the wave speed is 35,000 cm/s?

6.17 A trombone produces a sound with a wavelength of 100 cm. What frequency is it sounding if the air temperature is 25° C?

6.18 A symphony broadcast originating in Boston travels west at the speed of light (300,000 km/s) to a listener 4000 km distant. How long does it take the symphony sound to reach the listener? How long does it take the symphony sound within the concert hall to reach a listener 25 m away from the orchestra?

Activities

6.1 Observe longitudinal and transverse waves in a horizontally suspended slinky. Waves can also be seen in a slinky lying on a table.

6.2 Observe longitudinal and transverse waves in a one-dimensional array of suspended, spring-coupled masses.

6.3 Observe longitudinal waves in a one-dimensional array of suspended uncoupled masses. Note that transverse waves cannot be produced in the uncoupled masses.

6.4 Generate waves in a pan of water and watch them propagate. One drop from an eye dropper produces an impulse.

6.5 Measure sound speed in air by clapping your hands about 20–30 meters away from a plain, flat-walled building. Use a rhythm so that each clap coincides with the reflection of the previous clap. Measure the time between claps and the distance to the building and calculate the sound speed.

6.6 Find the frequencies of several tuning forks by comparing them with the output of a sine wave generator: Adjust the frequency of the generator until it matches that of the tuning fork you are using. How do the labeled frequencies on the tuning forks compare with the sine wave generator setting? How do you account for discrepancies?

6.7 Measurement of wavelength and sound velocity—Set up the apparatus shown in Figure 6.7. Two sinusoids will be seen on the screen of the oscilloscope, one from the direct connection and one coming via the microphone. Change the distance between the speaker and the microphone. You will notice that one of the sinusoids moves relative to the other. Set the microphone close to the speaker and note the relative phases of the two sinusoids on the scope. Slowly move the microphone away from the speaker until the traces again have the same relative phase. As you do this the microphone moves by a wavelength. What is the wavelength in meters? What is the frequency reading on the sine wave generator? Compute the sound speed in air from the relationship v = ?f? How does your result agree with the accepted value?

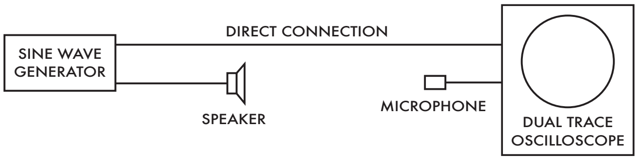

Figure 6.7 *Apparatus setup for measurement of wavelength.*

6.8 Measure speed of sound from time delay of sound relative to light. (J. P. Dabrowski, 1990, "Speed of Sound in a Parking Lot," *Phys. Tchr. 28 (Sep),* 410–411.)

Wave Phenomena

All waves, including sound and light and even water surface waves, exhibit the wave properties discussed in Chapter 6. All have a wave speed governed by the properties of the medium in which they travel. A simple relationship exists between wave speed, wavelength, and frequency. Certain wave phenomena, including reflection, refraction, diffraction, and the Doppler effect, are also common to various types of waves. In this chapter we will discuss each of these phenomena and show how each applies to sound waves. Interference, another wave phenomenon, is so important in acoustics that all of Chapter 9 will be devoted to it.

8.1 Reflection

One wave phenomenon is **reflection**, an abrupt change in direction of travel when a wave encounters a change of medium. When a wave encounters a surface, or any other discontinuity in the medium, part is reflected. Reflections are either regular or diffuse. A **regular (specular) reflection** occurs when a wave encounters a hard, smooth surface as illustrated in Figure 8.1. The angle of reflection is just equal to the angle of incidence so all of the wave bounces off the surface in the same direction and the wave merely changes direction. For example, a mirror reflects light waves in a regular manner. A **diffuse reflection** occurs when the waves encounter a rough surface whose "roughness features" are similar in size to the wavelength. As shown in Figure 8.1, the reflected waves no longer travel in one direction but in many different directions. This type of reflection occurs when light encounters a wall. The light reflects, but not in a regular manner as from a mirror. When sound waves are reflected in a relatively regular manner, an echo may be heard if the reflecting surface is sufficiently far away from a listener. When the sound is diffusely reflected by walls in a room, a listener may perceive a continuation (reverberation) of the sound.

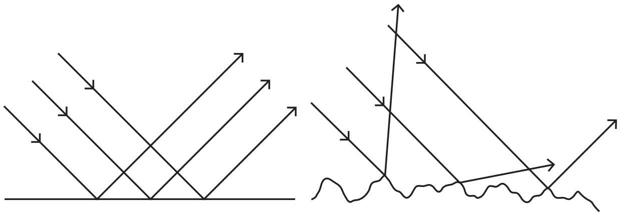

Figure 8.1 *Regular reflections from a smooth surface (left), and diffuse reflections from a rough surface (right).*

Listening environments should be properly designed to distribute reflected sound energy more or less uniformly over the entire audience area. Generally, concave surfaces are undesirable because they concentrate and focus waves as shown in Figure 8.2. The vertical dashed lines represent plane waves (no curvature of the wavefronts) traveling from left to right. The horizontal dashed arrows show the direction the waves travel. The plane waves are reflected from the concave surface as "curved" waves traveling away from the surface. Notice that the angle of reflection is equal to

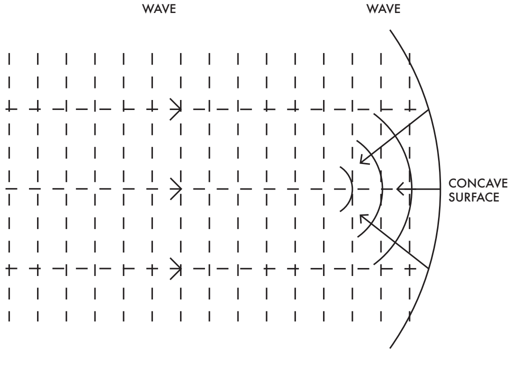

Figure 8.2 *Reflections from a concave surface. Incoming plane waves and their direction of travel are shown by dashed lines and dashed arrows, respectively. Reflected waves and their directions of travel are shown by solid curved lines and solid arrows, respectively.*

the angle of incidence at each point on the surface where reflection occurs. The arrows pointing away from the surface show the directions different parts of the reflected waves travel. It can be seen that these arrows all converge at a common point, the focal point for this concave parabolic surface. Waves striking this particular surface will tend to be focused when they are reflected. (We will often use arrows or rays perpendicular to wavefronts to show the direction waves are traveling. We will also use straight and curved lines to show pressure maxima in waves as they travel to different places in a medium.)

8.2 Refraction

The bending of waves when they pass from one medium into a medium having a different wave speed is called **refraction**. Light, for example, bends when it passes from air to water, because light travels more slowly in water than in air, as illustrated in Figure 8.3. Refraction of sound is most commonly observed when overlying layers of air are either warmer or cooler than underlying layers. The air near snow-covered ground is cooler than the overlying air and, consequently, the sound speed is lower in the air near the ground. In such circumstances a sound wave will be bent downward because sound travels more slowly closer to the ground, where the air is cooler, and the wave is bent toward the direction of lower speed, as illustrated at the left in Figure 8.4. Under such conditions the sound will travel great distances along the ground, an effect you may have noticed during a quiet nocturnal walk through the snow. In the summer the air is generally cooler higher above the surface, and sound is consequently bent upward as illustrated in Figure 8.4. (The frequency of the refracted wave remains the same although the wavelength changes.)

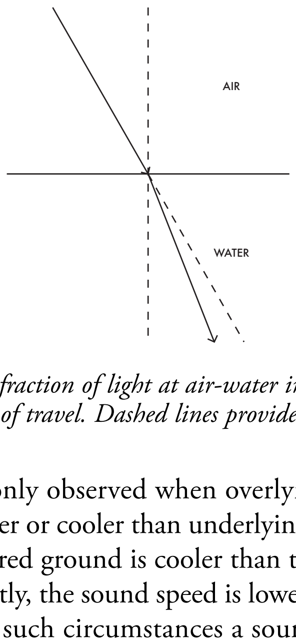

Figure 8.3 *Refraction of light at air-water interface. Arrows show directions of travel. Dashed lines provide references.*

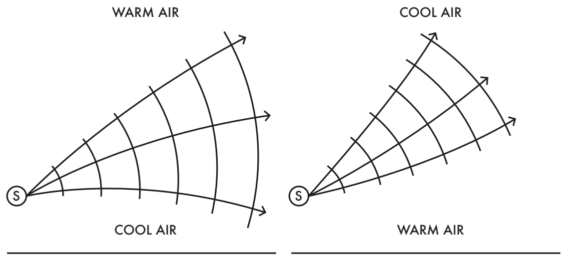

Figure 8.4 *Refraction of sound because of cooler and warmer layers of air. The arrows show the directions of wave travel which are perpendicular to the regions of pressure maxima shown by the curved lines.*

Refraction plays a role in sound channels often found in the ocean. When the wave speed in a layer of ocean water is lower than the wave speed in layers both above and below, the sound path is bent toward the center of the lower wave speed channel as illustrated in Figure 8.5. Sounds in these channels can travel great distances (as much as several thousand kilometers) and are used for communication among whales and between submerged vessels.

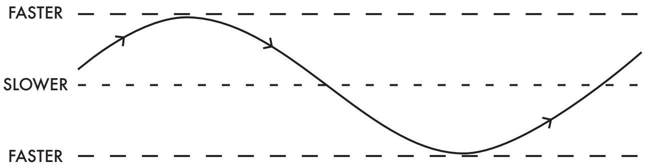

Figure 8.5 *Sound channel established by refraction in a layer of water with a lower wave speed than surrounding layers.*

Something similar to the sound channel effect occurred during the Civil War at the Battle of Gettysburg. The Confederate right was to attack the weak Union left position at the south end of Cemetery Ridge. The attack was to begin with an artillery barrage which would announce the assault. On hearing the barrage, the Confederate left was to make a show of force to keep the strong Union right from reinforcing the Union left. The Confederate left did not hear the artillery barrage and so did not make a show of force. Thus, the Union was able to strengthen its left and hold its position against the Confederate assault. "The hot temperatures near the ground probably caused a dramatic upward refraction of sound waves. Upon hitting another warm layer higher up, these waves could be refracted back downwards. On the previous day, Meade had been unable to hear the Gettysburg fighting from his position at Taneytown (12 miles away), yet the battle was clearly audible in Pittsburg, 150 miles from Gettysburg." (Ross, 1999.)

8.3 Diffraction

Diffraction is the bending of waves around obstacles or through openings. Figure 8.6 illustrates the bending of sound waves around a corner. We are able to hear around corners even though we cannot see around them. The amount of bending is large when the wavelength is equal

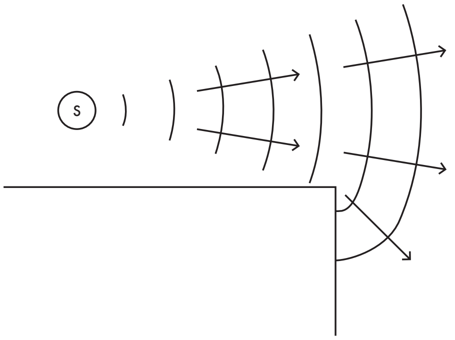

Figure 8.6 *Diffraction of sound around a corner.*

to or larger than the size of the object. Sound wavelengths are large, usually measured in terms of meters or centimeters. Wavelengths of light are of a smaller order measured in millionths of a meter. Sound is strongly diffracted around meter-sized objects while light is not.

Diffraction also occurs when waves pass through openings. Consider a wave incident upon an opening from the left, as shown in Figure 8.7, the crest of each wave being represented by a solid line. If the opening is quite large compared to the wavelength, as portrayed in Figure 8.7a, the wave passes through the opening and continues much as before. When the opening is smaller, however, as in Figure 8.7b, some bending of the wave is observed at the edges. When the opening is smaller than the wavelength, the diffraction of the waves is so substantial that the opening becomes essentially a new source of waves, as represented in Figure 8.7c. Note that diffraction always occurs but, to be noticeable, the opening must be about the same size as, or smaller than, a wavelength. Furthermore, the smaller the opening, the greater the diffraction. Figure 8.7d shows that for a longer wavelength and a larger opening the same amount of diffraction is observed.

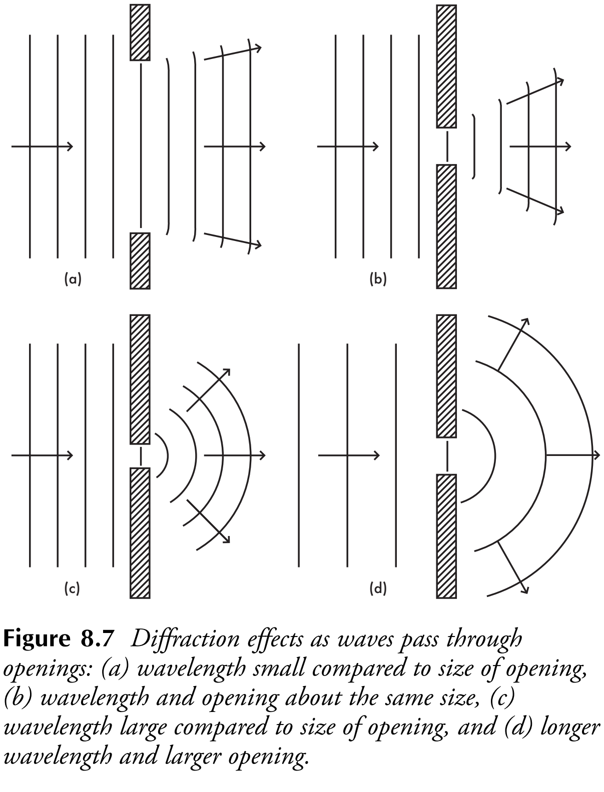

Figure 8.7 *Diffraction effects as waves pass through openings: (a) wavelength small compared to size of opening, (b) wavelength and opening about the same size, (c) wavelength large compared to size of opening, and (d) longer wavelength and larger opening.*

Diffraction through openings can be understood in terms of Huygen's principle which states that all points on a wave front behave as point sources that produce spherical secondary waves. In the limit, when an opening is very small relative to a wavelength, the opening behaves as a single point source, giving rise to spherical waves. In the limit, when an opening is very large relative to the wavelength, the opening behaves as many spherical sources whose combined output results in an approximately plane wave.

Diffraction depends on the ratio between the size of the opening and the wavelength. Sound waves can be conveniently measured in meters or centimeters, so diffraction of sound waves through openings smaller than a meter is an important effect which can easily be observed. You may have noticed that whenever someone in a dormitory plays their stereo loudly with their door open, you hear mostly bass sounds (the long waves). The shorter-wavelength treble sounds do not diffract much through doorways and around corners and, consequently, are not prominently heard in the hallway.

As examples of the relationship between wavelength and the size of a diffracting object, suppose we have a sound source with a frequency of 1000 Hz and a corresponding wavelength of 34 cm. If the sound waves pass through an opening having a diameter of 2 m, little diffraction will occur, as suggested in Figure 8.7a. However, if the waves pass through a 20 cm diameter opening significant diffraction will occur, as suggested in Figure 8.7c.

8.4 Doppler Effect

You have probably experienced the Doppler effect (at least for sound) even if you didn't understand it. As the cars on a road zoom past, you may have noticed a change in the sound's pitch as the cars approach and then pass you. This is an example of the Doppler effect. The **Doppler effect** is the change in the apparent frequency of a sound due to a relative motion between the sound source and the listener. Because we perceive frequency primarily as pitch, we hear a pitch change as the source of a sound passes us. When the horn on an approaching car is sounded, the pitch is higher than when the car is at rest. After the car passes us, the pitch of the horn is lower than normal.

The cause of such a pitch (or frequency) change can be illustrated by a still pool of water into which you throw your pet bug, Bugsy. If Bugsy remained stationary in the water it would create a concentric set of waves every time it splashed with its legs, as shown in Figure 8.8a. However,

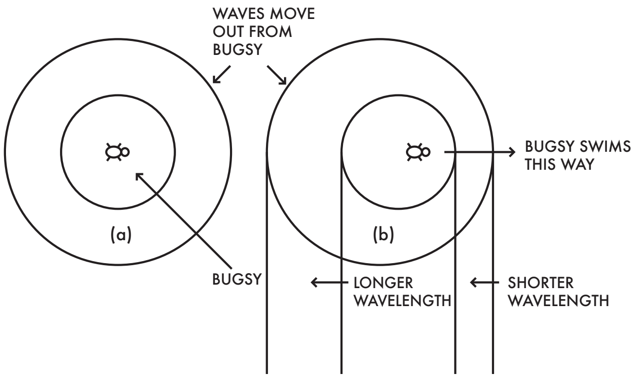

Figure 8.8 *(a) Concentric wavefronts for a vibrator at rest in the medium. (b) Displaced circular wavefronts for a vibrator moving in the medium.*

as it swims toward the right it creates new waves farther to the right. As the waves move outward, they no longer form concentric circles but rather look like those shown in Figure 8.8b. Note that the waves are closer together in the direction in which Bugsy is moving and farther apart in the direction away from which it is moving. Because the wavelength is the distance between waves, we can see that Bugsy's motion through the water shortens the wavelength of the waves in the direction toward which it moves and lengthens those in the direction away from which it moves. If you are sitting in the water at a location behind Bugsy you experience a longer wavelength when Bugsy is moving (Figure 8.8b) than when it is at rest in the water (Figure 8.8a). If you are located in front of Bugsy you experience a shorter wavelength when Bugsy is moving (Figure 8.8b) than when it is at rest (Figure 8.8a). Recall, however, that wavelength and frequency are inversely related—the longer the wavelength, the lower the frequency, and vice versa. Therefore, at a position where the source is moving away you will receive a lower frequency, while at a position where the source is approaching you will receive a higher frequency.

The Doppler effect applies to sound waves as well as to the water waves just discussed. Suppose one of your musician friends plays a C on his trumpet while he's riding in an open car. When the car is not moving you perceive a pitch appropriate for C. When the car is moving toward you at a fairly high speed you perceive a C# even though the trumpeter is sounding a C. When the auto moves away you hear a B. That change of pitch results from the Doppler effect.

As an example, suppose the car is moving at a speed of 20 m/s (approximately 45 mph). The car's speed is approximately 6% of the speed of sound and the change in frequency is approximately equal to this percentage of the original frequency. (See the appropriate formula in Appendix 5 for better accuracy.) If the frequency of the played note is 520 Hz (the C above middle C) then the change in frequency is approximately 30 Hz. The received frequency is then 550 Hz corresponding to a C# when the car approaches you and 490 Hz (B) when the car goes away from you.

The Leslie loudspeaker system, often used with electronic organs and by popular music groups, uses the Doppler effect to produce a frequency vibrato. In one version of the system the loudspeaker is rotated so that it has relative motion toward and away from a listener. In another version a baffle is rotated to produce apparent motion of the loudspeaker. As the loudspeaker moves toward the listener the apparent frequency is higher, and as it recedes the apparent frequency is lower. The rotation rate of the loudspeaker determines the fluctuation rate of the frequency.

As an analogy to the Doppler effect, suppose that two people work at opposite ends of a conveyor belt which moves at constant speed. A woman (the source) places cartons on the conveyor belt at the rate of one per second. A man (the receiver) removes the cartons at the other end of the belt. One day the source who always places one carton per second on the belt begins walking toward the receiver while continuing to put cartons on the belt at a rate of one carton per second. The receiver, who is accustomed to receiving exactly one carton per second is now confused because the frequency of cartons has increased to two per second. Hence, motion of the source of cartons toward the receiver results in an increased frequency of cartons, even though the source is outputting the cartons at the same frequency of one per second. When the source stops walking toward the receiver the frequency returns to one carton per second. The receiver, however, decides to investigate the cause of the disturbance. He begins to walk toward the source while still picking up one carton per second. Soon he notices that he has to pick up more cartons per second because he is moving toward the now-stationary source. Hence, an increase of frequency also results from a stationary source and a moving receiver. Similarly, relative motion between the source and the receiver (so that they are moving apart) results in a decrease in frequency, regardless of whether the source or the receiver moves.

8.5 Summary

Regular and diffuse reflections occur when a wave encounters a change of medium which results in an abrupt change in the direction of propagation. These phenomena account for echoes and sound focusing. When adjacent layers of air differ in temperature, the related wave speeds cause the sound to refract, or bend toward the cooler air which has a lower wave speed. Sound waves also bend around obstacles that are about the same size or smaller than a wavelength because of the phenomenon of diffraction. The Doppler effect arises when there is relative motion between a sound source and a listener; this changes the frequency the listener receives relative to the frequency the source sends.

References and Further Reading

Kelly, R. E. (1974). "Musical Pitch Variation Caused by the Doppler Effect," *Am. J. Phys. 42,* 452–455.

Olson, H. F. (1967). *Music, Physics and Engineering* (Dover). Chapter 1 contains some nice pictorial representations of refraction, diffraction, and reflection.

Ross, C. (1999). *Trial by Fire: Science, Technology and the Civil War* (White House Publishing Co.)

Questions

8.1 What happens to the wavelength when a wave travels from a less dense to a more dense medium?

8.2 Explain the difference between refraction and diffraction. To illustrate refraction, imagine running on a treadmill with different track speeds for each foot.

8.3 Why can we hear around corners but not see around corners?

8.4 What is the practical significance to the fact that sound waves can be refracted?

8.5 Assume that on summer days air near the ground is warmer than air higher above the ground, but that the opposite is true at night. Will an outdoor concert band be heard over greater distances during daytime or nighttime practices?

8.6 You are seated behind a large pillar at an outdoor concert. There are no reflected sounds to compensate for sound blocked out by the pillar. How much high-frequency sound would be blocked out by the pillar? Would the same amount of low-frequency sound be blocked out?

8.7 Use diffraction to explain why a trumpet radiates lower-frequency sounds almost uniformly in all directions but radiates higher-frequency sounds more to the front.

8.8 The observations associated with the Doppler effect (and illustrated in Figure 8.8) assume the listener is directly in front of or directly behind the source. How would observations differ for a listener positioned to one side of the source?

Exercises

8.1 If you can clap your hands and hear an echo 0.2 s later, how far away is the reflecting surface?

8.2 Calculate the frequency a listener receives if the frequency of the source is 100 Hz, the listener moves toward the source with a speed of 34 cm/s, and the source remains at rest. Assume that the speed of sound is 340 m/s. (Use the appropriate formula from Appendix 5.)

8.3 Repeat Exercise 8.2 but with a source frequency of 1000 Hz, a listener speed of 68 m/s away from the source, and a source speed of 0 m/s

8.4 Repeat Exercise 8.2 but with a source frequency of 500 Hz, a listener speed of 0 m/s, and a source speed of 17 m/s toward the listener.

8.5 Repeat Exercise 8.2 but with a source frequency of 200 Hz, a listener speed of 34 m/s toward the source, and a source speed of 34 m/s away from the listener.

8.6 The hole in a loudspeaker cabinet is 20 cm in diameter. What frequencies will pass through the hole and spread uniformly? What frequencies will pass through in a beam? What is the "transition" frequency between the two cases? (Refer to Figure 8.7 for relationships between wavelength, diffractor size, and amount of diffraction.)

8.7 Determine the speed of the open car carrying the trumpet player described in the text when the frequency of the higher tone is about 3% higher than that of C. Do the same when the frequency of the lower tone is about 4% lower than that of C.

8.8 One way of approximating the Doppler effect is to write f_l= f_s + ?f, where f_l is the frequency received by a listener, f_s is the source frequency, and ?f is a frequency change. ?f is positive when source and listener to approach each other and negative when they move away from each other. Starting from the appropriate equation in Appendix 5, show that ?f = $(v_l/v)f_s$ when $v_s = 0$.

8.9 Repeat Exercise 8.8, but show that ?f = $(v_s/v)f_s$ when v_l= 0 and $v_s/v<<1$.

Activities

8.1 Demonstrate the Doppler effect with a small loudspeaker connected with a strong cable to an oscillator so it can be whirled about.

8.2 Fill a flat glass cake pan with lightly colored water and light it from below. Drop a small object, such as a marble, into it at different places relative to the sides of the pan and observe the reflected wave patterns. (Dropping water from an eye dropper may also work.)

8.3 Use the setup of Activity 8.2, but form barriers of aluminum foil in various shapes and observe the results.

8.4 Doppler effect—Take a small tape recorder and record the sounding of an auto horn. Next, place the recorder beside a relatively straight stretch of road. Have the auto get up to a speed of 10–20 m/s (30–50 mph) and sound its horn as it approaches and then passes the recorder. Also, note the speedometer reading. Play the recorder into a spectrum analyzer and measure the most significant frequencies for the auto at rest, for the approaching auto, and for the receding auto. Use the frequency formula for the Doppler effect (see Appendix 5) to calculate the approach speed of the auto from the measured frequencies of the horn for the auto at rest and approaching. Compute the receding velocity of the auto in a similar manner. How closely do the calculated speeds compare with each other and with the speedometer reading?

8.5 Fabricate two "person size" parabolic reflectors. Place them facing each other across a room. Have two people stand at the reflectors' focal points and carry on a conversation across the room.