Chapter Eleven

WAVES AND SOUND

KEY IDEAS

Waves transfer energy without the transfer of mass. Mechanical waves, such as sound, require a medium for transmission, whereas electromagnetic waves, such as visible light, do not.

A wave may be longitudinal, transverse, or a combination of both, depending on the direction in which the medium vibrates in relation to the movement of the wave's energy. Longitudinal waves exhibit parallel vibrations; in transverse waves the vibrations are perpendicular.

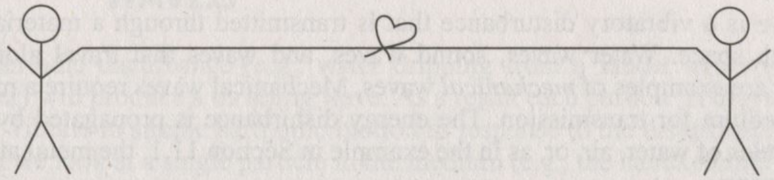
The characteristics of a periodic wave include speed, wavelength, frequency and period, and amplitude. Among the properties of periodic waves are reflection, refraction (the change in the direction of a wave that enters a medium at an angle), interference (the combination of two or more waves simultaneously in a medium), diffraction (the apparent "bending" of a wave around an obstacle), and the Doppler effect (the apparent change in the frequency of a wave as perceived by an observer because of the relative motion between the wave source and the observer).

KEY OBJECTIVES

At the conclusion of this chapter you will be able to:

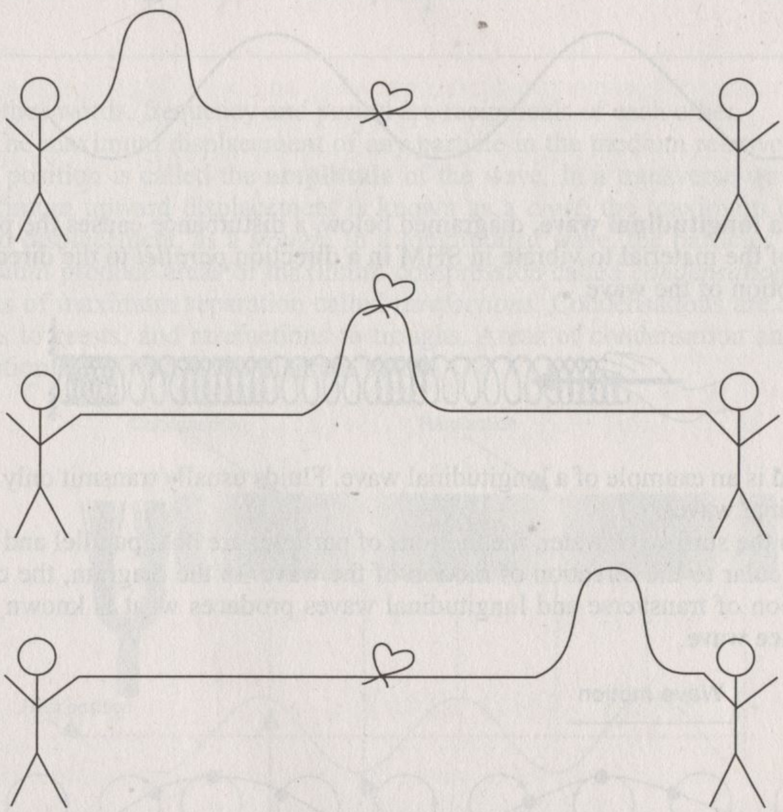
- Define the terms *periodic wave, wave motion, transverse wave, longitudinal wave,* and *surface wave,* and provide examples of each.
- Compare and contrast mechanical waves with electromagnetic waves.
- Define the terms *period, frequency, amplitude,* and *wavelength,* and solve problems that relate these quantities to wave speed.
- Use a diagram of a periodic wave to identify the following: crest, trough, amplitude, phase, and wavelength.
- Define the term *reflection*, and apply the law of reflection.
- Define the term *ray*, and apply it to various types of periodic waves.
- Define the term *refraction*, and apply Snell's law.
- Define the terms *constructive interference, destructive interference, resonance,* and *diffraction.*
- Explain how interference can produce standing waves and beats.
- Define the term *Doppler effect*, and explain this phenomenon.

11.1 DEFINITION OF WAVE MOTION



The diagram represents a coiled spring held between two people; a handkerchief is tied to the spring. If one person quickly jerks the end of the spring up and down, there will be a disturbance in the spring. When the disturbance reaches the other person's hand, it will cause the hand to jerk. Therefore, the disturbance, or *wave pulse,* transfers energy. A moving particle can also transfer energy, but its mass is transferred as well.

If we look at the handkerchief tied to the spring in the diagrams below, however, we can see that it has vibrated about the spring's rest position, that is, it has moved up and down, but it has not moved along with the energy. A wave pulse, or a series of identical, repeating, evenly spaced pulses (called a **periodic wave**), transfers energy, but not mass.



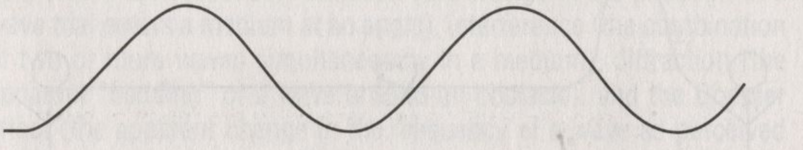
indicates that material is part of the New York State core curriculum.

11.2 TYPES OF WAVES

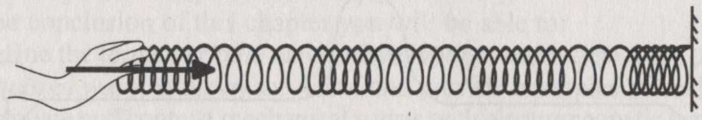
A wave is a vibratory disturbance that is transmitted through a material or through space. Water waves, sound waves, and waves that travel along a spring are examples of *mechanical* waves. Mechanical waves require a material medium for transmission. The energy disturbance is propagated by the molecules of water, air, or, as in the example in Section 11.1, the metal atoms of a spring.

Light waves, microwaves, and radio waves are examples of *electromagnetic* waves. Electromagnetic waves do not need a material medium; they are the result of changes in the field strengths of electric and magnetic fields and can travel in space (a vacuum). Since electromagnetic waves cannot be observed directly, we will use mechanical wave models to explore wave properties and behavior. Light will be studied in greater detail in Chapter 12.

Mechanical waves can be divided into three different types: transverse, longitudinal, and surface waves. In a **transverse wave**, the particles of the medium vibrate or exhibit simple harmonic motion (SHM) about a rest position *perpendicular* to the direction of motion of the wave. Waves on a string, as shown below, are an example of a transverse wave.

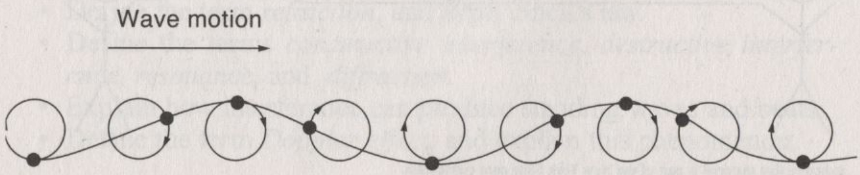


In a **longitudinal wave,** diagramed below, a disturbance causes the particles of the material to vibrate in SHM in a direction *parallel* to the direction of motion of the wave.



Sound is an example of a longitudinal wave. Fluids usually transmit only longitudinal waves.

On the surface of water, the motions of particles are both parallel and perpendicular to the direction of motion of the wave. In the diagram, the combination of transverse and longitudinal waves produces what is known as a **surface wave**.



11.3 CHARACTERISTICS OF PERIODIC WAVES

A periodic disturbance (e.g., water dripping from a faucet into a sink of water) will produce a traveling wave. As a result each particle in the medium will vibrate in simple harmonic motion in response to the disturbance.

If we look at a single particle in the medium (e.g., the handkerchief on the spring in Section 11.1), we see that it moves up and down as we send a traveling wave through the spring. The time it takes for its motion to repeat itself is called the **period** (T), and it is measured in seconds. The number of times the motion repeats itself in a time interval of one unit of time is known as the **frequency** (f) of the wave. Frequency is measured in hertz (Hz), which is equivalent to cycles per second or reciprocal seconds (s^{-1}).

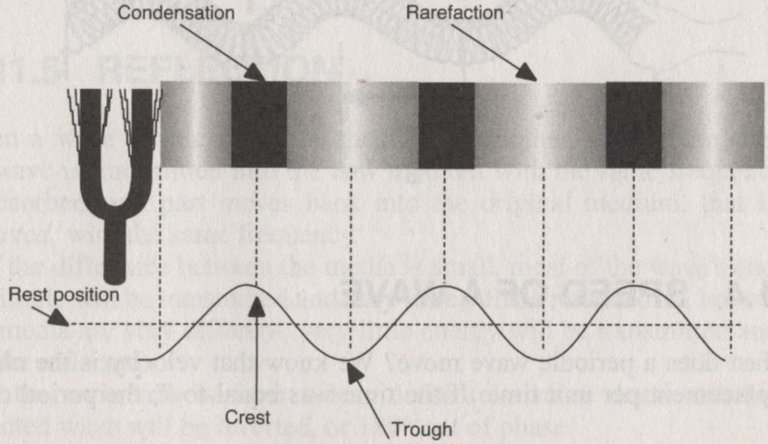
Frequency and period are inversely proportional to each other and are related by this equation:

PHYSICS CONCEPTS

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

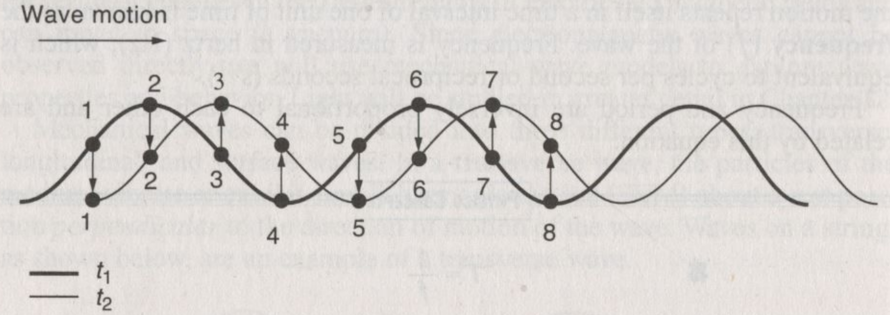
In other words, frequency and period are reciprocals of each other.

The maximum displacement of any particle in the medium relative to its rest position is called the **amplitude** of the wave. In a transverse wave the maximum upward displacement is known as a *crest*; the maximum downward displacement, as a *trough*. In a longitudinal wave, the particles in the medium produce areas of maximum compression called *condensations* and areas of maximum separation called *rarefactions*. Condensations are analogous to crests, and rarefactions to troughs. Areas of condensation and rarefaction are shown in the diagram below.

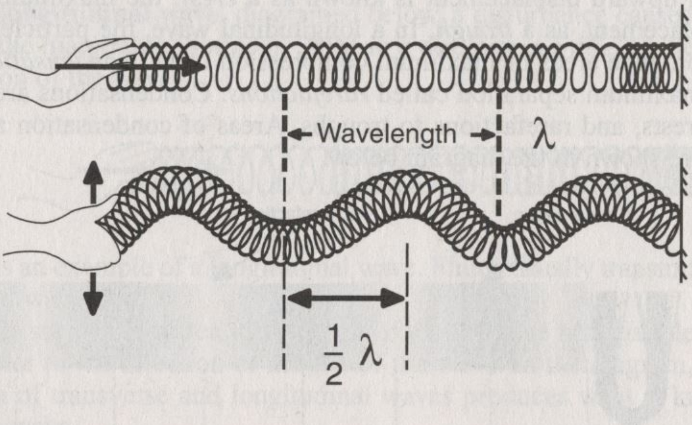


Amplitude is related to the energy carried by the wave. In sound waves, amplitude corresponds to loudness; in light, to brightness.

Points on a periodic wave that are at equal displacements from their rest position and are experiencing identical movements, that is, are moving in *the same direction* toward or away from the rest position, are said to be *in phase*. Points on a periodic wave that are at equal displacements from their rest position but are experiencing motion in *opposite directions* from each other are described as being *180° out of phase* or completely out of phase. In the diagram, points 1 and 5, 2 and 6, 3 and 7, 4 and 8 are in phase. Points 1 and 3, 2 and 4, 3 and 5, 4 and 6, 5 and 7, 6 and 8 are completely out of phase.



The distance between two successive points on a periodic wave that are in phase is called the **wavelength** (λ). Wavelength is measured in meters. Successive points that are 180° out of phase are therefore separated by a distance of one-half wavelength.



11.4 SPEED OF A WAVE

How fast does a periodic wave move? We know that velocity is the change in displacement per unit time. If the time was equal to T, the period of the wave motion, the wave would move a distance of one wavelength (λ). Therefore, $v = \frac{\lambda}{T}$. Since period and frequency are reciprocals of each other, we can rewrite the equation as follows:

PHYSICS CONCEPTS

$$v = f\lambda$$

PROBLEM

What is the wavelength of a sound wave whose speed is 330 meters per second and whose frequency is 990 hertz?

SOLUTION

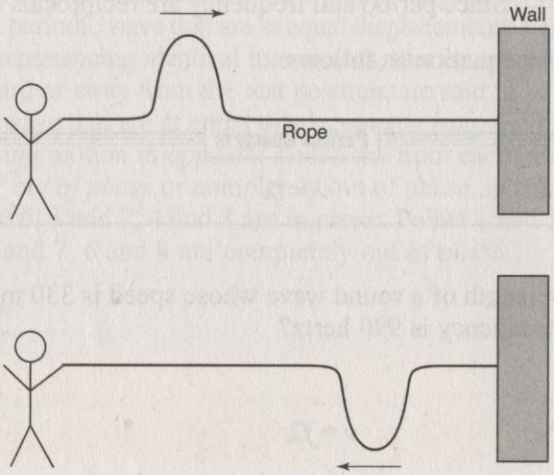
All electromagnetic waves travel in space at the speed of light, which is denoted by the letter c and approximately equal to 3.0×10^8 meters per second. Generally, the speed of a mechanical wave depends only on the properties of the medium, not on the amplitude or frequency of the wave. A wave with large amplitude transmits more energy than a wave with low amplitude, but both travel at the same speed through a given medium. If two waves have the same speed, the wave with the higher frequency will have a shorter wavelength than the wave with the lower frequency. This is a direct result of the equation $v = f\lambda$.

11.5 REFLECTION

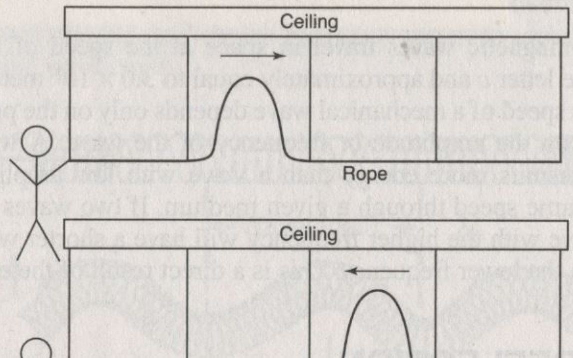
When a wave travels from one medium to another, part of the energy of the wave is transmitted into the new medium with the same frequency, part is absorbed, and part moves back into the original medium, that is, it is *reflected*, with the same frequency.

If the difference between the media is small, most of the wave's energy or amplitude will be transmitted and very little will be reflected. If, however, the two media are very different, very little energy will be transmitted and most will be reflected.

If the wave travels from a less dense to a more dense medium, the reflected wave will be inverted, or 180° out of phase.



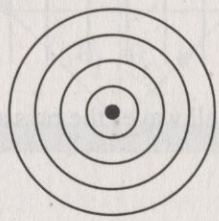
If, on the other hand, the wave travels from a more dense to a less dense medium, the reflected wave will *not* undergo a phase change.



Although transverse waves are used in the two diagrams above to illustrate this property, longitudinal waves behave in the same manner.

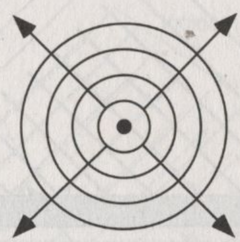
Wave Shape

A wave can have various shapes, depending on the source that produces it. If a person drops pebbles into a pond and then views the result from above, the diagram below shows what is seen.

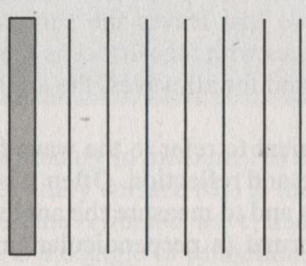


The pebbles are known as a *point source,* and the wave is circular, that is, it spreads out evenly in all directions. The circles in the diagram represent the crests of the wave and are called *wave fronts*.

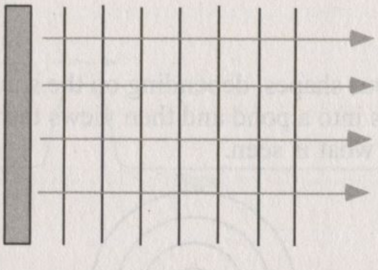
A line that indicates the direction of motion is called a **ray**. The rays of circular waves are radial lines.



If the source of the waves is broad, such as a wooden plate bobbing in the water, the result will be a series of plane waves, as shown in the diagram below.



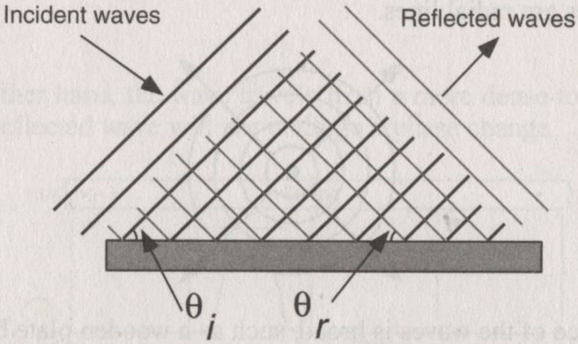
In the next diagram the wave fronts are straight lines. The rays all point in the same direction, that is, they are parallel to one another. At distances very far from a point source, waves become nearly plane in shape.



The diagrams show that in all waves the rays are perpendicular to the wave fronts.

Incident and Reflected Waves

When a plane wave strikes a reflecting surface at an angle, it is reflected at the same angle, as shown in the diagram below.



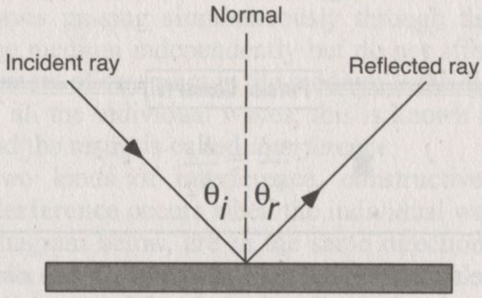
The wave that strikes the surface is called the *incident* wave. The angle it makes with the surface is the angle of incidence (represented by θ_i in the diagram). Similarly, the wave that leaves the surface is termed the *reflected* wave, and the angle it makes with the surface is the reflected angle (θ_r. in the diagram). In every case, and for all waves, the angle of incidence is equal to the angle of reflection.

It is not always convenient to refer to the wave fronts themselves in measuring angles of incidence and reflection. Often it is easier to refer to the rays associated with the waves and to measure the angles of incidence and reflection with respect to a normal (a perpendicular line drawn to the surface). This relationship is known as the law of reflection.

PHYSICS CONCEPTS

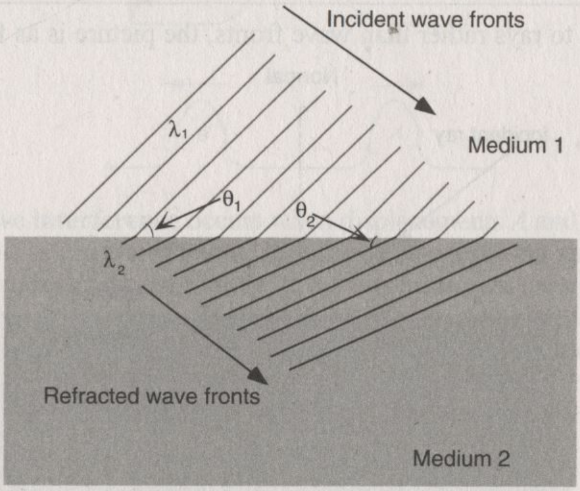
$$\theta_i = \theta_r$$

This situation is diagrammed below.



11.6 REFRACTION

If a wave passes from one medium to another at an angle to the boundary, and its speed changes, its direction in the second medium will also change, as shown in the diagram below.



The wave that strikes the boundary in medium 1 is the *incident* wave, and the angle it makes with the boundary surface (θ_1) is the angle of incidence. The wave in medium 2 is called the *refracted* wave, and the angle it makes with the boundary surface (θ_2) is the angle of refraction.

As the wave enters the second medium, its frequency does not change; therefore, its change in velocity is accompanied by a change in its wavelength. In the diagram, the wavelength in medium 2 is less than the wavelength in medium 1 (λ_1); consequently, the speed of the wave in medium 2 is also less than the speed of the wave in medium 1. This happens when the wave is traveling from a less dense medium to a more dense medium. The opposite would be true if the wave were traveling from a more dense to a less dense medium. The wavelength of the wave would increase as would the speed of the wave.

PHYSICS CONCEPTS

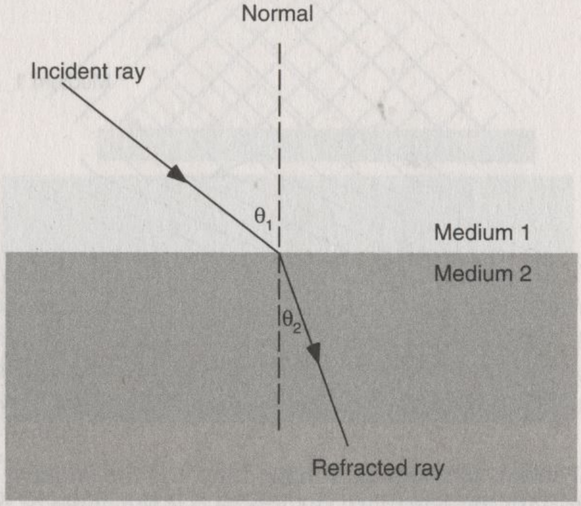
$$\frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$$

We could prove this statement using the relationship $v = f\lambda$. Using simple trigonometry, it can be shown that the ratio of the speeds in the two media is related to the ratio of the sines of the angles in these media. This relationship is known as Snell's law, after the Dutch astronomer and mathematician Willebrord Snell.

PHYSICS CONCEPTS

$$\frac{\sin \theta_2}{\sin \theta_1} = \frac{v_2}{v_1}$$

If we refer to rays rather than wave fronts, the picture is as follows:



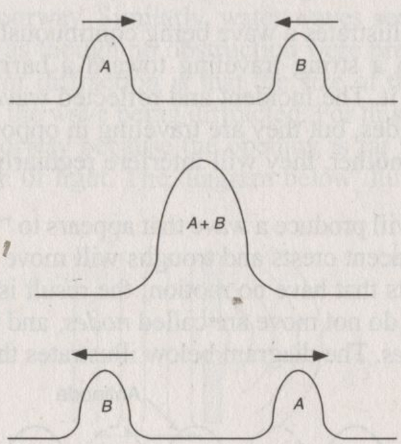
Once again, we measure the angles of incidence and refraction with respect to a normal.

By examining the sizes of the angles, we can draw conclusions about the relative speeds of the waves in the two media. The ray representing a slower wave is positioned closer to the normal than is the ray representing a faster wave. We will explore this phenomenon further in Chapter 12.

11.7 INTERFERENCE

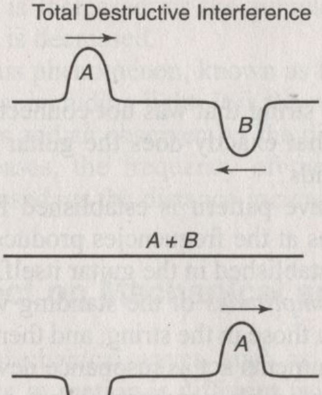
Two or more waves passing simultaneously through the same area of a medium affect the medium independently but do not affect each other. The resultant displacement of any point in the medium is the algebraic sum of the displacements of all the individual waves; this is known as the principle of *superposition*, and the result is called *interference*.

There exist two kinds of interference, constructive and destructive. **Constructive interference** occurs when the individual wave displacements, A and B in the diagram below, are in the same direction. In this case, the resulting amplitude, $A + B$, is greater than any individual wave amplitude.

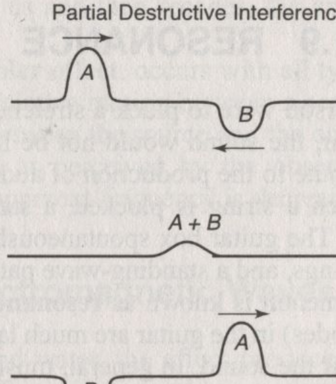


Destructive interference occurs when displacements A and B are in opposite directions, as illustrated below. In this case, the resulting amplitude is less than any individual wave amplitude. If the displacements are equal in magnitude, complete or maximum destructive interference occurs. If the displacements are not equal in magnitude, the result is partial destructive interference.

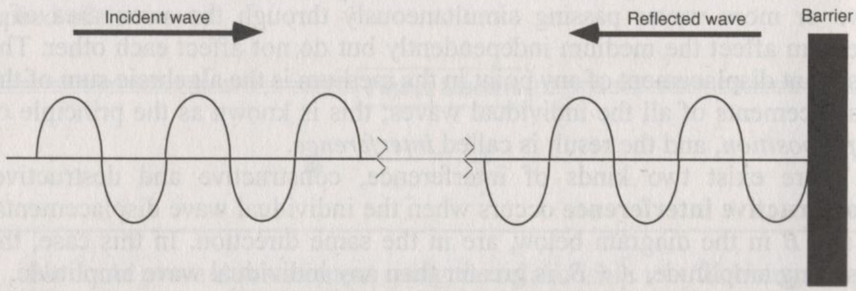
Total Destructive Interference



Partial Destructive Interference

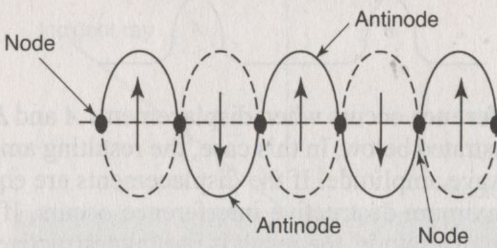


11.8 STANDING WAVES



The diagram above illustrates a wave being continuously produced by an up-and-down motion on a string traveling toward a barrier and the reflected wave emerging from it. The incident and reflected waves have the same frequencies and amplitudes, but they are traveling in opposite directions. When the waves pass one another, they will interfere regularly, both constructively and destructively.

This interference will produce a wave that appears to "stand still" in the horizontal direction. Adjacent crests and troughs will move vertically in opposite directions about points that have no motion; the result is known as a *standing wave*. The points that do not move are called *nodes,* and the crest-trough combinations are *antinodes*. The diagram below illustrates this phenomenon.



11.9 RESONANCE

If a person were to pluck a stretched guitar string that was not connected to a guitar, the sound would not be heard. What exactly does the guitar *body* contribute to the production of audible sounds?

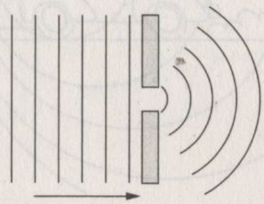
When a string is plucked, a standing wave pattern is established in the string. The guitar box spontaneously vibrates at the frequencies produced by the strings, and a standing-wave pattern is established in the guitar itself. This phenomenon is known as **resonance**. The *amplitudes* of the standing waves (antinodes) in the guitar are much larger than those in the string, and therefore we hear the sound. In general, musical instruments act as resonance devices.

Sometimes, resonance can be an unwanted phenomenon. Years ago, a gale-force wind caused a bridge in Tacoma, Washington, to resonate at its *natural frequency of vibration*. The energy produced by the standing-wave pattern was great enough to cause the bridge to collapse. When bridges and like structures are built today, devices are incorporated to prevent the production of these destructive standing-wave patterns.

11.10 DIFFRACTION

Diffraction is the bending of a wave around an obstacle. If a person stands beside an open door, he or she can usually hear conversation taking place in the room. As the sound waves emerge through the door, they are able to "bend around" the doorway. Similarly, water waves seem to be able to pass through pier barriers as though no obstruction were present.

The requirement for diffraction is that the size of the opening be on the order of the length of the wave being diffracted. For this reason, light will *not* diffract through a doorway because the opening is far too large in comparison to the wavelength of light. The diagram below illustrates the process of diffraction.



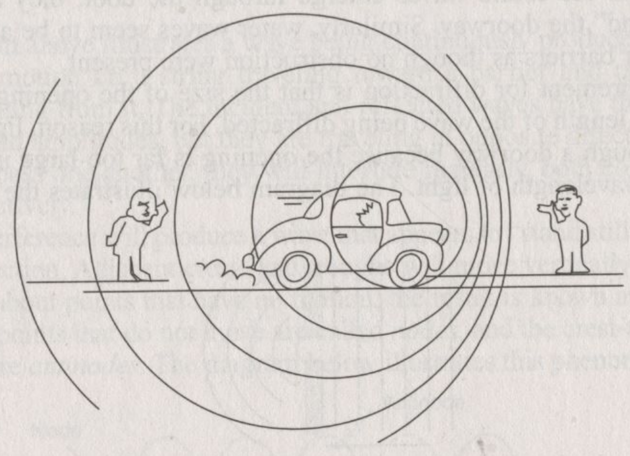
11.11 DOPPLER EFFECT

All of us are familiar with the sound of a siren on a moving vehicle—a fire engine, for example. As the vehicle approaches, the *apparent* pitch of the siren is increased; as the vehicle passes us and then recedes, the apparent pitch is decreased.

This phenomenon, known as the **Doppler effect**, occurs with all types of waves, including light. It is the result of relative motion between a source of waves and an observer. As the distance between the source and the observer decreases, the frequency of the source, as perceived by the observer, is increased; as the distance increases, the apparent frequency is decreased.

Effect on Mechanical and Electromagnetic Waves

For mechanical waves, such as sound and water, the effect produced by a source in motion is different from the effect experienced by an observer in motion, even though the general outcome for both is similar. For example, if an observer is moving toward a stationary source of sound, his or her ear drum receives more waves than if the observer were at rest, and the apparent frequency of the sound is increased. If, however, the source is moving toward a stationary observer, the result is a series of sound waves that are crowded together on the side nearest the observer. The result is that the observer's ear drum receives more waves than if the source were at rest, and the frequency of the sound appears to be increased. The following diagram illustrates the situation in which a source of sound is in motion and the observers are stationary.

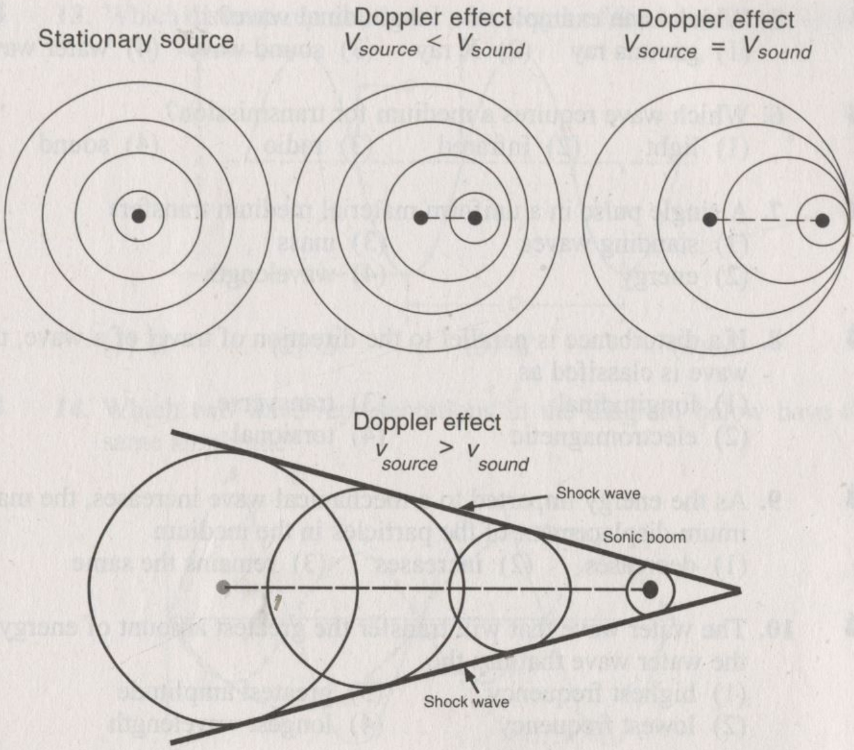


For electromagnetic waves, such as visible light, the frequency change is recorded as a *color shift*, a phenomenon important in astronomy and astrophysics. An increase in frequency exhibits a blue shift. A decrease in frequency exhibits a red shift.

Bow Waves, Shock Waves, and Sonic Booms

If you have ever seen a duck swimming on a lake or pond, you may have observed a V-shaped wave produced by the duck. This phenomenon, known as a *bow wave,* is also produced by a boat in motion on a body of water. A bow wave is a special case of the Doppler effect. As the duck (or boat) travels on the water, it produces water waves. If the speed of the traveler is *greater* than the speed of the water waves, a bow wave results.

When planes exceed the speed of sound, they produce *shock waves,* which are exactly analogous to bow waves. The diagram below illustrates how shock waves are formed. A shock wave is accompanied by an explosionlike sound known as a *sonic boom*.



Chapter Eleven **WAVES AND SOUND**

PART A AND ... STIONS

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   (2) antinodes ... eriodic wave

2. Waves transfer energy bet... oints with no transfer o...
   (1) work ... ss
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3. Compression waves in a ... example of
   (1) longitudinal waves ... larized waves
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   (2) compressional wave (4) torsional wave