9.1 Production and Propagation of Sound and Electromagnetic Waves

SECTION OUTCOMES

- Apply the law of reflection to predict wave behaviour.
- Describe how sound and electromagnetic radiation, as forms of energy transfer, are produced and transmitted.
- Compare and describe the properties of sound and electromagnetic radiation.

KEY TERMS

- compression
- rarefaction
- loudness
- pitch
- quality
- echolocation
- linear propagation of light
- ray model
- light ray
- law of reflection
- regular reflection
- diffuse reflection

To the average person, sound is simply a part of the everyday world — something that is used for communication and entertainment. To physicists, however, sound is a unique entity that can be explained in terms of mechanical waves. Sound transmits energy, travels around corners, reflects off barriers, and requires a medium through which to travel. Unlike waves in water and on a spring, you cannot see sound waves. In this section, you will learn how sound is transmitted and the meaning of properties of waves such as amplitude and frequency as they apply to sound waves. You will also consider the relationship of these wave characteristics to electromagnetic radiation.

Sound Waves

As you learned in Chapter 8, vibrating objects produce mechanical waves. To produce sound, the vibrations must be much faster than those you studied with water waves and springs. For example, humans can hear sound with frequencies between 20 Hz and 20 000 Hz. Some examples of vibrating objects that produce sound waves are shown in Figure 9.1.

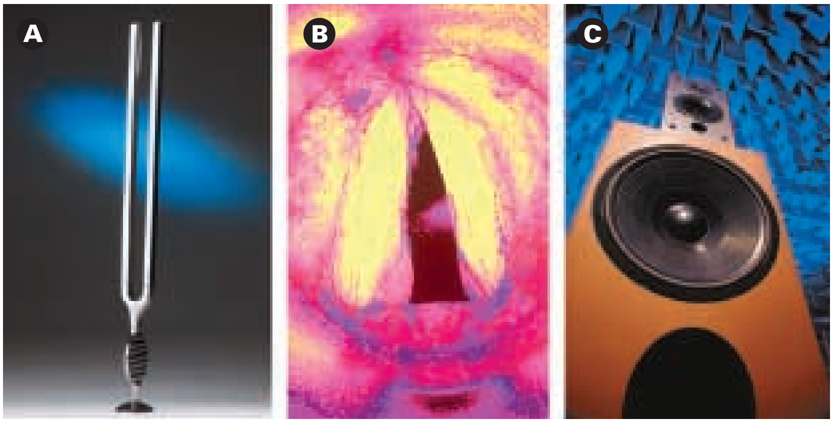


Figure 9.1 **(A)** Tuning forks are artificial devices that are designed to vibrate at one specific frequency. **(B)** Humans can make their vocal cords vibrate at a variety of frequencies by controlling the air that is forced between them and by muscle action. **(C)** In audio speakers, electrical signals are converted into vibrations of a cone.

Sound Waves Are Longitudinal Waves

If you use a strobe light to make the vibrations of a large speaker cone appear in slow motion, you will see that the cone is moving in and out, toward and away from the listener. When the speaker cone moves out, the air molecules in front of it are pushed together to produce a small volume of higher pressure air called a **compression**. When the speaker cone moves back, it produces an expanded space for the air molecules to spread out in. The result is a volume of lower pressure air called a **rarefaction**. This alternating pattern of compressions and rarefactions spreads outward through the room.

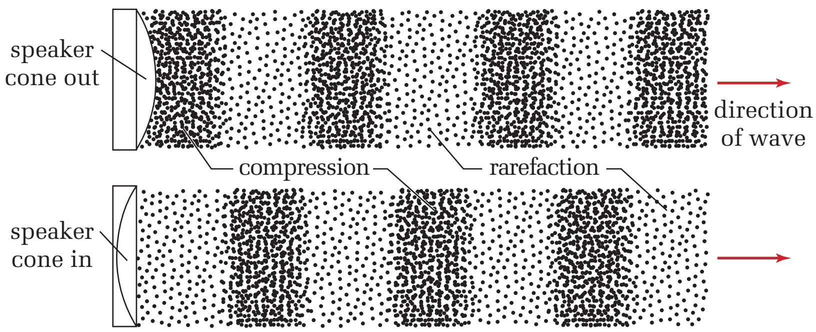


Figure 9.2 When a loudspeaker cone moves out, it exerts a force on the molecules in the air. The molecules move outward until they collide with more molecules. Individual molecules vibrate back and forth, but the collisions carry the sound energy throughout the room.

As you will recall from Chapter 8, there are two distinct types of waves — transverse waves and longitudinal waves. For transverse waves, the vibrations are perpendicular to the direction of the wave motion; for longitudinal waves, the vibrations are parallel to the direction of the wave motion. The above analysis of the sound produced by speakers demonstrates that sound waves are longitudinal. As shown in Figure 9.3, the vibrations in a sound wave correspond to the changes in air pressure at a point in space — that is, crests that are produced by compressions and troughs that are produced by rarefactions. The height of the curve represents the air pressure at that point in space.

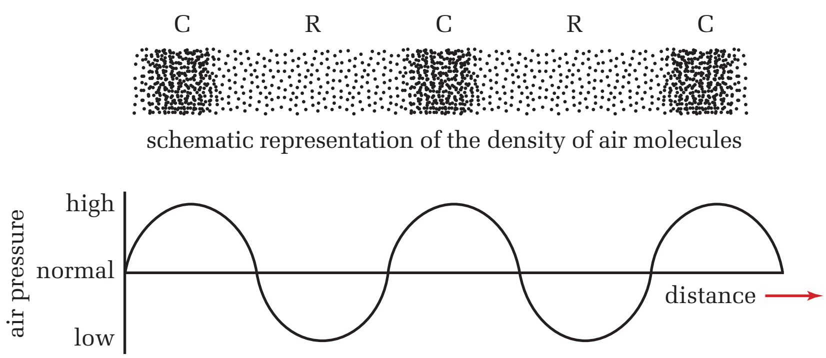


Figure 9.3 Compressions are volumes of maximum pressure, and rarefactions are volumes of minimum pressure.

MISCONCEPTION

But That's Just Theory!

In everyday conversation, people often dismiss ideas with the phrase, "Yes, but that's just theory." This implies a misconception that theory is unreliable. While some untested theories may well be unreliable, the theories that you study in physics have been subjected to very rigorous testing. Scientists generally trust these theories much more than they trust the experiences of particular individuals. If you claimed to have invented a perpetual motion machine (a machine that would keep running forever without energy inputs), it would be very unlikely that physicists would take you seriously, even if they had not tested your machine. According to thermodynamic theory (in particular, the law of conservation of energy) such a machine is impossible. Scientists consider thermodynamic theory, because of the rigorous testing that it has undergone, extremely reliable.

Properties of Sound

Humans can distinguish between sounds in a variety of ways. Sounds vary in **loudness** (perceived intensity). Jet aircraft engines are so loud that airport workers have to wear ear protection when working near them. On the other hand, the breathing of a sleeping baby is so quiet that new parents can become anxious about their child's welfare.

Sounds also vary in **pitch** (perceived frequency). Flutes and piccolos produce very similar sounds. The main difference between the two is a matter of pitch. In general, the sound of the piccolo is higher and that of the flute is lower. Sounds also vary in another important way called **quality**. The sound of a flute or whistle is described as pure, and that of a cello or organ as rich. It is the quality of a sound that enables you to identify it as being made by a piano rather than a trumpet, even when the two instruments play notes with the same loudness and pitch.

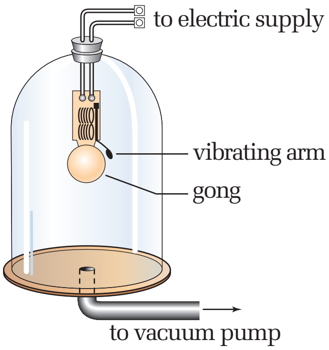
A wave model for sound must relate the loudness, pitch, and quality of the sounds that you hear to specific properties of sound waves. Everyday experience makes it clear that loudness is related to energy. To produce a louder sound from a bell, you have to hit it with more force. Yelling requires significantly more effort than whispering. Loudness, then, is in some manner connected to the **amplitude** of the sound wave. Pitch, on the other hand, is related to the frequency of the sound wave.

Pure sounds are produced by sources vibrating at only one natural frequency. Sound quality arises when the source of the sound vibrates at *several* of its natural frequencies at the same time. As shown in Figure 9.4, the superposition of these component waves — even just two of them — produces a complex wave form with a variety of smaller crests and troughs.

The conceptual links between sound perceptions and their corresponding sound wave characteristics are summarized in Figure 9.5.

PHYSICS FILE

To demonstrate that sound requires a medium through which to travel, an electric bell is sealed inside a bell jar and a vacuum pump removes the air. When the electric bell is turned on, it produces a loud ringing sound. As the vacuum pump removes the air from the bell jar, the loudness of the ringing decreases.



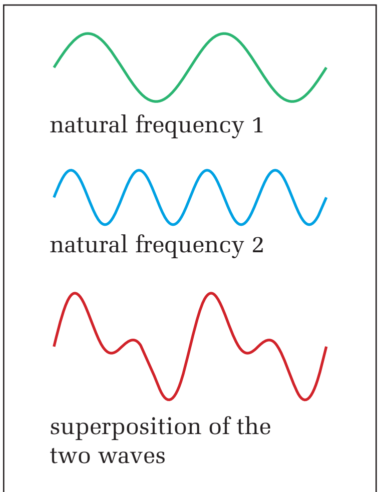


Figure 9.4 When only two frequencies are added together, the resultant wave becomes complex. The quality of this sound is richer than a pure fundamental tone.

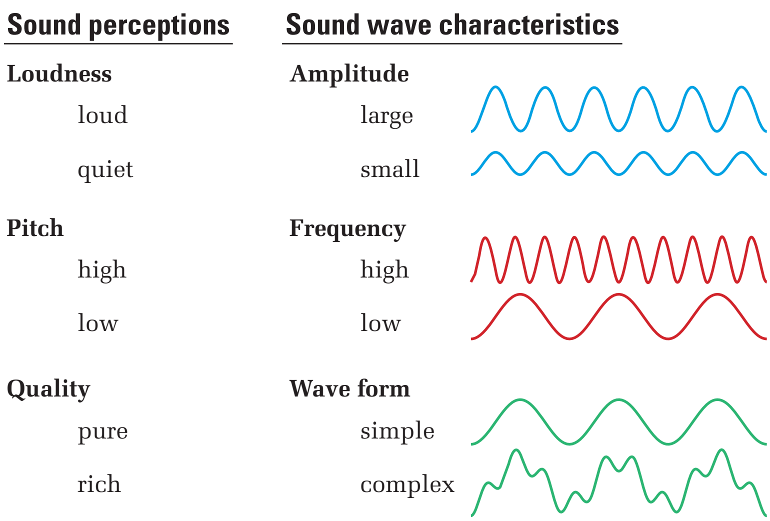


Figure 9.5 Characteristics of sounds and sound waves

Electromagnetic Waves

Electromagnetic waves are unique among waves because they do not require a medium through which to travel. In fact, for many years physicists debated whether light, a form of electromagnetic wave, was made up of waves at all. Since early physicists were unable to demonstrate the property of interference, they preferred the theory that light consisted of particles too small to measure. Isaac Newton could explain reflection, refraction, and even colour with a particle theory of light. Eventually, however, Thomas Young (1773–1829) was able to demonstrate the interference of light waves. You will replicate Young's experiment later in this chapter.

You might wonder how a vibrating object could generate a wave if the wave could travel and transport energy through a vacuum. The answer was provided by James Clerk Maxwell (1831–1897), whose mathematical derivations revealed that an accelerating charge would generate an electromagnetic wave. Maxwell's theories have since been verified by many different physicists.

As you have learned in previous science courses, like electric charges repel and unlike electric charges attract. Charges exert these forces on each other at a distance and even through a vacuum. As you will learn in Chapter 14, electric charges have an influence on the space around them, and when other charges are in that space, they experience a force. Physicists say that the charges have created an electric field in space and the field exerts a force on other charges. If the charges are accelerating, the condition of the field is changing. In fact, the accelerating charge also creates a magnetic field. The strength of the force that the field exerts on another charge in the space changes in an oscillatory manner. An electromagnetic wave is, in fact, this oscillating field created by the accelerating charge. Figure 9.6 shows how physicists represent an electromagnetic wave.

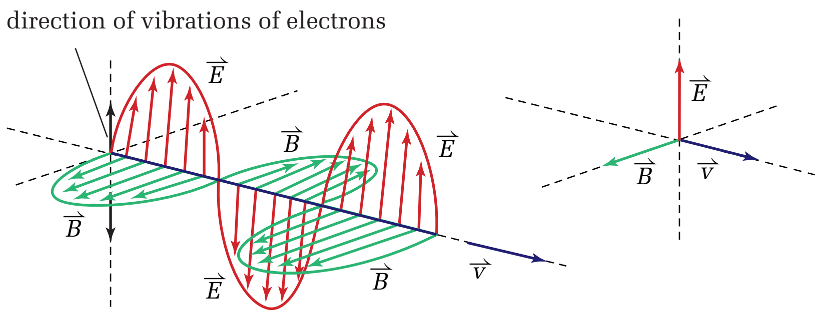


Figure 9.6 The length of the arrows labelled $\vec{E}$ indicate the strength of the electric force that would be exerted on a charge if it was located at the base of the arrow. The arrows labelled $\vec{B}$ represent the magnetic effects.

Radio and television broadcast towers cause electrons to vibrate in the antenna and generate the electromagnetic waves that carry their signal. Other electromagnetic waves have frequencies that are too high to produce in this way. Figure 9.7 provides a summary of ways that electromagnetic waves are produced along with their frequencies and wavelengths. Visible light is simply that range of wavelengths that your eyes can detect. The colour that you perceive is determined by the wavelength of the light. The amplitude of an electromagnetic wave, like a mechanical wave, is related to the amount of energy that is being transmitted. For visible light, you can relate the amplitude to the brightness of the light.

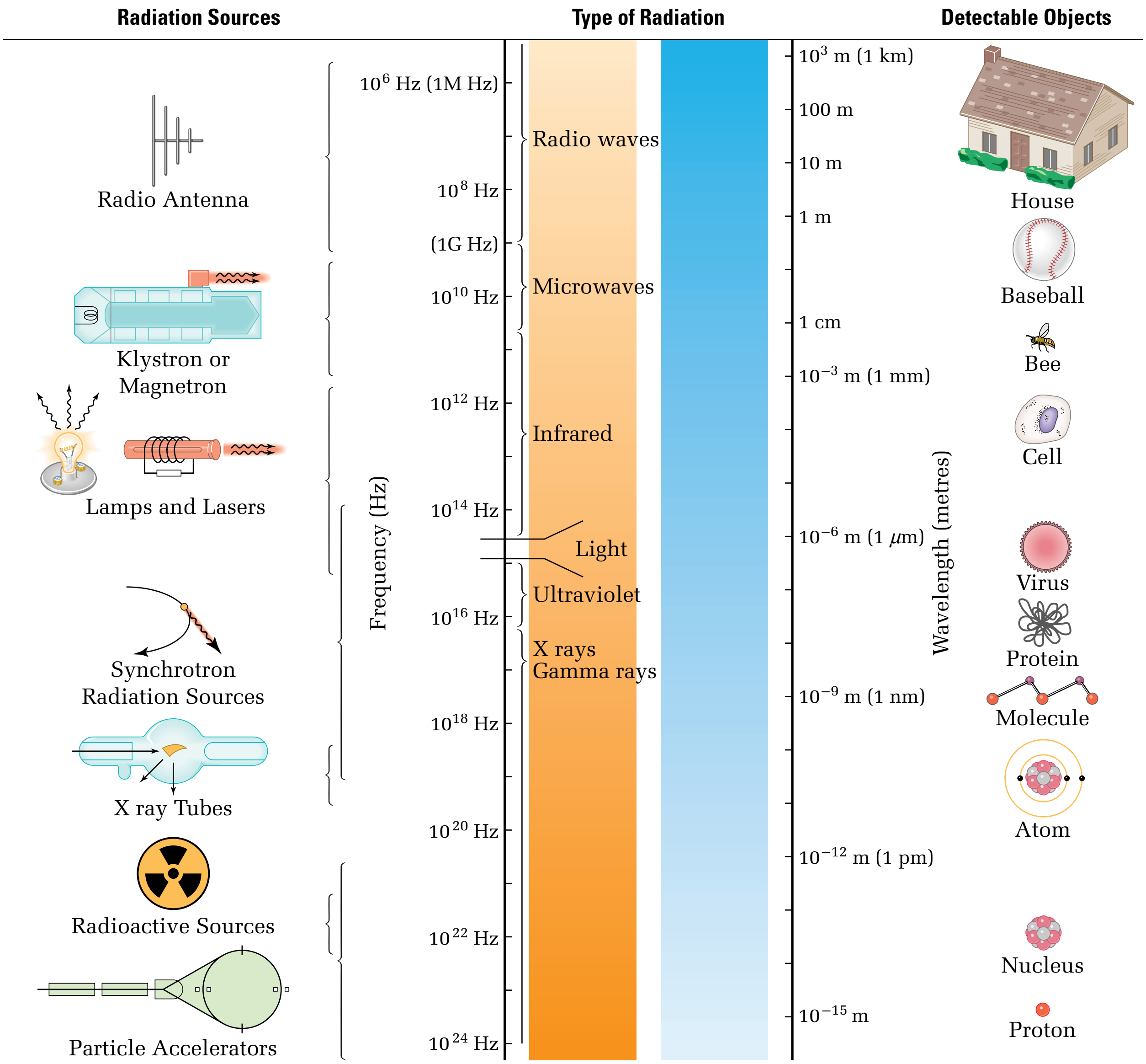


Figure 9.7 The electromagnetic spectrum includes a range of frequencies that covers more than 18 orders of magnitude. The subdivisions are artificial and, to some extent, determined by the mechanism that is used to produce them.

Reflection of Sound Waves

If you have ever stood in a canyon and yelled "hello," you know that sound waves reflect. Of course, you called the reflection an echo. Some animals have a far more refined auditory system than humans. Toothed whales or *odontocetes* and most species of bats are able to generate and interpret ultrasonic pulses that reflect off obstacles and prey. This process, called **echolocation**, allows animals to pinpoint not only the object's exact location, but also (using Doppler shifts) its speed and direction.

Dolphins, part of the toothed whale family, have very specialized vocal and auditory systems. They make whistle-type vocal sounds using their larynx, which does not contain vocal cords. The echolocation and navigation clicks are produced in their nasal sac region. Dolphins are able to generate sounds ranging in frequency from 250 Hz to 150 kHz. The lower range frequencies, from 250 Hz to 50 kHz, are thought to be used primarily for communication between dolphins, while the higher frequencies are used for echolocation.

Echolocation clicks produced by dolphins, each lasting from 50 ms to 128 ms, are grouped into "trains." A large, flexible, gelatinous outcropping on the front of the dolphin's skull, called a melon, focuses the clicks. The melon is filled mostly with fatty tissue and is easily shaped by the muscles to act as an acoustical lens for the high-pitched clicks. Research has shown that the high-pitched sounds do not travel as far in water as lower frequency noises, resulting in effective echolocation ranges from 5 to 200 m away for targets of 5 cm to 15 cm in length. Dolphins produce a wide range of sounds, varying in frequency, volume, wavelength, and pattern. They are able to identify size, shape, speed, distance, direction, and even some internal structure of the objects in the water. For example, a dolphin can detect flatfish lying beneath a layer of sand on the seabed.

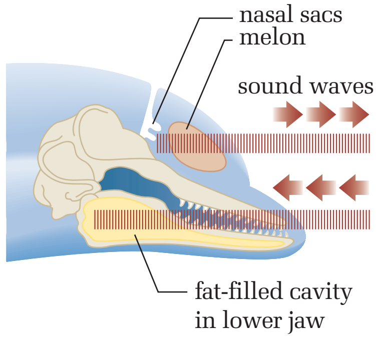


Figure 9.8 The echolocation clicks are generated in the nasal sacs, focussed by the melon, and received by the fat-filled region in the lower jaw.

Figure 9.9 Notice the slightly contorted shape of the melon as this dolphin focusses echolocation clicks. Tests have demonstrated that dolphins are able to distinguish between different-shaped objects contained within a closed box. Essentially, they are able to accomplish naturally what we do with ultrasounds to examine expectant mothers.

Figure 9.10 Most species of bats are able to "see" using ultrasonic sounds, enabling them to catch their prey in the darkness of night.

Reflection of Light

Every time you look in a mirror, you are aware that light reflects. In fact, nearly everything you see is due to reflected light reaching your eyes. That all forms of electromagnetic waves reflect becomes obvious when you consider radar transmitters and receivers. Satellite dishes for television also reflect the microwaves that are bringing news and entertainment from distant satellites.

Until now, the wavefront model of light has been very helpful in modelling the properties of waves. However, when you start to study the reflection of light, the ray model, mentioned in Chapter 8, is more useful.

The observation that light travels in straight lines is such a fundamental property that it has been accorded the status of a principle. The principle of **linear propagation of light** leads to the very useful **ray model** of light. A **light ray** is an imaginary arrow that points in the direction of the propagation of light. Like mechanical waves, the direction in which light energy travels is perpendicular to the wavefronts as shown in Figure 9.11. Thus light rays are always perpendicular to wavefronts. The wavefront model can explain the properties of light, but wavefronts are more difficult to sketch and interpret than light rays. Therefore, you will be using light rays to understand, describe, and predict the properties of light through out this chapter.

PHYSICS FILE

Isaac Newton believed that light consisted of extremely rapidly moving *particles* and many other scientists of his time followed his teachings. Later, Christian Huygens demonstrated that light travelled with *wave*-like properties such as constructive and destructive interference. Eventually, Max Plank, Albert Einstein, and others demonstrated that, when light interacts with matter, it behaves like particles or packets of energy now called photons. Today, scientists accept the "wave-particle" duality of the nature of light. Light travels like a wave and interacts with matter like a particle. Nevertheless, physicists still seek a more complete model of light.

Language Link

The word "ray" is derived from the Latin word *radius*. Usually, light fans out radially from a point source of light. What are some other examples of radial phenomena?

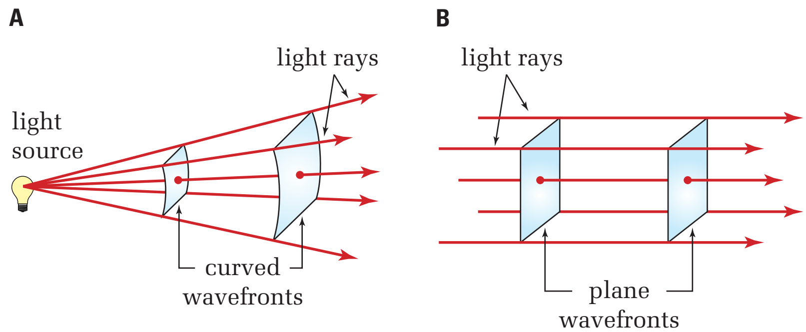


Figure 9.11 **(A)** When the light waves are close to the light source, the wavefronts appear as parts of a sphere, and the light rays gradually diverge (spread out) from one another. **(B)** When the light waves are at a great distance from the light source, the wavefronts can be considered parallel to one another. The light rays are also parallel, indicating the direction in which the light is travelling.

Reflection

In Chapter 8, you briefly considered plane water waves reflecting from a straight barrier. The law of reflection, introduced in connection with water waves, applies to all types of waves. Examine Figure 9.12 to review the terms and symbols scientists use in discussing reflection. You always draw a normal (or perpendicular) line from the reflecting surface from the point at which a light ray strikes a reflecting surface. The angle between the incident ray and the normal line is the angle of incidence, θ_i. The angle between the reflected ray and the normal line is the angle of reflection, θ_r. The **law of reflection** states that the angle of reflection is always equal to the angle of incidence. This law applies to all surfaces.

Language Link

The word "normal" is derived from the Latin word *norma*. What does *norma* mean? Why is this appropriate for the use of "normal" in mathematics and physics?

THE LAW OF REFLECTION

The angle of incidence, θ_i, equals the angle of reflection, θ_r, and the incident light ray, the reflected light ray, and the normal to the surface all lie in the same plane.

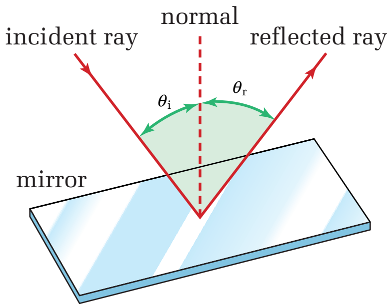


Figure 9.12 The angle of incidence, θ_i, equals the angle of reflection, θ_r. Both of these angles are measured with respect to the normal, a line drawn at right angles to the mirror surface at the point of incidence.

History Link

There is a legend that the ancient Greek mathematician and inventor, Archimedes, used mirrors to set fire to Roman ships around 212 B.C.E. In 1973, the Greek historian, I. Sakkas, set out to test whether Archimedes could have done so. He lined up 70 soldiers with flat copper shields and directed them to reflect sunlight to a rowboat anchored 50 m from shore. The boat soon caught fire.

This doesn't prove the story was true, but it does show that Archimedes could have used such a method.

Regular and Diffuse Reflection

Why is it that you can see yourself in a mirror, but you cannot see yourself in a piece of paper, such as this page in your textbook, when you hold it in front of your face? The quick answer is that the mirror surface is much smoother than the surface of the paper. Try looking at other shiny surfaces, such as the cover of your textbook. You might be able to see a faint reflection of your face on the book cover.

How smooth does a surface have to be to behave like a mirror? If you magnify the surface of a mirror several hundred times, the surface still appears flat and smooth. However, the magnified surface of a page in a book is quite irregular, as shown in Figure 9.13.

To understand what happens to the light when it strikes these two kinds of surfaces, use the light ray model to see the path of the light. When a set of parallel light rays hit the mirror surface in Figure 9.14, the reflected light rays are also parallel to one another. This type of reflection is called **regular** (or specular) **reflection**. Each of the parallel light rays that hit the irregular surface in Figure 9.14 is reflected in a different direction. This type of reflection is called **diffuse reflection**. However, the law of reflection still

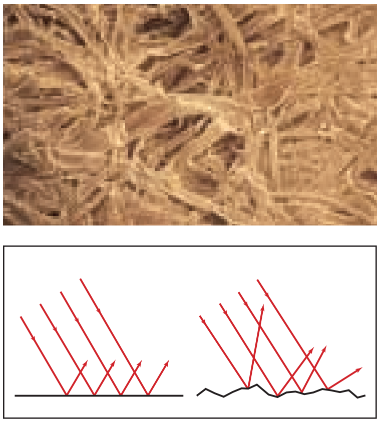


Figure 9.13 **(A)** The page of a book viewed under a microscope. **(B)** Which of the ray diagrams illustrates reflection off paper?

applies for every light ray reflecting from the irregular surface. The surfaces of many common objects, such as most types of cloth, paper, brick and stone surfaces, and pieces of wallpaper, reflect light in this way.

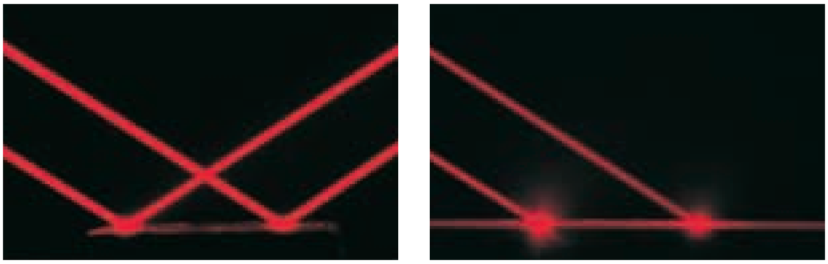


Figure 9.14 A laser beam is a group of parallel light waves that are close enough together to form a fine beam of light. Notice that the laser beams reflected from the mirror are parallel, but those that strike the rough surface appear as fuzzy, round dots because the incoming parallel light rays in the beam are reflected in many different directions.

9.1 Section Review

1. **K/U** The amplitude of a sound wave represents what property of sound?
2. **C** Describe the motion of a molecule or particle as a sound wave passes.
3. **C** Explain the meaning of the "quality" of sound.
4. **K/U** The amplitude of an electromagnetic wave represents what property of the space through which it travels?
5. **C** Describe two significant differences between sound and electromagnetic waves.
6. **MC** Imagine that you are in a completely dark cave or room. How might you estimate the size of the space in which you are standing?
7. **C** Explain the relationship between a wavefront and a ray.
8. **I** Design a demonstration using billiard balls that you could use to explain the difference between regular and diffuse reflection to a grade six class.