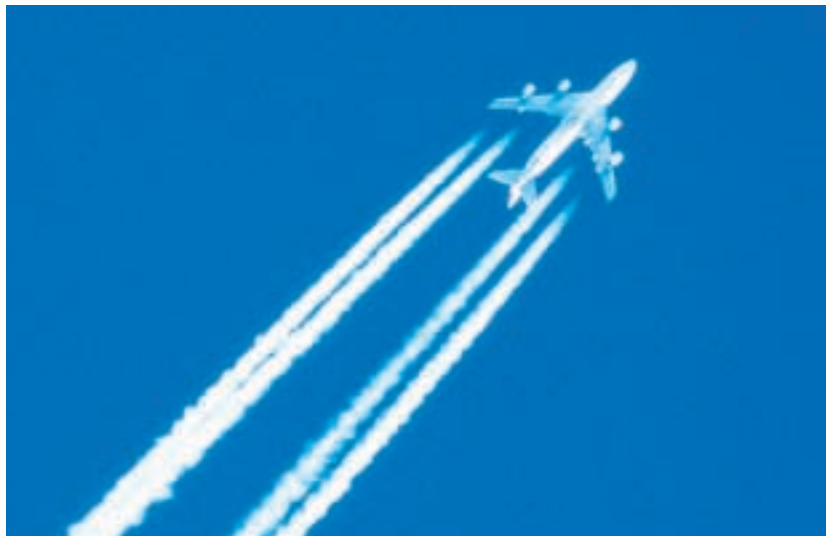# Factors Related to the Speed of Waves

Figure 9.15 Why do you see a jet in one part of the sky and hear the roar of the engines coming from another part of the sky?

You hear jet engines roaring and begin to search the skies. You look in the direction from which the sound is coming and see nothing. Finally you locate the jet, but it appears to be far ahead of its own sound. On a stormy night, you see a flash of lightning in the distance and a few seconds later you hear the roll of thunder. However, your physics teacher told you that lightning and thunder happen at the same time. Why does the information reaching your eyes and ears seem so contradictory? You probably already know that the answer lies in the difference between the speed of light and the speed of sound.

The situations above are easily explained. Can you explain, based on the speed of sound, why on a cool, clear night, you can hear sounds from a greater distance than you could during the day? Can you explain the strange appearance of objects seen through a glass of water, based on the speed of light? Many phenomena are a result of differences in the speed of sound and light depending on the medium — or, in the case of light, absence of a medium — through which they travel. In this section, you will explore several of these phenomena.

The Speed of Sound in Air: A Wave Property

As you learned in Chapter 8, the speed of a wave is determined by the properties of the medium through which it travels. Friction in a medium slowly decreases the amplitude of a wave, but does not affect its speed. If sound is a wave, then it should have a constant speed that is determined by the medium through which it travels. Sound should also travel at different speeds in different media.

Sound waves travel through air by means of moving molecules. Molecular speeds in a gas, however, depend on the temperature of the gas. Therefore, the speed of sound in air should increase with temperature. This is indeed the case. At a temperature of 0°C and a pressure of 101 kPa, the speed of sound in air is 331 m/s, and for each 1°C rise in temperature, the speed of sound increases by 0.59 m/s.

THE SPEED OF SOUND IN AIR

The speed of sound in air is 331 plus the product of 0.59 and the Celsius temperature.

$$v = 331 + 0.59T_C$$

Quantity	Symbol	SI unit
speed of sound	v	$\frac{m}{s}$ (metres per second)
temperature of air	T_C	not applicable* (°C is not an SI unit)

Unit Analysis

$$\frac{m}{s} + \frac{\frac{m}{s}}{°C}(°C) = \frac{m}{s}$$

*Note: This formula is based on the Celsius temperature scale and cannot be used with the Kelvin scale. How would you modify the equation so that it would apply to the Kelvin scale?

The Speed of Sound in Solids and Liquids

In general, sound travels fastest in solids, slower in liquids, and slowest in gases. The speed of sound in water is almost five times faster than its speed in air. This difference is great enough to be noticed by the human ear. A swimmer who is 1500 m away from a loud noise (perhaps a cannon being fired) would hear the sound that travelled through the water 1 s after it was produced. The same sound travelling through the air, however, would not be heard until 5 s after it was produced.

Knowledge of the speed of sound in different materials is the basis for a variety of techniques used in exploring for oil and minerals, investigating the interior structure of Earth, and locating objects in the ocean depths.

Table 9.1 The Speed of Sound in Some Common Materials

Material	Speed (m/s)
Gases (0°C and 101 kPa)	
carbon dioxide	259
oxygen	316
air	331
helium	965
Liquids (20°C)	
ethanol	1162
fresh water	1482
seawater (depends on depth and salinity)	1440–1500
Solids	
copper	5010
glass (heat-resistant)	5640
steel	5960

MODEL PROBLEMS

Applying the Speed of Sound Equation

1. **Suppose the room temperature of a classroom is 21°C. Calculate the speed of sound in the classroom.**

Frame the Problem

■ At a *temperature of 0°C* and a pressure of 101 kPa, the *speed of sound in air* is 331 m/s.

■ For each *1°C rise in temperature* the speed of sound increases by 0.59 m/s.

Identify the Goal

The speed of sound, v

Variables and Constants

Known   **Unknown**

$T_C = 21°C$ v

Strategy	**Calculations**
Use the equation relating the speed of sound in air to the ambient temperature.	$v = 331 + 0.59T_C$
Substitute in the known values.	$v = 331 \, \dfrac{m}{s} + 0.59 \, \dfrac{\frac{m}{s}}{°C} \, (21°C)$
Simplify.	$v = 331 \, \dfrac{m}{s} + 12.39 \, \dfrac{m}{s}$ $v = 343.39 \, \dfrac{m}{s}$

The speed of sound in the classroom is 3.4×10^2 m/s.

Validate

The speed of sound increases with temperature. At 0°C, the speed is about 330 m/s. The temperature is about 20°C above that, and increases approximately 0.5 m/s for each degree of increase in temperature. Thus, the speed should be about 340 m/s.

2. **The temperature was 4.0°C one morning as Marita hiked through a canyon. She shouted at the canyon wall and 2.8 s later heard an echo. How far away was the canyon wall?**

Frame the Problem

- The *speed of sound* can be calculated from the *temperature*, which is given.

- The *distance* the sound travels can be calculated from the *speed* of sound and the *time* for the echo to return.

- The sound travels to the wall and back, so the distance to the wall is half the distance that the sound travels.
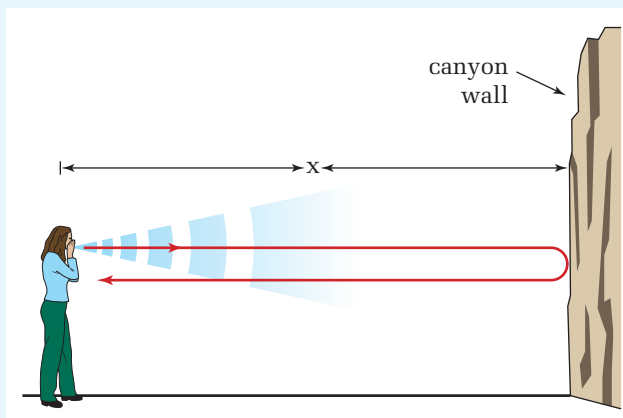
Sound echoing off a canyon wall

Identify the Goal

The distance, x, to the wall

Variables and Constants

Known	Unknown
$\Delta t = 2.8$ s	v
$T_C = 4.0°C$	Δd
	x

Strategy

Calculations

Use the equation for the *velocity* (speed) of sound in air.

$$v = 331 + 0.59 T_C$$

Substitute in the known values.

$$v = 331 \, \frac{m}{s} + 0.59 \, \frac{\frac{m}{s}}{°C} (4.0°C)$$

Simplify.

$$v = 331 \, \frac{m}{s} + 2.36 \, \frac{m}{s}$$
$$v = 333.36 \, \frac{m}{s}$$

Find the *distance* to the wall and back by rearranging the formula for the *velocity* of any entity.

$$v = \frac{\Delta d}{\Delta t}$$

$$\Delta d = v(\Delta t)$$

Substitute in the known values.

$$\Delta d = 333.36 \, \frac{m}{s} \, (2.8 \, s)$$

Simplify.

$$\Delta d = 933.41 \text{ m}$$

The distance to the wall, x, is half the distance to the wall and back, Δd.

Substitute in the known values.

$$x = \frac{\Delta d}{2}$$

Simplify.

$$x = \frac{933.41 \text{ m}}{2}$$
$$x = 466.7 \text{ m}$$

The canyon was 4.7×10^2 m away.

Validate

Sound at 4°C is not travelling much faster than it is at 0°C. Thus, the sound is travelling at approximately 330 m/s. In 2.8 s, this sound will have travelled about 3×330 m, or 1000 m. However, the sound travelled to the wall and back, so the distance to the wall is only half of 1000 m, or about 500 m.

> **PROBLEM TIP**
>
> In problems such as this one, always remember that the sound travels from the source *to the reflector and back*. Thus, the distance from the source to the reflector is only half of the distance that the sound travelled.

PRACTICE PROBLEMS

1. What is the speed of sound in air at each of the following temperatures?
   (a) −15°C (b) 15°C
   (c) 25°C (d) 33°C

2. For each speed of sound listed below, find the corresponding air temperature.
   (a) 352 m/s (b) 338 m/s
   (c) 334 m/s (d) 319 m/s

3. A ship's horn blasts through the fog. The sound of the echo from an iceberg is heard on the ship 3.8 s later.
   (a) How far away is the iceberg if the temperature of the air is −12°C?
   (b) How might weather conditions affect the accuracy of this answer?

4. An electronic fish-finder uses sound pulses to locate schools of fish by echolocation.

What would be the time delay between the emission of a sound pulse and the reception of the echo if a school of fish was located at a depth of 35 m in a lake? Assume the temperature of the water is 20°C.

5. You want to estimate the length of a large sports complex. You generate a loud noise at one end of the stadium and hear an echo 1.2 s later. The air temperature is approximately 12°C. How far away is the far wall of the stadium from your position?

6. (a) How long does it take for sound to travel 2.0 km in air at a temperature of 22°C?
   (b) The speed of light is 3.0×10^8 m/s. How long does it take for light to travel 2.0 km?
   (c) The rumble of thunder is heard 8.0 s after a flash of lightning hits a church steeple. The temperature is 22°C. How far away is the church?

QUICK LAB

At the Speed of Sound

TARGET SKILLS
- Performing and recording
- Analyzing and interpreting
- Communicating results

A rough determination of the speed of sound in air can be performed using echolocation. Stand at least 50 m from a large outside wall of your school. Measure the distance to the wall. Clap two wooden blocks together, and listen for the echo. Estimate the time interval (a fraction of a second) that it takes for the echo to return. Clap the blocks together repeatedly with a steady rhythm, so that the time interval between a clap and its echo is the same as the time between the echo and the next clap. When you do this, the time between your claps is equal to twice the time that it takes the sound to travel to the wall and back. Thus, the period of your clapping is equal to the length of time it takes sound to travel four times the distance to the wall.

Maintaining this rhythm, have your partner measure the length of time that it takes for 20 claps and echoes.

Analyze and Conclude

1. Determine the period of your clapping and the time it takes the sound to travel to the wall. Calculate the speed of sound in air. How accurate is your answer?

2. Assume that your answer to question 1 is correct. Calculate the temperature of the air. Is this a reasonable value? Explain.

3. Use a thermometer to measure the actual temperature of the air. Discuss the discrepancy between your predicted value and your measured value.

Mach Number

Since the speed of sound in air varies with temperature and pressure, it is not possible to classify specific speeds as subsonic, sonic, and supersonic. Austrian physicist Ernst Mach devised a method to describe these classes of speeds as ratios of the speed of the jet (or other object) to the speed of sound in air that has the temperature and pressure of the air in which the jet is flying. The ratio is now known as the **Mach number**. A mach number of less than one indicates that an object is moving slower than the speed of sound for temperature and pressure conditions the same as those in which the object is flying. Mach one means that it is flying at precisely the speed of sound and a Mach number greater than one indicates that the object is moving faster than the speed of sound.

The Speed of Light

The speed of light is much more difficult to measure than the speed of sound. Many scientists tried and failed and began to believe that light travelled instantaneously. Nevertheless, scientists continued to make attempts to determine the speed of light. Finally, in 1905, Albert A. Michelson (1852–1931) made the most accurate measurement of the speed of light of any that had been made previously. In fact, it was extremely close to the value of modern measurements made with lasers. Michelson perfected a method developed by Jean Foucault (1819–1868) and illustrated in Figure 9.16. Michelson set up an apparatus on Mount Wilson in California and positioned a mirror 35 km away. A light source reflected off one side of an eight-sided mirror, then off the distant mirror, and finally off the viewing mirror. The rate of rotation (up to 32 000 times per minute) of the eight-sided mirror had to be precise for the reflection to be seen. By determining the exact rotation rate that gave a reflection and combining that with the total distance that the light travelled, he calculated the speed of light to be 2.997×10^8 m/s. This value is amazingly close to the currently accepted value of 2.99792458×10^8 m/s. The speed of light in a vacuum is such an important constant that physicists have given its own symbol, c.
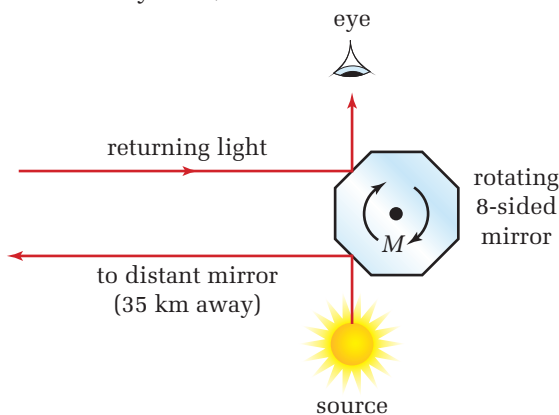
Figure 9.16 Until the laser was developed, Michelson's measurements of the speed of light using an apparatus similar to this were the best measurements of the speed of light that were available.

Motion of Source or Observer

Submarines navigate through the murky depths of the oceans by sending and receiving sound waves. Whales and bats do the same, but with considerably more precision. For people, the ability to develop sound technologies as tools for navigation requires an understanding of the effect of motion on sound waves. If the source of the sound is moving, how does that affect the perception of the observer? Does motion of the observer influence the perception of sound?

The Doppler Effect

Have you ever noticed how the sound of an emergency vehicle's siren seems to increase in pitch as it approaches? Then, just as the vehicle passes, the pitch suddenly appears to drop. The phenomenon responsible for the apparent change in pitch is called the **Doppler effect**. The siren of an emergency vehicle generates exactly the same sound at all times. The apparent changes in pitch as the vehicle approaches, then recedes, results from the motion of the vehicle as the source of the sound.

When the source of a sound is stationary, the sound will radiate outward in the shape of a three-dimensional sphere. This effect is shown in two dimensions in Figure 9.17 A. When the source of a sound is moving relative to the observer, the wave fronts appear as shown in Figure 9.17 B. During the time between successive compressions, which initiate a wave front, the source has moved toward the observer. Therefore, each new compression is nearer to the front of the previously created compression. This motion reduces the effective wavelength of the sound wave and the frequency appears greater. The same line of reasoning explains why the pitch seems to drop as the source of the sound moves away from an observer.

Figure 9.17 The Doppler effect
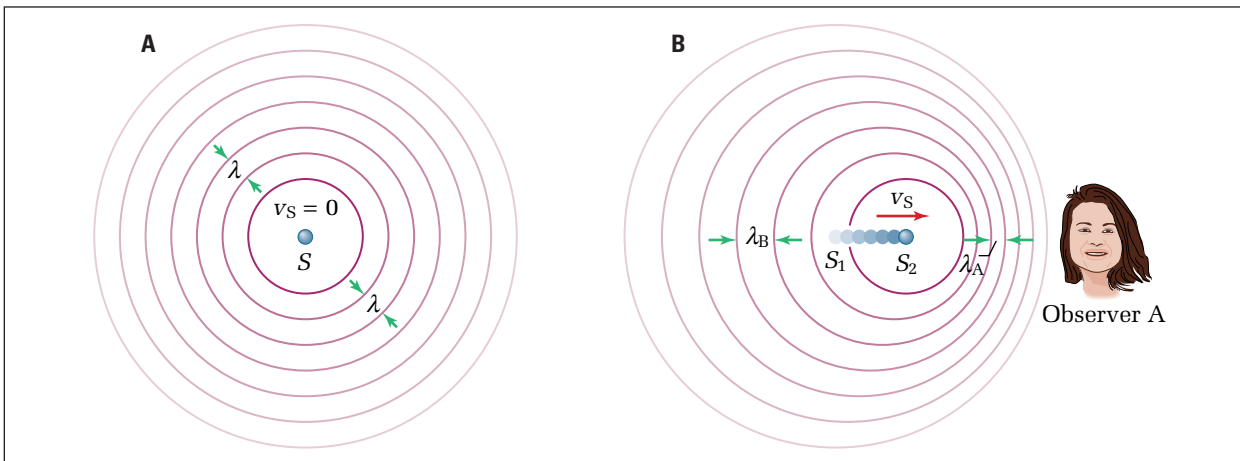
Conceptual Problems

- Draw a diagram similar to Figure 9.17 B that demonstrates the Doppler effect as (a) a source moves away from your stationary position and (b) you move toward a stationary source.

- A friend puts a battery and a siren from a toy into a Nerf™ ball. She connects the battery and tosses you the ball with the siren wailing. Describe what you will hear and what she will hear as the ball moves through the air.

- Why does the wavelength of a sound generated from a moving source *decrease* as the speed that the source moves toward you increases? Why (in terms of the wave equation) does the frequency *increase*?

- Draw a diagram that illustrates sound waves surrounding a source that is moving at the speed of sound.

Sonic Booms

An extreme case of the Doppler effect occurs when an object travels at or beyond the speed of sound as shown in Figure 9.18. Figure 9.19 demonstrates compression waves generated by a source moving at various speeds.

If you have ever put your hand out of the window of a moving car, you will know that the pressure of the air on your hand is substantial. Your hand is colliding with air molecules and generating a longitudinal wave that moves out from your hand. Moving your hand through water provides a more visual example of the same phenomenon, except with transverse waves.

Imagine that you are able to keep holding your hand outside of the car as it accelerates toward the speed of sound. The pressure on your hand would become immense, but nothing compared to the pressure that you would feel as you reach and exceed the

Figure 9.18 The shock wave as a jet breaks the sound barrier is visible because the increased pressure causes water vapour to condense.
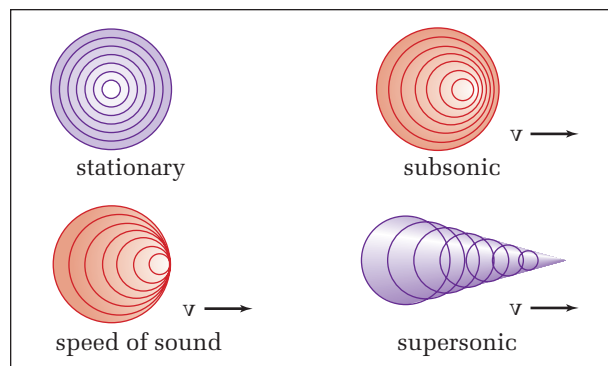

stationary   subsonic

speed of sound   supersonic

Figure 9.19 Sound waves propagating outward from a source moving at various speeds

Figure 9.20 The large bow wave is the result of the boat moving faster than the speed of the waves in water.
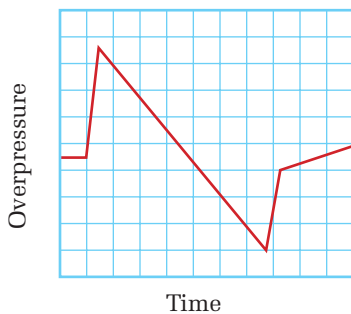

Figure 9.21 Pressure, measured on the ground, versus time as an F-18 fighter jet flies overhead at an altitude of 9000 m and a speed of Mach 1.20. The "N-wave" change in pressure is characteristic of sonic booms.

speed of sound. If you are travelling slower than the speed of sound, although the pressure is great because of the increased number of air molecule collisions that you are experiencing, the wave fronts are still moving away from your hand. At the speed of sound, you are moving with the same speed as the wave fronts. Now the compressive wave fronts that you generate with your hand cannot move away from your hand. Each successive wave front combines with the ones made before it, creating a massive compression. This area is called the overpressure.

The photo of the large bow wave in front of the boat moving through the water in Figure 9.20 demonstrates how the wave fronts build up when the source is travelling faster than the waves can move in the medium. Likewise, behind your hand a massive rarefaction, or area of extremely low pressure, exists. This rapid change in air pressure, from very high to very low, is called a shock wave and is heard as a sonic boom. Figure 9.21 shows what a typical sonic boom pressure profile looks like.

Examine the wavefronts for supersonic motion in Figure 9.19. Notice that many wavefronts converge along a V-shaped path behind the source. Of course, in three dimensions, it forms a cone. This superposition of compressional wavefronts creates extremely large pressure changes as the cone moves. You hear the results as a sonic boom. Figure 9.22 shows you how sonic boom trails behind the source that is moving faster than the speed of sound. Supersonic jets usually fly at very high altitudes because although the sonic boom cone then covers more area on the ground, it is significantly weaker. The sonic boom cone sweeps over a path on the ground that is approximately 1 km wide for every 250 m of altitude. Therefore, a jet flying faster than the speed of sound at an altitude of 10 000 m will create a sonic boom across a 40 km wide path of land beneath the jet. The higher a jet flies, the wider the path of the sonic boom, but the lower the energy level on the ground.

The pressure change from typical atmospheric pressure to the maximum pressure of the compressional wave of a sonic boom occurs over a time interval of 100 ms for a fighter jet and in approximately 500 ms for the space shuttle or the *Concorde*. Such a sudden, drastic pressure change can force windows to flex beyond their elastic limit, and shatter.
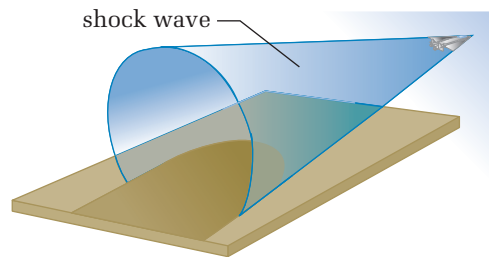
shock wave

Figure 9.22 The sonic boom trails behind the jet, growing larger but weaker as it expands.

Faster than the Speed of Light?

When an object such as a star is moving toward or away from Earth, the speed of the light coming toward Earth is still measured to be 2.9989×10^8 m/s, but the wavelength changes in much the same way as it does for sound waves. For sound, the pitch changes, but for visible light the wavelength determines colour, so the apparent colour changes. If the star is moving away from Earth, the wavelength will seem longer. Since red light has the longest wavelength of visible light, astronomers call the change in wavelength a red shift. If a star is moving toward Earth, the wavelength seems shorter and the change is called a blue shift.

You have probably heard that no object having mass can travel at the speed of light. This observation is true for light travelling through a vacuum, as you will see in Chapter 17. However, particles such as electrons can travel faster than the speed of light in a medium such as water. When this occurs, you do not hear a boom, of course, but you see an eerie blue glow called **Cerenkov radiation** — named after the Russian scientist who studied it. It is basically the same effect for light as the Doppler effect is for sound.

Refraction and Light Waves

When you look through a window, objects usually appear just the same as they do when looking only through air. Why do the windowpanes in Figure 9.23 cause so much distortion? Why does the curved side of a beaker cause distortion? Windowpanes and beakers are transparent, so if light penetrates these materials, why do some of them cause distortions, while others do not? Can you think of any situations in which air alone can cause distortion?

Figure 9.23 Imagine looking at the world through these windowpanes. Why was this kind of glass once used in windows?

Figure 9.24 Light refracts, or bends, toward the normal when it passes from air into water or glass.

Is the spoon in Figure 9.24 really broken? "Of course not!" It is actually the light rays that were bent. The change in direction of the light as it passes at an angle from one material into another is a result of refraction.

Refraction is the changing of the speed of a wave when it travels from one medium into another. Light travels as a wave, and therefore experiences refraction. When light travels from one medium into another at an angle, the difference in the speed causes a change in the direction of the light (Figure 9.24). The shimmering effect you see above a barbecue grill, the distorted view of objects viewed through a glass bottle, and even rainbows are all results of the refraction of light.

Index of Refraction

The values for the speed of light in different media are extremely large, unwieldy numbers. Physicists developed a more useful constant called the **index of refraction** (or **refractive index**). The index of refraction is a ratio of the speed of light in a vacuum to the speed of light in a specific medium. Since the term represents a ratio of two values having the same units, the units cancel, leaving the constant unitless.

INDEX OF REFRACTION

The index of refraction of a material is the ratio of the speed of light in a vacuum to the speed of light in that material.

$$n = \frac{c}{v}$$

Quantity	Symbol	SI unit
index of refraction	n	none
speed of light in a vacuum	c	$\dfrac{m}{s}$ (metres per second)
speed of light in a specific medium	v	$\dfrac{m}{s}$ (metres per second)

Unit Analysis

$$\frac{\text{metres per second}}{\text{metres per second}} = \frac{\frac{\cancel{m}}{\cancel{s}}}{\frac{\cancel{m}}{\cancel{s}}} = \text{no unit}$$

Table 9.2 Index of Refraction of Various Substances*

Substance	Index of Refraction (n)	Substance	Index of Refraction (n)
vacuum	1.00000	solids at 20°C	
gases at 0°C, 1.013×10^5 Pa		ice (at 0°C)	1.31
hydrogen	1.00014	quartz (fused)	1.46
oxygen	1.00027	optical fibre (cladding)	1.47
air	1.00029	optical fibre (core)	1.50
carbon dioxide	1.00045	Plexiglas™ or Lucite™	1.51
liquids at 20°C		glass (crown)	1.52
water	1.333	sodium chloride	1.54
ethyl alcohol	1.362	glass (crystal)	1.54
glycerin	1.470	ruby	1.54
carbon disulfide	1.632	glass (flint)	1.65
		zircon	1.92
		diamond	2.42

* Measured using yellow light, with a wavelength
  of 589 nm in a vacuum.

The index of refraction of a material can be determined by methods that do not involve measuring the speed of light in that material. Once the value is measured, however, you can use it to calculate the speed of light in that material. The index of refraction has been determined for a large number of materials, some of which are listed in Table 9.2.

Notice that the values for the index of refraction are always greater than one, because the speed of light in a vacuum is always greater than the speed of light in any material. Notice, also, that media in which the speed of light is low have large indices of refraction: When you divide a constant by a small number, the ratio is large. For example, the speed of light in water ($n = 1.33$) is 2.26×10^8 m/s, whereas the speed of light in zircon ($n = 1.92$) is 1.56×10^8 m/s.

The term **optically dense** refers to a refractive medium in which the speed of light is low in comparison to its speed in another medium. For example, based on the previous values given for zircon and water, you would say that zircon is more optically dense than water. The speed of light in air and other gases is so close to that of the speed of light in a vacuum that the index of refraction of these materials is considered to have a value of one, or unity, for most practical purposes. You will notice in Table 9.2 that the index of refraction in gases differs from that in a vacuum only in the fifth significant digit.

The index of refraction, and therefore the speed of light, for all wavelengths (colours) of light is the same when light is travelling in a vacuum. For any other given material, the index of refraction varies slightly, however, depending on the wavelength of the light passing through it. Therefore, different wavelengths of light travel at different speeds in the same medium. To avoid confusion, physicists have chosen to report the values for the speed of light of a specific colour. They have chosen the yellow light emitted by the sodium atom, which has a wavelength of 589 nm in a vacuum.

Figure 9.25 Streetlights are usually filled with sodium vapour. The yellow light it produces is preferred, because it penetrates fog and mist better than the blue-green light produced by mercury vapour.

Snell's Observations

For thousands of years, people have known that various types of crystals can change the direction of light when it passes from air into the crystals. Scientists also knew long ago that the amount of refraction depended on the both the material that made up the crystal and the angle at which the incident light crossed the boundary between the air and the crystal. Numerous scientists tried to identify a mathematical relationship that could describe refraction, but it was not until 1621 that Willebrord Snell (1580–1626), a Dutch mathematician, discovered the relationship experimentally.

To describe Snell's discovery, you need to define a new, but related, angle — the **angle of refraction**, θ_R. The angle of refraction is defined as the angle that the refracted ray makes with the normal line.

Snell discovered that when light travels across a boundary from one medium into another, the ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant value for all angles of incidence greater than zero. When the angle of incidence is zero, the angle of refraction is also zero and the direction of the light is unchanged. Snell's observations can be described mathematically by the following expression.

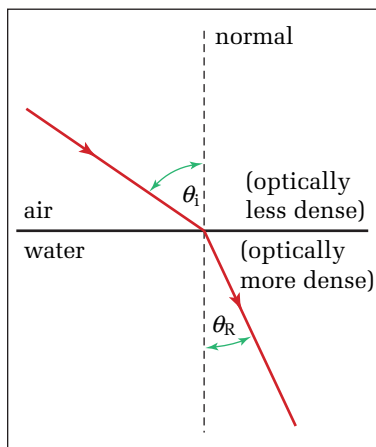$$\frac{\sin \theta_i}{\sin \theta_R} = \text{a constant}$$

Figure 9.26 Light refracts (bends) toward the normal when passing from air into water.

When the incident medium is a vacuum (or air), the constant in Snell's relationship is actually the same value as the index of refraction, n, of the refracting medium. For example, the constant for light travelling from air into water is 1.33. This relationship provides a means of determining the speed of light in any specific medium. For a given angle of incidence, simply measure the angle of refraction when light travels from air into the medium, and determine n. Use the calculated value of n to determine the velocity, v, for that medium. In addition, since many indices of refraction are known, you can identify an unknown material by measuring the angle of refraction in that medium, calculating n, and then comparing it to values of n of known materials.

History Link

Astronomer and mathematician Ptolemy of Alexandria (Claudius Ptolemaeus, approximately 85–168 B.C.E.) made accurate measurements and kept data tables of angles of incidence and refraction of several materials. At a different time in his career, he also developed a set of trigonometric ratios, including sine ratios. He never identified the link between these ratios and the angles of incidence and refraction, however. Which scientific theory is Ptolemy most famous for?

MODEL PROBLEM

Index of Refraction

Light travels from air into an unknown liquid at an angle of incidence of 65.0°. The angle of refraction is 42.0°. Determine the index of refraction of the unknown liquid.

Frame the Problem

- Make a sketch of the problem.

- The *angles of incidence and refraction* are known.

- The index of refraction relates the angles of incidence and refraction when the incident medium is *air*.

- *Air* is the incident medium.
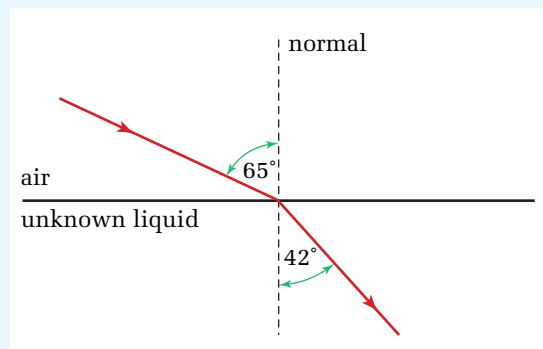
Identify the Goal

The index of refraction, n, of the unknown liquid

Variables and Constants

Known	Unknown
air	n
θ_i	
θ_R	

Strategy

Use Snell's constant

Since the incident medium is air, the constant is the index of refraction, n, of the liquid.

Substitute in the known values.

Calculations

$$\frac{\sin \theta_i}{\sin \theta_R} = \text{a constant}$$

$$n = \frac{\sin \theta_i}{\sin \theta_R}$$

$$n = \frac{\sin 65.0°}{\sin 42.0°}$$

$$n = \frac{0.9063}{0.6691}$$

$$n = 1.354$$

The index of refraction of the unknown liquid is 1.35.

Validate

The absence of units is in agreement with the unitless nature of the index of refraction.

The value is between one and two, which is very reasonable for an index of refraction.

PRACTICE PROBLEMS

7. Light travels from air into a material at an angle of incidence of 59°. If the angle of refraction is 41°, what is the index of refraction of the material? Identify the material by referring to Table 9.2, Index of Refraction of Various Substances.

8. A beam of light travels from air into a zircon crystal at an angle of incidence of 72.0°. What is the angle of refraction in the zircon?

9. What is the angle of incidence of light travelling from air into ethyl alcohol when the angle of refraction is 35°?

Snell's constant ratio is observed for any two media, even when neither medium is air. However, the value of the constant is not the same as the index of refraction of either medium. For example, when light is travelling from water into crown glass, the constant is found to be 1.143. This is a different value than that shown in Table 9.2 for either material. An additional observation shows that the constant might be less than one. In the case of light travelling from quartz into water, the ratio of the sine of the angle of incidence to the sine of the angle of refraction is 0.914. Nevertheless, there is still a relationship between Snell's constants and the indices of refraction of any two media. Many observations and comparisons revealed that Snell's constant is, in fact, the ratio of the indices of refraction of the two media:

$$\frac{\sin \theta_i}{\sin \theta_R} = \frac{n_R}{n_i}$$

For example, Snell's constant for light travelling from water into crown glass (1.143) is the ratio of the index of refraction of crown glass (1.523) to that of water (1.333). This relationship, known as **Snell's law**, is usually rearranged and expressed mathematically as shown in the box below.

SNELL'S LAW

The product of the index of refraction of the incident medium and the sine of the angle of incidence is the same as the product of the index of refraction of the refracting medium and the sine of the angle of refraction.

$$n_i \sin \theta_i = n_R \sin \theta_R$$

Quantity	Symbol	SI unit
index of refraction of the incident medium	n_i	unitless
angle of incidence	θ_i	none (degree is not a unit)
index of refraction of the refracting medium	n_R	unitless
angle of refraction	θ_R	none (degree is not a unit)

In addition to the mathematical relationship, a geometric relationship exists between the incident ray and refracted ray. *When light travels across a boundary between two different materials, the refracted ray, the incident ray, and the normal line at the point of incidence all lie in the same plane.*

Inspection of Snell's law reveals an important general result of the relationship. When light travels from an optically less dense medium into an optically more dense medium, the refracted ray bends toward the normal. Conversely, when light travels from an optically more dense medium into an optically less dense medium, the refracted ray bends away from the normal.

● *Conceptual Problem*

- Use Snell's law to verify the statements in the last paragraph about the directions of bending of the refracted ray and the optical density of the incident and refracting media.

TARGET SKILLS

- **Performing and recording**
- **Analyzing and interpreting**
- **Predicting**

When a scientist collects data and finds a mathematical relationship from the data alone, the relationship is said to be based on empirical evidence. The mathematical relationship is not derived from more fundamental principles. Often, the empirical relationship leads a scientist to more experiments that reveal more fundamental scientific principles.

Snell's law was originally based on empirical evidence. It was more than 300 years before scientists determined the speed of light and were then able to explain refraction on the basis of the ratio of the speed of light in a vacuum and in a medium. In this investigation, you will verify Snell's law empirically and then use it to make predictions.

Problem

Verify Snell's Law.

Equipment

- ray box
- semicircular block of a material
- protractor
- sheet of paper (or polar coordinate graph paper)

Procedure

1. Make a data table with the following headings: Angle of Incidence (θ_i), Angle of Refraction (θ_R), $\sin \theta_i$, and $\sin \theta_R$.

2. Draw a horizontal line across the sheet of paper so that the paper is divided into half.

3. Down the centre of the page, from top to bottom, draw a dashed line at right angles to the horizontal line. This line is the normal line for the air-medium interface.

4. Using a protractor, draw lines on the top half of the page to represent the path of the incident light in air for all of the angles shown in the diagram at right.
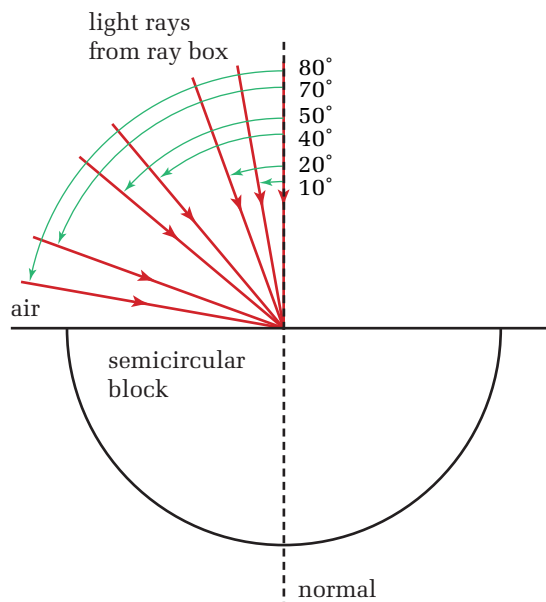
5. Place the semicircular block of material on the page so that the straight side is positioned on the horizontal line. Position the centre of the flat side of the block where the normal line crosses the horizontal line (refer to the diagram).

6. Shine a single light ray from the ray box along the 10° line that you drew on the paper. The ray should strike the flat side of the block of material at the centre and pass through the block. Mark the paper at the point where the light ray exits the semicircular side of the block. Label the incident light ray and the corresponding refracted light ray at the point where it comes out through the semicircular side.

7. Repeat step 6 for each of the angles of incidence shown in the diagram.

8. Remove the semicircular block and draw lines from the centre point where the rays entered the block to the points where they exited. These lines are the paths of the refracted rays.

9. Measure each angle of refraction and enter the data in your table.

10. Determine the values of the sines of the angles of incidence and refraction, and enter the data in your table.

Analyze and Conclude

1. What happens to the light when it passes from air into the refracting medium?

2. As the angle of incidence increases, does the angle of refraction increase more rapidly or less rapidly?

3. Predict what will happen if the angle of incidence continues to increase. Is there a maximum value for the angle of incidence?

4. Plot a graph of θ_i versus θ_R.

5. Plot a graph of $\sin \theta_i$ versus $\sin \theta_R$.

6. Compare the two graphs. How might such a comparison help scientists to develop empirical relationships?

7. Determine the slope of the graph of $\sin \theta_i$ versus $\sin \theta_R$. What does the slope of this line represent?

8. Compare the accepted value of the index of refraction of the material used in the investigation with the experimental value you just obtained.

9. Comment on the experimental results in terms of verification of Snell's law. Suggest reasons for any discrepancies.

10. Using your experimental value of the index of refraction of the material, predict the angles of refraction for angles of incidence of 30° and 60°.

11. Test your predictions.

Apply and Extend

12. Imagine doing the experiment in reverse. Your refracted rays become incident rays and your incident rays become refracted rays. Which angles (incidence or refraction) will approach 90° more rapidly?

13. Predict what will happen as the incident angle approaches 90°.

14. If possible, develop a method for testing your prediction and carry out the test.

Finding the Angle of Refraction

Light travels from air into a ruby crystal at an angle of incidence of 45°. Determine the angle of refraction of the light in the ruby.

Frame the Problem

- Sketch and label a ray diagram.

- Light travels from *air*, an *optically less dense* medium, into ruby, an *optically more dense* medium.

- The refracted ray should *bend toward the normal* line.

- You can use *Snell's law* to determine the extent of the bending of the refracted ray.
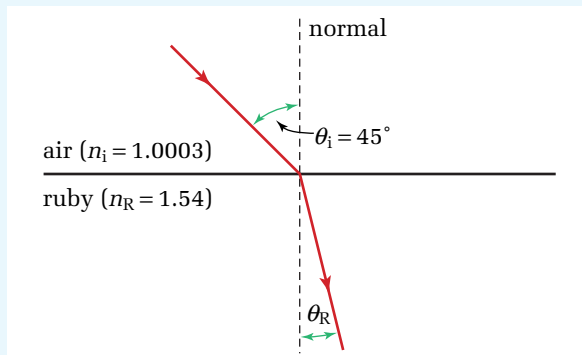
Identify the Goal

The angle of refraction, θ_R, in ruby

Variables and Constants

Known	Implied	Unknown
$\theta_i = 45°$	$n_i = 1.00$	θ_R
	$n_R = 1.54$	

Strategy

Use Snell's law to solve the problem.

Calculations

$n_i \sin \theta_i = n_R \sin \theta_R$

Substitute first

$1.00 \, \sin \, 45° = 1.54 \, \sin \theta_R$

$\dfrac{1.00(0.7071)}{1.54} = \dfrac{\cancel{1.54} \sin \theta_R}{\cancel{1.54}}$

$\sin \theta_R = 0.4592$

$\theta_R = \sin^{-1}(0.4592)$

$\theta_R = 27.33°$

Solve for θ_R first

$\dfrac{n_i \sin \theta_i}{n_R} = \dfrac{\cancel{n_R} \sin \theta_R}{\cancel{n_R}}$

$\sin \theta_R = \dfrac{n_i \sin \theta_i}{n_R}$

$\theta_R = \sin^{-1}\left(\dfrac{n_i \sin \theta_i}{n_R}\right)$

$\theta_R = \sin^{-1}\left(\dfrac{1.00 \sin 45°}{1.54}\right)$

$\theta_R = \sin^{-1}\left(\dfrac{0.7071}{1.54}\right)$

$\theta_R = \sin^{-1}(0.4592)$

$\theta_R = 27.33°$

The angle of refraction in ruby is 27°.

Validate

The angle of refraction is less than the angle of incidence, which is to be expected when light travels from an optically less dense medium (air) into an optically more dense medium (ruby). The magnitude of the angle of refraction is realistic.

PRACTICE PROBLEMS

10. A beam of light passes from air into ethyl alcohol at an angle of incidence of 60.0°. What is the angle of refraction?

11. A beam of light passes from ethyl alcohol into air. The angle of refraction is 44.5°. Determine the angle of incidence.

Refraction and the Wave Model for Light

Have you been wondering how a change in the speed of a wave can cause it to change its direction? The ray model is excellent for visualizing the angles and helping you to set up the calculations, but it is not as helpful as the wave model for visualizing the reason for the change in direction.

Although you cannot see the shape of light waves, recall your study of water waves and envision light waves in the same way. What happens to the shape of the waves when they pass from an optically less dense medium into a more dense medium, where the velocity is slower? Recall from your study of mechanical waves that the frequency of waves does not change. From the wave equation, $v = \lambda f$, you can see that if the velocity decreases and the frequency remains the same, then the wavelength must decrease. Figure 9.27 shows the behaviour of wavefronts of light waves as they pass from air into water at an angle of incidence of 0°. In this case, there is no change in direction, but the wavefronts are closer together because the wavelength is shorter.

Figure 9.28 (A) on the next page shows light wavefronts approaching the interface between two media (air and water) at an angle. You can take the same approach as shown in Figure 9.27 to see why the change in direction occurs. In Figure 9.28 (A), the left edge of each wavefront reaches the interface and begins to slow down, while the rest of the wavefront continues at the faster speed. The dashed lines show where the wavefronts would have been if the speed had not decreased. In a sense, the wavefronts themselves are bending, because one end is travelling more slowly than the other. The direction of the wavefronts (which is, of course, the direction of a light ray) bends toward the normal.
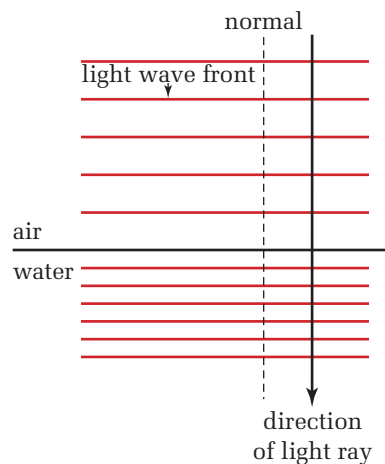

Figure 9.27 Plane light waves, represented by a ray, are travelling from air into water.

COURSE CHALLENGE:
SPACE-BASED POWER

Twinkling Stars Point to a Problem

Design an experiment to test whether microwave frequencies are more or less likely than light to be refracted by variations in the atmosphere.
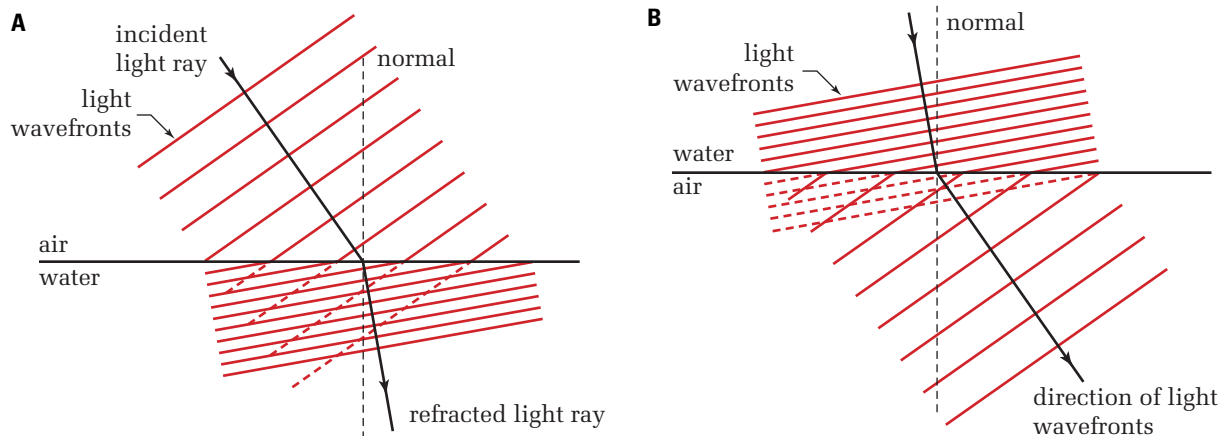
A
incident light ray
normal
light wavefronts
air
water
refracted light ray

B
normal
light wavefronts
water
air
direction of light wavefronts

Figure 9.28 **(A)** The left edges of the wavefronts are bent backwards because the waves travel slower in the water than they do in air. **(B)** The left edges of the wavefronts bend forward, because the waves travel faster in air than in water.

The opposite situation is illustrated in Figure 9.28 (B), where light is travelling from water into air. The edge of the wavefront that reaches the air first speeds up, leaving the other side behind. Again, the wavefronts bend, causing the light ray to bend away from the normal.

Reversibility of Light Rays

How do parts (A) and (B) of Figure 9.28 differ? How are they the same? In Figure 9.28 (A), the ray is travelling from air into water, and the refracted ray bends toward the normal. In part (B), the ray is travelling in the opposite direction, from water into air. The refracted ray bends away from the normal. If you rotated Figure 9.28 (B) and then superimposed the two figures, you would see that the rays that are travelling in opposite directions have exactly the same shape. This situation is always true. If a new ray of light is directed backward along the path of a refracted ray, it will follow the same path after passing across the boundary between the two media. This outcome is called the **principle of reversibility of light**.

• *Conceptual Problem*

- Use Snell's law to verify the principle of reversibility. Explain your reasoning in detail.

Refraction of Sound Waves

Sound waves refract just as light and water waves do, although it is not a phenomenon that you experience frequently. You rarely observe sound passing across a defined interface from one medium to another. However, air temperature affects the speed of sound, and air temperatures can change significantly in air relatively close to the ground. Figure 9.29 illustrates one situation in which refraction of sound is clearly observable. Instead of changing direction suddenly at an interface between two media, the direction of sound changes gradually as it passes through air of differing temperatures. Lightning is always accompanied by thunder, because the lightning superheats the air which expands faster than the speed of sound. This sudden expansion results in a sonic boom. Although the thunder is extremely intense at its source, it is rarely heard more than 25 km away because the sound refracts upwards away from the ground.
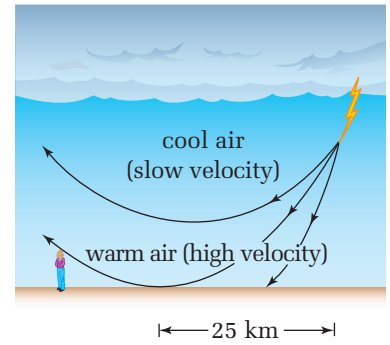

Figure 9.29 Sound travels faster in warmer air and therefore the sound of thunder is refracted upward away from the surface of Earth.

• *Conceptual Problem*

- Use the same reasoning that was used above to explain why you do *not* hear thunder at a great distance to explain why you *do* hear sounds from long distances on a cool, clear night.

Total Internal Reflection

So far, you have studied refraction of light as it travels from an optically less dense medium into an optically more dense medium, and as it travels from an optically more dense medium into an optically less dense medium. Have you noticed anything unusual that occurs in the second case, but not in the first? Complete the Quick Lab on the opposite page and focus on any differences that you observe between light travelling from the optically less dense into the more dense medium, compared to light travelling in the opposite direction.

When light travels from an optically more dense material into an optically less dense one, the refracted light bends away from the normal. As you can see in Figure 9.30, for all angles of refraction up to and including 90°, the light is simultaneously reflected and refracted. The amount of reflected light gradually increases and the amount of refracted light gradually decreases as the angle of incidence increases. Notice that the angle of refraction increases more rapidly than the angle of incidence.

Figure 9.30 The incident light in the Plexiglass™ is both partially refracted and partially reflected for all angles of incidence **(A)** up to the critical angle, θ_c, for the Plexiglas™ and **(B)** at the critical angle. **(C)** As soon as the angle of incidence exceeds the critical angle, total internal reflection occurs.

Observing Total Internal Reflection
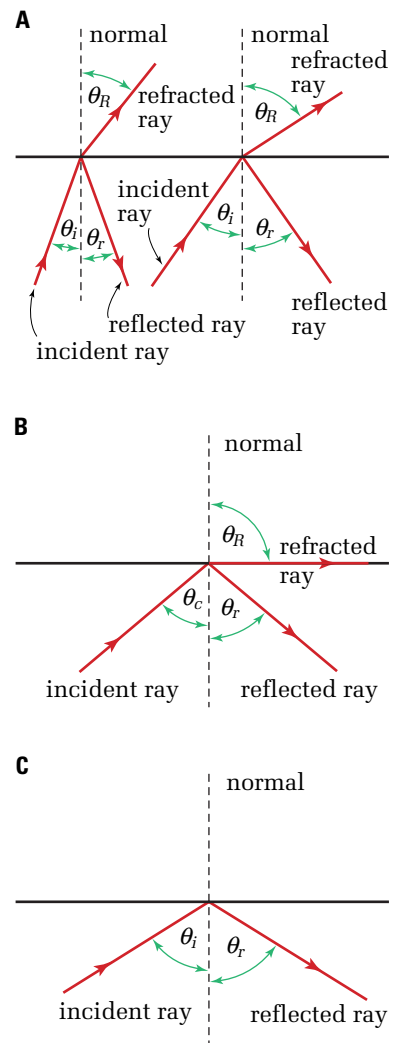
In this lab, you will observe the same object, a pencil, from three different perspectives. Position a 1.0 L beaker so that you can observe it from the top, side, and bottom. Fill the beaker with water. Observe the motion of a pencil as it is slowly submerged into the water at a very small angle with the horizontal, as shown in the first part of the diagram.

In each of the following cases, gradually move the pencil under the surface of the water, after referring to the indicated part of the diagram. Observe the appearance of the pencil:

- from almost directly above the water, as shown in (B)
- from the side, so that you are looking toward the surface of the water as shown in (C)

- from the side, looking at the surface of the water from below, as shown in (D)
- from below, looking up through the bottom of the beaker

Analyze and Conclude

1. Describe in detail the appearance of the pencil as you saw it from each perspective.

2. Describe the most significant difference that you observed between one perspective and the others.

3. Explain how and why the appearance of the pencil differed so greatly from the different perspectives. What properties of light and its interaction with various materials were responsible for these differences?

A   B   C   D   E
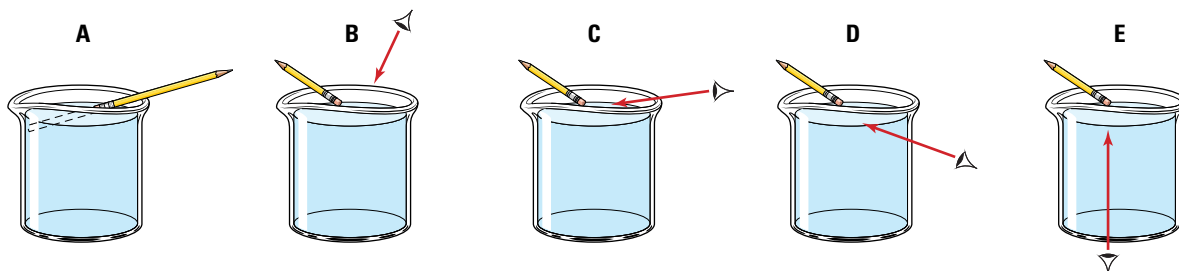
The angle of refraction can be increased only until it reaches its maximum possible value of 90°, as seen in Figure 9.30 (A). The maximum angle of refraction in any medium is 90°, because it is not physically possible to exceed this value without having the light remain in the original medium. In that case, the light would no longer be refracted, but would be reflected.

The angle of incidence, for which the angle of refraction is exactly 90°, is called the **critical angle**, θ_c as illustrated in Figure 9.30 (B). In fact, something very interesting occurs when the angle of incidence is increased beyond the critical angle — all of the incident light is completely reflected back into the optically more dense Plexiglas™, as shown in Figure 9.30 (C). None of the light is refracted

into the optically less dense air. The interface between the two media behaves as if it was a perfect mirror surface. This phenomenon is called **total internal reflection**.

Even the most efficient (metallic) mirrored surfaces absorb from 8 percent to 11 percent of the incident light. By contrast, when total internal reflection occurs in a glass prism, *none* of the light is absorbed during reflection and only about 2 percent of the light is absorbed by the glass itself.

TOTAL INTERNAL REFLECTION

The two conditions required for total internal reflection to occur are as follows.

- The light must travel from an optically more dense medium into an optically less dense medium.

- The angle of incidence must exceed the critical angle, θ_c, associated with the material.

You can determine the critical angle, θ_c, for light travelling from diamond into air by using Snell's law, as demonstrated in the following problem.

MODEL PROBLEM

Finding θ_c

Determine the critical angle for diamond.

Frame the Problem

- Make a sketch of the problem. Label all of the media, angles, and rays.

- Light is travelling *from* an optically *more dense* material *into* an optically *less dense* material

- The *critical angle* of incidence corresponds to an angle of refraction equal to 90°.

- The needed *indices of refraction* are listed in Table 9.2.
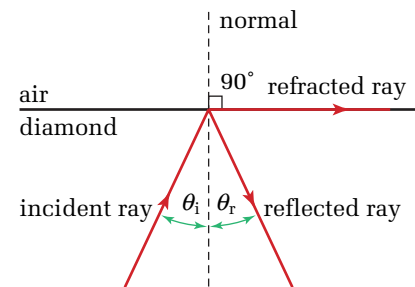
A light ray striking a diamond-air interface, with an angle of incidence equal to θ_c

Identify the Goal

Calculate the critical angle, θ_c, for diamond.

continued from previous page

Variables and Constants

Implied	Unknown
$n_{air} = 1.0003$	$\theta_{c/diamond}$
$n_{diamond} = 2.42$	
$\theta_{air} = 90°$	

Strategy

The critical angle of incidence, $\theta_{c/diamond}$, occurs when the angle of refraction is exactly 90°.

Use Snell's law.

Find the required indices of refraction by using Table 9.2.

Substitute values into the formula, using the fact that $\theta_i = \theta_{c/diamond}$ when $\theta_R = 90°$.

Evaluate.

Calculations

$$n_i \sin \theta_i = n_R \sin \theta_R$$

$$2.42 \ \sin \theta_{c/diamond} = 1.0003 \sin \ 90°$$

$$\sin \theta_{c/diamond} = \frac{1.0003 \times 1.000}{2.42}$$

$$\sin \theta_{c/diamond} = 0.4133$$

$$\theta_{c/diamond} = \sin^{-1} 0.4133$$

$$\theta_{c/diamond} = 24.415°$$

The critical angle of incidence for diamond is 24.4°.

Validate

The angle of incidence is less than the angle of refraction.

PRACTICE PROBLEMS

12. Determine the critical angle for ethyl alcohol.

13. The critical angle for a new kind of plastic in air is 40°. What is the critical angle for this plastic if it is immersed in water?

14. Optical fibres, made of a core layer surrounded by cladding, trap transmitted light by ensuring that the light always strikes the core-cladding interface at an angle greater than the critical angle. Calculate the critical angle between the core-cladding interface.

15. While swimming in a friend's pool, you allow yourself to slowly sink to the bottom exactly 3.0 m from the edge of the pool. As you sink you fix your gaze on the edge. Calculate how deep your eyes must be below the surface for total internal reflection to occur.

PROBLEM TIP

When using Snell's law to determine the critical angle for a transparent material, the value for the sine of the angle of refraction will always be unity (one), because the maximum angle of refraction is 90°.

Applications of Total Internal Reflection

What do driveway reflectors, binoculars, and optical fibres all have in common? Each technology is based on total internal reflection of light. You can understand the operation of these devices by studying total internal reflection in a simple glass prism, such as the one illustrated in Figure 9.31. Notice that the cross section of the prism is an isosceles right triangle. The critical angle for most types of glass and plastic is less than 45°. When light enters the prism perpendicular to the glass surface on one of the shorter sides of the prism, it will strike the longer side at an angle of 45°, as shown in Figure 9.31 (A). Because the angle of incidence at the glass-air interface is greater than the critical angle for glass (θ_c is in the range of 40° to 43°), the light undergoes total internal reflection and passes out into the air perpendicular to the third glass surface.

If the light enters the glass prism on the longer side, as shown in Figure 9.31 (B), the light strikes both glass-air interfaces and is totally internally reflected twice inside the prism. The light finally leaves the prism through the same side that it entered, having been reflected back parallel to its original path.

Optical devices such as periscopes, binoculars, and cameras use transparent glass or plastic prisms as reflectors to change the direction of light by either 90° or 180°, as shown in Figure 9.32. In some cameras, a single pentaprism, similar to that shown in Figure 9.32 (C), reflects the light into the viewing eyepiece. As discussed earlier, prisms are particularly efficient at reflecting light — even more efficient than high-quality mirrors. The extra amount of light reflected by prisms provides a brighter image than a mirror, which can be very important when using periscopes, binoculars, cameras, and other optical devices in dim light.
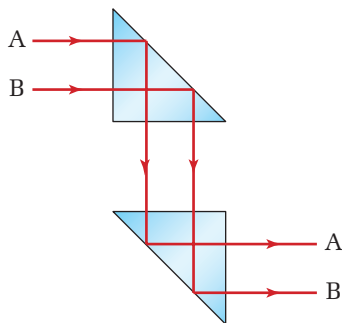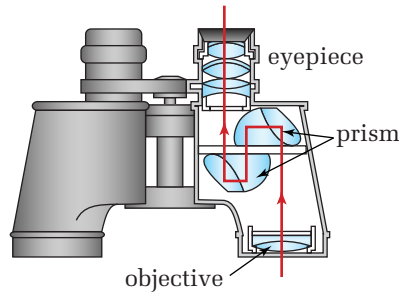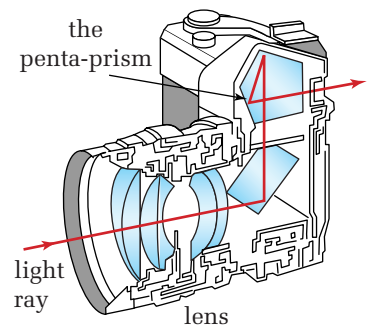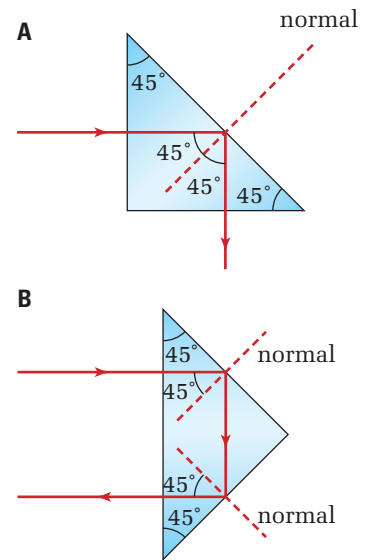

Figure 9.31 The direction of the light can be changed by either 90° or 180° as the light undergoes total internal reflection inside a single 45°–45°–90° prism.

Figure 9.32 **(A)** In a periscope, total internal reflection occurs once in each prism to laterally displace the light the desired amount. Notice that the image remains upright.

(B) In a pair of binoculars, total internal reflection occurs twice in each prism, making it possible both to reduce the length of the binoculars and to achieve lateral displacement of the image.

(C) The principle of total internal reflection is also incorporated into the design of some cameras.

One of the most widely used applications of total internal reflection is found in a familiar device known as a **retroreflector**. Anyone travelling in any type of road vehicle, or even on a bicycle, uses retroreflectors as a safety precaution. A retroreflector is an optical device that reflects light directly backward, parallel to its original path. Car and bicycle reflectors and markers used to identify hazards on highways and roads are all designed to reflect light by means of total internal reflection.

As the light ray diagram in Figure 9.33 shows, light travelling from a car headlight toward a bicycle reflector passes through the reflector's glass and strikes the many sets of flat, angled surfaces at the back of the device. The light undergoes total internal reflection at the 45° surfaces, before passing out through the front of the reflector and back toward the light source. If a single plane mirror was used, the light would be reflected uselessly off to the side of the road.

Optical Fibres

Perhaps one of the most innovative and exciting ways in which total internal reflection is integrated with technology is in the transmission of information carried by light energy in optical fibres. An optical fibre is a very fine strand of a special kind of glass. When light shines into one end of an optical fibre, total internal reflection causes the energy to be confined within the fibre (Figure 9.34). The light travels along the inside of the length of the fibre, carrying information in the form of pulses. Even if the optical fibre is literally tied in knots, the light will still travel through the fibre until it reaches the other end.

A typical optical fibre is about the thickness of a human hair. As illustrated in Figure 9.35, on the next page, the fibre consists of a glass core, roughly 50 μm in diameter, surrounded by a thin layer known as "optical cladding," which is made of another type of glass. The cladding increases the total outside diameter to about 120 μm. The glass core has a slightly higher index of refraction ($n = 1.5$) than the optical cladding layer ($n = 1.47$), as is required for total internal reflection. By surrounding the entire length of the core, the outer layer of glass cladding ensures that the critical angle of incidence of the core remains constant throughout the entire length of the fibre.

Because the difference in refractive indices of the two materials that make up an optical fibre is very small, the critical angle of the glass core can be as high as 78.5°. Consequently, only light entering the optical fibre at angles of incidence greater than 78.5° can be transmitted along it. What happens to any light that enters the optical fibre at angles up to and including the critical angle of incidence for the core? The angle, θ_A, that is shown in the Figure 9.35 is called the "acceptance angle" for the fibre, and in the case of this fibre, the θ_A is 11.5° (90° − 78.5°). Any light entering the fibre at an
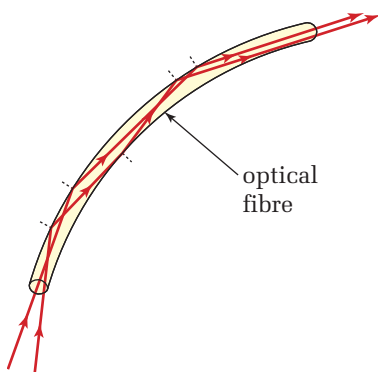

Figure 9.34 The light travelling inside the optical fibre will continue to undergo total internal reflection along the interior wall of the fibre until it reaches the other end.

angle less than the acceptance angle will meet the cladding at an angle of incidence greater than the critical angle, θ_c, and will experience total internal reflection. The light enters the fibre and then travels along it, reflecting from side to side in a zigzag path until it reaches the other end.

Groups of optical fibres are often bundled together to produce what are called "optical fibre cables," which are usually covered with a protective plastic covering (Figure 9.36). Because these cables have a small diameter (some less than a millimetre) and are flexible, they can fit into spaces too small for metallic wires. They can also be used safely in corrosive and explosive environments.

The optical fibres are made from a very special form of ultra-pure fused silica (sand). An optical fibre cannot be made of ordinary glass, because internal impurities reduce by a factor of 100 000 the intensity of any light entering it, after the light travels a distance of only 5 m. Currently, the very pure form of glass used in optical fibres is so transparent that light can travel up to 50 km along the fibre. To appreciate the purity of this glass, note that normal sunlight penetrates to a depth of only about 100 m in ordinary seawater before it is completely absorbed, and at depths below this, there is total darkness.

Clearly, sending information along an optical fibre requires a unique light source. The unique properties of laser light allow audio, video, and text based data to be transmitted simultaneously over long distances. When the signals are received they can be separated and processed individually. The light produced by a laser is called "coherent light," because in laser light, the light waves emitted by the source leave perfectly in phase with each another and are all of the same wavelength. All other types of light sources give off light waves randomly, so the light waves are not in phase.

The development in 1970 of the ultra-pure glass required to transmit light signals many kilometres made it possible to use optical fibres as a practical telecommunications medium. Developments in laser light sources and signal receivers meant that, by 1980, it was possible to establish a worldwide installation of optical fibre communication systems. Some of the advantages of using optical fibres rather than metal conductors are the ability to significantly increase the amount of transmitted data, reductions in both weight and size, lower operating costs, and increased security in transmitting sensitive data.
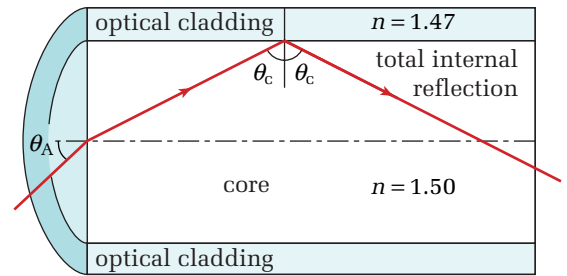

Figure 9.35 Only light that has an angle of incidence of more than 78.5° will be totally internally reflected down the entire length of the optical fibre.
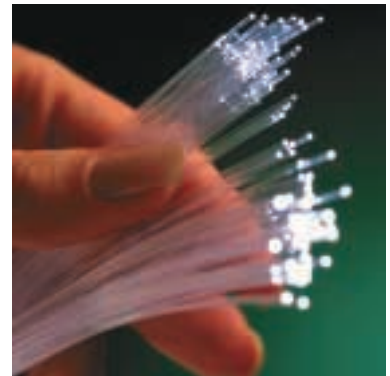

Figure 9.36 Total internal reflection between the optical fibre core and cladding allows the transmission of information in the form of light pulses.

QUICK
LAB

**Determining the
Critical Angle**

TARGET SKILLS

• **Initiating and planning**
• **Predicting**
• **Performing and recording**

So far in this unit, the light ray model has been a very useful visual scientific model for analyzing and predicting the behaviour of light. A mathematical formula is another very powerful and commonly used type of scientific model that can be used for the same purposes. For example, Snell's law can be used to predict the critical angle of incidence for any material.

■ Given the index of refraction for a known material, use Snell's law to predict the critical angle of incidence for the material, and then design an investigation to experimentally verify the prediction.

■ Prepare an appropriate list of required equipment and materials. The transparent material to be used in the investigation will be specified by your teacher.

■ Design a procedure for testing your prediction and present it to your teacher for approval. After it has been approved, carry out the procedure and record and analyze all required data.

Analyze and Conclude

Compare the theoretical predictions and the experimental (empirical) evidence, and account for any discrepancies.

9.2   Section Review

1. **C** Provide a logical reason for the increase in the speed of sound in air with a rise in the temperature of the air.

2. **K/U** Define Mach number.

3. **C** Given that the speed of any wave obeys the wave equation, $v = \lambda f$, and the speed of light is much greater than the speed of sound, comment on the values of wavelength and frequency for light compared to sound.

4. **C** An ambulance is not moving when it turns on its siren. As the ambulance starts moving, you hear the pitch of the siren rise. How is the ambulance moving relative to you?

5. **K/U** What causes sonic boom?

6. **MC** Why do supersonic aircraft fly extremely high?

7. **C** Can anything with mass travel faster than the speed of light? Explain.

8. **K/U** What is the fundamental definition of the index of refraction?

9. **C** Using a diagram of wavefronts, explain why light changes direction when passing across the interface between two media.

10. **C** Give an example of the refraction of sound.

11. **MC** Why are prisms often used in high-quality optical instruments in place of mirrors?

12. **I** Imagine that you are using Snell's law to find the angle of refraction and in the last step, your calculator indicates that an error has occurred. Assume that you have entered the data correctly. Explain what probably happened.