11.1 Refraction of Light

Key Terms
refraction
refracted ray
angle of refraction
index of refraction
dispersion

Some aeronautic engineers need to study patterns of moving air so that they can design shapes to reduce air friction. How can they see something that is transparent? The colours in **Figure 11.1** show moving air. As air hits the cone, it gets compressed in different ways. Compressed air has a higher density than uncompressed air. Even though air is transparent, a technique called Schlieren photography uses certain properties of light to create the light and dark regions where changes in density occur. Then, a computer converts the light and dark regions into different colours. All of this is possible because of a property called *refraction*. **Refraction** is a property of light in which the speed of light and its direction of travel change.

refraction the bending of light as it travels, at an angle, from a material with one refractive index to a material with a different refractive index

Understanding Refraction

To understand refraction, consider a familiar analogy. What happens if you are riding in a golf cart and you hit some mud or gravel? The front wheels suddenly slow down, but the back wheels keep going and the golf cart twists around. Similarly, when light travels from one medium into a different medium, both its speed and direction may change.

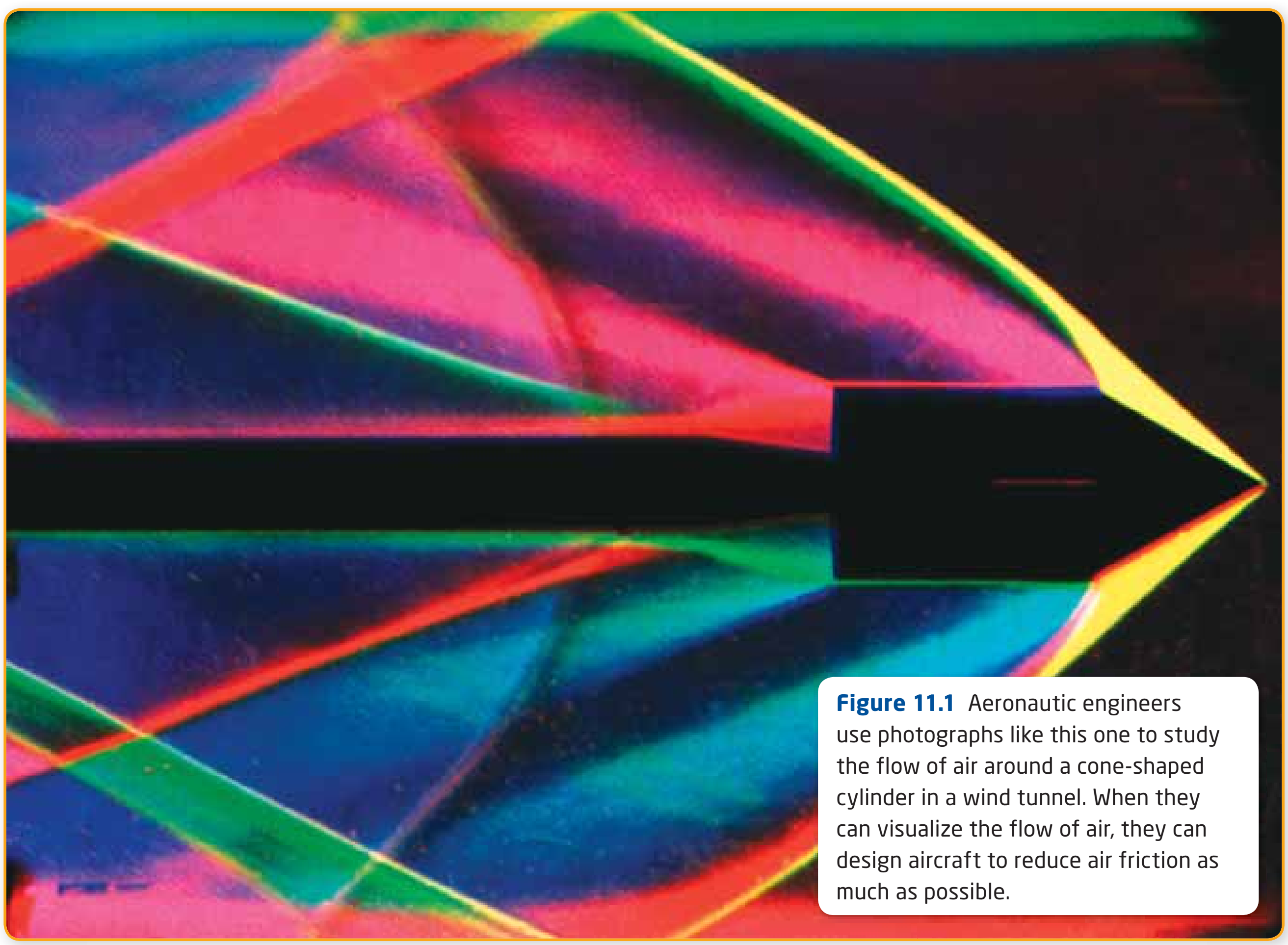


Figure 11.1 Aeronautic engineers use photographs like this one to study the flow of air around a cone-shaped cylinder in a wind tunnel. When they can visualize the flow of air, they can design aircraft to reduce air friction as much as possible.

Describing Refraction

As mentioned in Chapter 10, light has many properties. For example, light reflects from smooth surfaces according to the two laws of reflection. There are additional properties of light that are important in describing refraction. Light travels in a straight line and at a constant speed as long as the medium it is travelling in is the same. However, when light travels from one medium to another, for example, from air to water, the light rays refract (bend). Recall that this means that both its direction and speed change. **Figure 11.2** shows how a beam of light refracts as it enters a container of water.

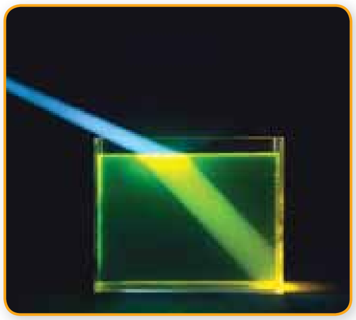


Figure 11.2 Dust particles in the air scatter the light and allow you to see the beam. A fluorescent substance in the water emits a green light, which allows you to see the path of the light beam in the water.

Since light travels as a wave, it is helpful to use the wave model of light along with the concept of a ray to visualize the mechanism that causes light to change direction. To see how the wave model of light and the concept of a ray fit together, look at **Figure 11.3**. Scientists often choose a specific part of a wave to follow and call it a wave front. As you can see in **Figure 11.3**, the crests, or high points, of the waves are *wave fronts*. The ray (red arrow), which shows the direction in which the waves are travelling, is perpendicular to the wave fronts.

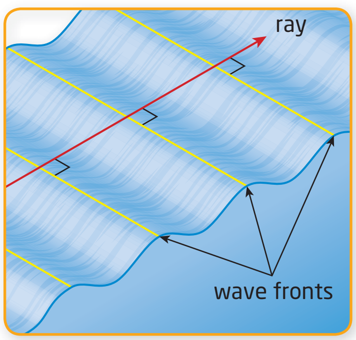


Figure 11.3 All the points on a wave front move together in the direction in which the wave itself is moving.

To visualize what happens when a wave front reaches the surface between two media—called the *boundary*—imagine each wave front as a row of students in a marching band. **Figure 11.4** shows the movement of the band as it marches from an area of firm ground to an area of mud. The mud is so sticky that the students cannot march as fast. As each student reaches the mud, he or she slows down. The slower students "pull" the line back and cause a bend in the line, representing the wave front. As a result, the direction in which the entire row is marching changes. The larger red arrow in the diagram shows the direction in which the band, as a whole, is moving. This is what happens when a light wave crosses the boundary between two media: its speed changes.

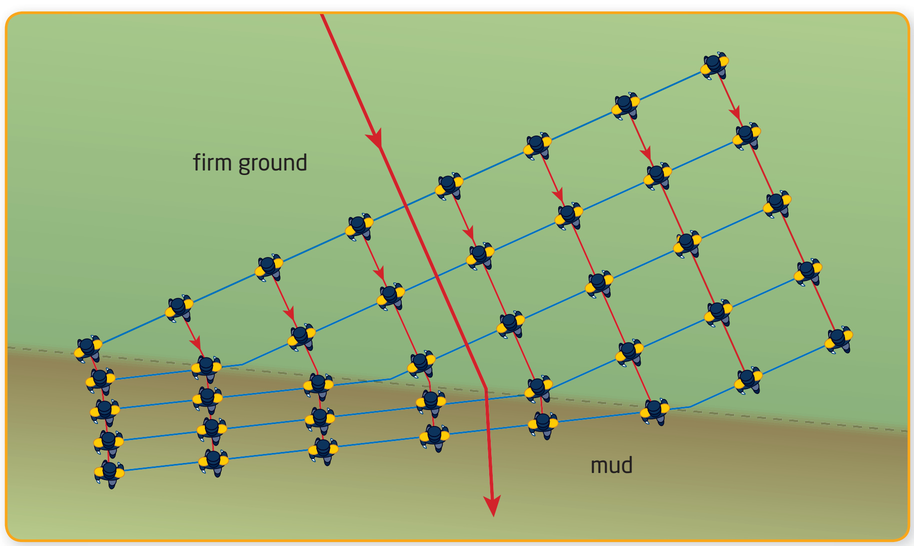


Figure 11.4 Each row of students represents the crest of a wave. When one end of the wave front slows down, the direction of the wave changes. This analogy, like all analogies, has limitations. However, it can help you visualize refraction.

Suggested Investigation

Inquiry Investigation 11-A, Investigating Refraction, from Air to Water, on page 476

Learning Check

1. What property of light changes from one medium to another?
2. Define the term *refraction*.
3. Examine **Figure 11.2**. Explain why light bends when it enters the water. Include a ray diagram with your explanation.
4. Think of an analogy, other than a marching band, that helps you understand why light refracts when it goes from one medium to another. Include a sketch to illustrate your analogy.

Fermat's Principle

The exact path of light as it travels from one medium to another can be found by applying Fermat's principle, which says that when light travels from one point to another, it follows the path that will take the least time. In a single medium, the path that takes the least time is a straight line. When travelling from one medium to another, the path that takes the least time is not a straight line.

Compare the dashed line in **Figure 11.5** with the solid, bent line going from point A in air to point B in water. In air, where light travels faster, the solid line is longer than the dashed line. In water, where light travels slower, the solid line is shorter than the dashed line. Light travels a longer distance in air and a shorter distance in water than it would if it followed a straight line. Following the bent path (solid line) takes less time than following the straight path (dashed line).

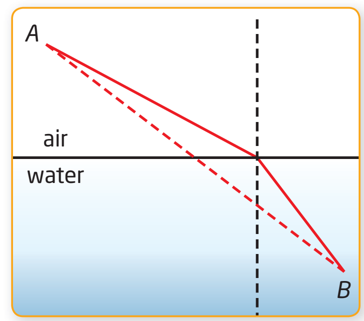


Figure 11.5 When light travels a greater distance in air (where light travels faster) and a shorter distance in water (where light travels slower), the time of travel is minimized.

Describing Refraction Using Rays

Most of the terms used to describe refraction are the same as the terms used to describe reflection. In **Figure 11.6**, notice that in addition to the incident ray and the reflected ray, there is now a third ray called the **refracted ray**. As you can see, the incident ray is divided into two rays—one that reflects and one that refracts. (The word *refract* comes from the Latin word *refringere*, which means to break up). Because there is an additional ray, there is an additional angle to keep track of. The new angle is the **angle of refraction**, shown by the upper-case *R*. The angle of refraction is the angle between the normal and the refracted ray.

refracted ray the ray that is bent upon entering a second medium

angle of refraction the angle between the normal and a refracted ray

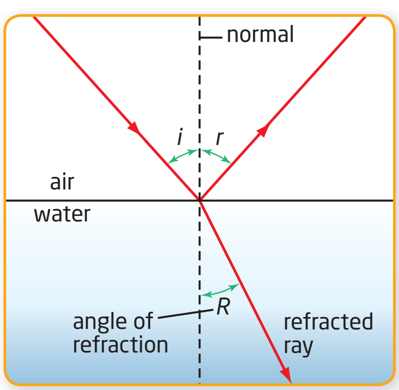


Figure 11.6 Note the new terms: angle of refraction and refracted ray.

Suggested Investigation

Real World Investigation 11-C, Saving Time, on page 478

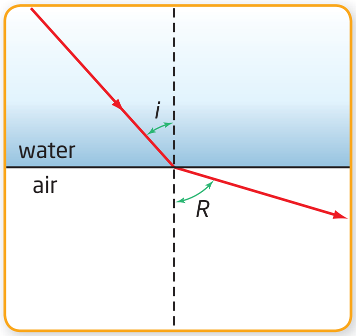


Figure 11.7 Going from water to air, the refracted ray is bent away from the normal.

The Direction of the Refracted Ray

In **Figure 11.6**, a light ray travels from a medium in which its speed is faster (such as air) to a medium in which its speed is slower (such as water). The refracted ray bends toward the normal. However, in **Figure 11.7**, a light ray travels from a medium in which its speed is slower to a medium in which its speed is faster, and the refracted ray bends away from the normal. Note that reflection always occurs. However, when discussing only refraction, the reflected ray will be omitted from the diagrams to focus on the angle of refraction and the refracted ray. Later in the chapter, you will see that the reflected rays are important. For now, as in **Figures 11.6** and **11.7**, only the refracted ray will be drawn.

Index of Refraction

How much a light ray refracts is determined by the extent of the change in the speed of light as it travels from one medium to another. When light passes from one medium to the next and the change in the speed of light becomes greater, the angle of refraction becomes greater.

The speed of light is 3.00 × 108 m/s in a vacuum, such as space, where there is no matter. The speed of light is less than 3.00 × 108 m/s in any other medium. For example, the speed of light in water is 2.26 × 108 m/s. These numbers are extremely large and inconvenient to use for describing relative speeds. Therefore, scientists have devised a much easier system for describing relative speeds.

The **index of refraction** is the ratio of the speed of light in a vacuum to the speed of light in a given medium. The symbol for the index of refraction is *n*, the symbol for the speed of light in a vacuum is *c*, and the symbol for the speed of light in any given medium is *v*. Therefore, you can express the index of refraction in mathematical form as shown below.

index of refraction the ratio of the speed of light in a vacuum to the speed of light in a given medium

Study Toolkit

Multiple Meanings The word *index* has multiple meanings. Drawing a word map like the one on page 448 can reinforce your understanding of a word's multiple meanings.

Index of Refraction

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

n is the index of refraction

c is the speed of light in a vacuum

v is the speed of light in a medium

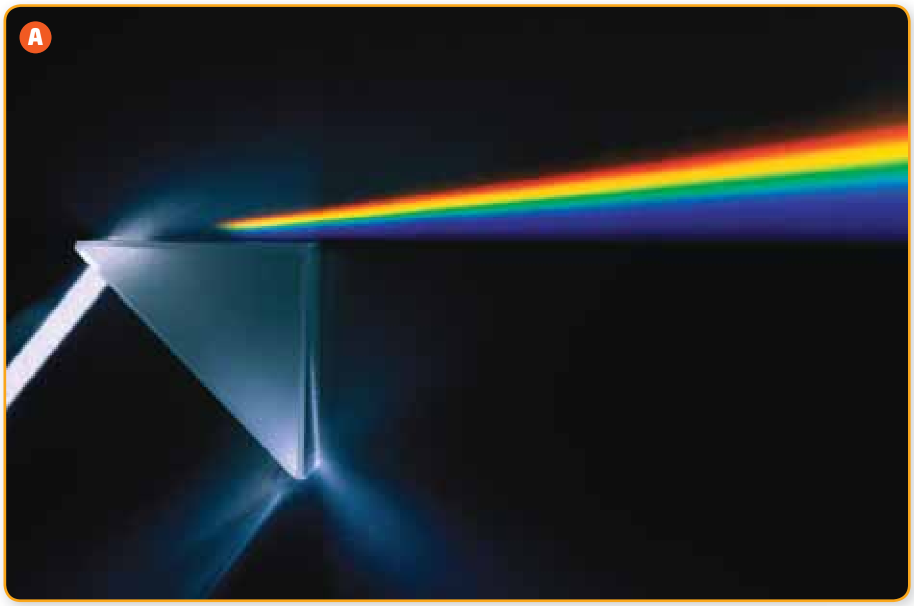
For example, the index of refraction of water is in a given medium.

$$\frac{\text{speed of light in a vacuum}}{\text{speed of light in water}} = \frac{3.00 \times 10^8 \text{ m/s}}{2.26 \times 10^8 \text{ m/s}} = 1.33$$

Dispersion

In **Figure 11.8A**, white light, which includes all the wavelengths of visible light, is refracting twice: once when it enters the prism and again when it leaves the prism. When the white light leaves the prism, the light is separated into a spectrum of colours. This process is called **dispersion**. This is also illustrated in **Figure 11.8B**. Notice that blue light bends more than red light. So, blue light must travel slower than red light. In fact, each colour of light travels at a slightly different speed in any medium. Only in a vacuum do all the wavelengths of light, and all other forms of electromagnetic waves, travel at the same speed—3.00×10^8 m/s.

dispersion the process of separating colours by refraction



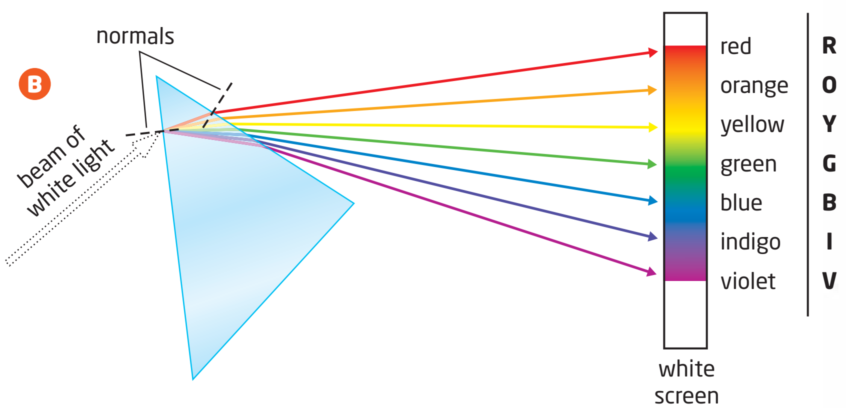


Figure 11.8 **A** When white light leaves the prism, it is refracted again. Since each colour of light travels at a different speed, each colour of light refracts a different amount. **B** You can remember the order of the colours of light in a spectrum by remembering the name Roy G. Biv, which stands for red, orange, yellow, green, blue, indigo, violet.

Sense of scale

A single aluminum atom is about the size of a nanometre. A nanometre is one billionth of a metre.

Suggested Investigation

Inquiry Investigation 11-B, Analyzing the Index of Refraction, on page 477

Go to **scienceontario** to find out more

Reporting Indices of Refraction

If each colour of light has its own index of refraction, what value do you use as the index of refraction for "light"? Scientists have agreed to use one specific wavelength of light as a standard for reporting. When scientists were first studying indices (plural of *index*) of refraction, one of the easiest pure colours to produce was a yellow with a wavelength of 589 nm (nm is the symbol for nanometre, which is 10^{-9} m). This wavelength of light is emitted from heated sodium vapour. So scientists use yellow as a standard for reporting the index of refraction for light.

When reporting the index of refraction for a gas, remember that gases are affected by both temperature and pressure. Liquids and solids are affected much less by pressure, but they can be affected by temperature. So, in tables of indices of refraction, such as **Table 11.1**, the temperature (in °C) is reported for liquids and solids, but both the temperature and pressure (in kPa) are reported for gases. Notice that the index of refraction is always greater than 1. This is because the speed of light is always higher in a vacuum than in a medium. As the speed of light decreases due to the medium, the index of refraction increases.

The indices of refraction (n) for the solids and liquids at 20°C in **Table 11.1** have been measured. Therefore, you can count on the accuracy of the values when you work with the substances at room temperature. All the liquids are clear and colourless. You may recognize the names of some of the substances, such as the liquid carbon disulfide. Carbon disulfide is an example of a solvent. The solid called fused quartz is used in making lenses and mirrors. It is not the same as the mineral with the common name quartz. The three types of glass (crown, crystal, and flint) have different values of n because different substances are added in the glass-making process, and that process varies.

If you know the index of refraction of a substance, you can calculate the speed of light in that substance. See the Sample Problem on page 455.

Table 11.1 Indices of Refraction of Various Substances

Substance	Index of Refraction (n)
Vacuum	1.000 00
Gases at 0°C and 101.3 kPa	
Hydrogen	1.000 14
Oxygen	1.000 27
Air	1.000 29
Carbon dioxide	1.000 45
Liquids at 20°C	
Water	1.333
Ethyl alcohol	1.362
Glycerol	1.470
Carbon disulfide	1.632

Substance	Index of Refraction (n)
Solids at 20°C	
Quartz (fused)	1.46
Plexiglas™ or Lucite™	1.51
Glass (crown)	1.52
Sodium chloride	1.54
Glass (crystal)	1.54
Ruby	1.54
Glass (flint)	1.65
Zircon	1.92
Diamond	2.42

Sample Problem: Calculating the Speed of Light in Different Media

Problem

Calculate the speed of light in fused quartz.

Solution

Look up the index of refraction for fused quartz in **Table 11.1**.

$n = 1.46$

Write the equation that relates the index of refraction to the speed of light in the medium.

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

Speed in the medium (v) is the unknown variable, so arrange the equation to solve for v.

$$nv = \frac{c}{\cancel{v}}\cancel{v}$$

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

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

Insert the values for the index of refraction for fused quartz and the speed of light in a vacuum, and calculate v.

$$v = \frac{3.00 \times 10^8 \text{ m/s}}{1.46}$$

$$= 2.05 \times 10^8 \text{ m/s}$$

The speed of light in fused quartz is 2.05×10^8 m/s.

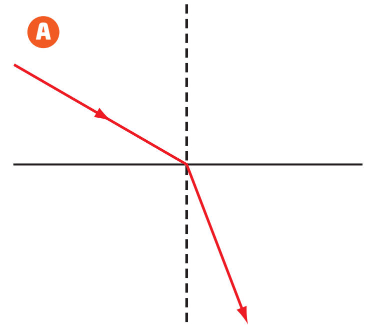
Check Your Solution

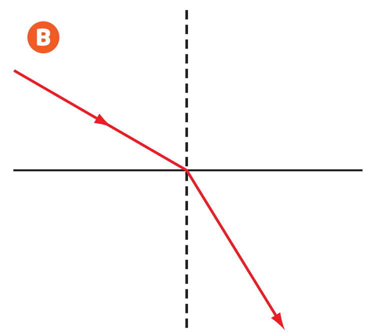
The value for v is smaller than the speed of light in a vacuum, which it must be. The units are metres per second, which they should be for speed.

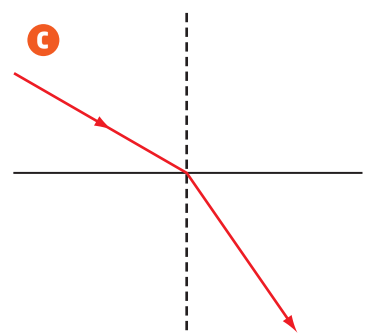
Practice Problems

1. Calculate the speed of light in flint glass.
2. Calculate the speed of light in crown glass.
3. **a.** The speed of light in a solid is 1.24×10^8 m/s. Calculate the index of refraction.
   b. Use **Table 11.1** to identify the substance.
4. The diagrams at the right show the path of light as it passes from air into the three solids in the first three problems. The angle of incidence is the same for all three solids. Examine the index of refraction values in the problems, and identify each solid.

GRASP
Go to **Science Skills Toolkit 11** to learn about an alternative problem solving method.







Use these diagrams to answer question 4.

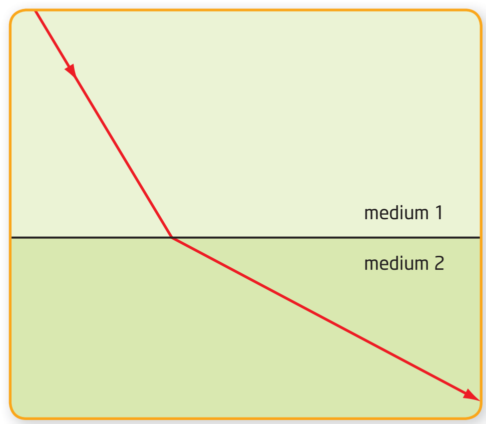
Section 11.1 Review

Section Summary

- Light rays refract when they cross a boundary between media in which the speeds of light are different.
- If a light ray goes from a medium in which its speed is higher (such as air) into a medium in which its speed is lower (such as water), the refracted ray bends toward the normal.
- If a light ray goes from a medium in which its speed is lower (such as water) into a medium in which its speed is higher (such as air), the refracted ray bends away from the normal.
- The index of refraction of a medium is the ratio of the speed of light in a vacuum to the speed of light in the medium $n = \frac{c}{v}$. A ratio greater than 1 results.
- Dispersion is the separation of the various colours of light when white light crosses the boundary between different media at an angle.
- The speed of each wavelength of light is different in any given medium. The speed of all wavelengths of light is 3.00×10^8 m/s in a vacuum.

Review Questions

K/U **1.** In the diagram on the right, a light ray is crossing the boundary between air and water. Which medium is air, and which medium is water? Explain your reasoning.



Use this diagram to answer question 1.

K/U **2.** Define the index of refraction.

T/I **3.** Calculate the speed of light in glycerol.

K/U **4.** Why must a table that lists indices of refraction of gases include the temperature and pressure of the gases?

K/U **5.** When white light exits a prism, the light is dispersed.

a. Explain the dispersion of white light through a prism.

b. Which colour of light travels faster in glass: yellow or violet? Explain your reasoning. Review **Figure 11.8** if necessary.

C **6.** Use the symbols n, v, and c to show why the index of refraction of any substance is always greater than 1.

A **7.** "Light can travel across the boundary between two media that have different indices of refraction without bending." What is the angle of incidence for which this statement is true? Use a diagram to support your answer.

T/I **8.** Suppose that you have two blocks of glass that look very similar. You are asked to determine which block is crown glass and which block is flint glass. Describe a method you could use to do this. What equipment would you need?