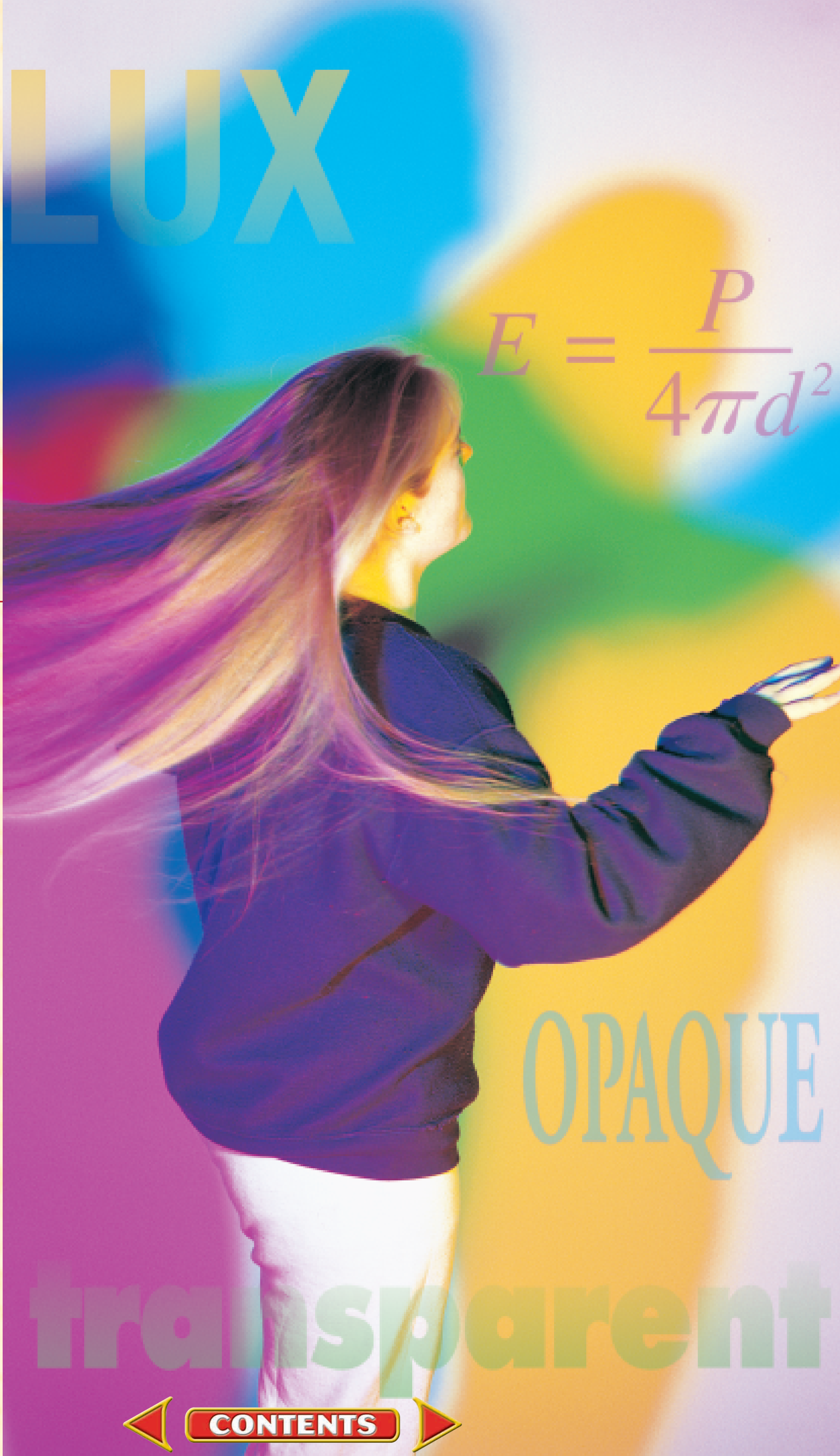
# Colors to Mix and Match

**Explain how each of the colors in the shadows is formed.**

*Look at the text on page 384 for the answer.*



CHAPTER

# 16 Light

Light and sound are two ways you receive information about the world around you. Of the two, light seems to provide the greater variety of information. The human eye can detect tiny changes in the size, position, brightness, and color of an object. Our eyes can usually distinguish shadows from solid objects and sometimes distinguish reflections of objects from the objects themselves.

Our major source of emitted light is the sun. Other natural sources of emitted light include flames, sparks, and even fireflies. In the past hundred years, humans have been able to produce several other kinds of emitted light. Incandescent bulbs, fluorescent lamps, television screens, lasers, and tiny light-emitting diodes (LEDs) are each a result of humans using electricity to produce light.

Although there are a variety of emitted light sources, most of the light waves that reach our eyes are reflections from objects in the environment. Light is reflected not only by mirrors, shiny metals, and white paper, but also by the moon, flowers, and even black cloth. In fact, it is difficult to find an object that does not reflect at least a small amount of light.

Emission and reflection are just two of the ways that light interacts with matter. In the next few chapters, you will learn the principles that govern how light moves through matter. You will also learn the effects that mirrors and lenses can have on light. Although light is only a small portion of the entire range of electromagnetic waves, your study of light will be, in many ways, a study of the entire spectrum of electromagnetic radiation.

## WHAT YOU'LL LEARN

- You will understand the fundamentals of light, including its speed, wavelength range, and intensity.
- You will describe the interactions between two or more light waves and between light waves and matter.

## WHY IT'S IMPORTANT

- Light is a primary sensor to how the universe behaves. From learning about the biological patterns on Earth to discovering the astronomical rules of outer space, scientists rely upon detecting light waves.

PHYSICS Online

To find out more about light, visit the Glencoe Science Web site at **science.glencoe.com**

CLICK HERE

# 16.1 Light Fundamentals

Early scientists considered light to be a stream of particles emitted by a light source. However, not all of the properties of light could be explained by this theory. Experiments showed that light also behaves like a wave. Today, the nature of light is explained in terms of both particles and waves. In this chapter, you will apply what you have learned about mechanical waves to the study of light.

### OBJECTIVES

- **Recognize** that light is the visible portion of an entire range of electromagnetic frequencies.
- **Describe** the ray model of light.
- **Solve** problems involving the speed of light.
- **Define** *luminous intensity, luminous flux*, and *illuminance.*
- **Solve** illumination problems.

**Color Conventions**

- Light rays are **red.**

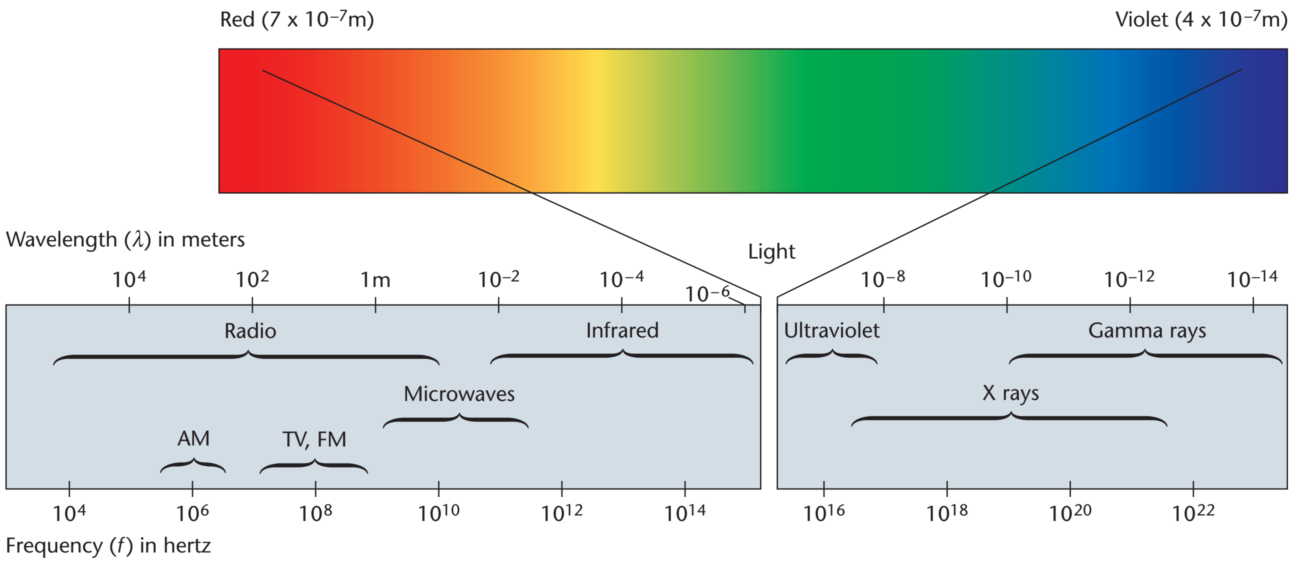
## The Facts of Light

What is light? **Light** is the range of frequencies of electromagnetic waves that stimulates the retina of the eye. Light waves have wavelengths from about 400 nm ($4.00 \times 10^{-7}$ m) to 700 nm ($7.00 \times 10^{-7}$ m). The shortest wavelengths are seen as violet light. As wavelength increases, the colors gradually change to indigo, blue, green, yellow, orange, and finally, red, as shown in **Figure 16–1.**

Light travels in a straight line in a vacuum or other uniform medium. How do you know this? If light from the sun or a flashlight is made visible by dust particles in the air, the path of the light is seen to be a straight line. When your body blocks sunlight, you see a sharp shadow. Also, our brains locate objects by automatically assuming that light travels from objects to our eyes along a straight path.

The straight-line path of light has led to the **ray model** of light. A ray is a straight line that represents the path of a narrow beam of light. The use of ray diagrams to study the travel of light is called ray optics or geometric optics. Even though ray optics ignores the wave nature of light, it is useful in describing how light is reflected and refracted.

**FIGURE 16–1** The visible spectrum is a very small portion of the whole electromagnetic spectrum.



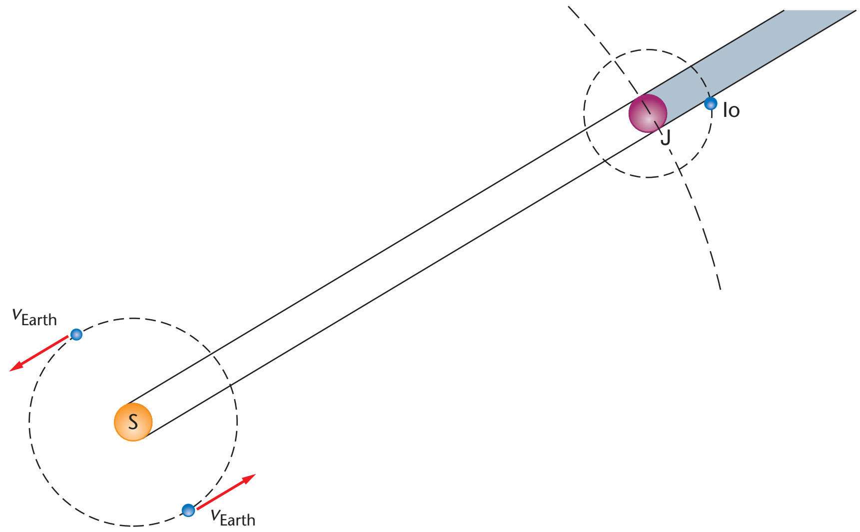



**FIGURE 16–2** Roemer measured the time of an eclipse of one of Jupiter's moons, Io. During successive eclipses, the moon would come around faster or slower, depending on whether Earth was moving toward or away from Jupiter. (not to scale)

## The Speed of Light

Before the 17th century, most people believed that light travels instantaneously. Galileo was the first to hypothesize that light has a finite speed and to suggest a method of determining it. His method, however, was not sensitive enough, and he was forced to conclude that the speed of light is too fast to be measured at all over a distance of a few kilometers. Danish astronomer Ole Roemer (1644–1710) was the first to determine that light does travel with a measurable speed. Between 1668 and 1674, Roemer made 70 careful measurements of the 42.5-hour orbital period of Io, one of the moons of Jupiter. He recorded the times when Io emerged from Jupiter's shadow, as shown in **Figure 16–2.**

He found that the period varied slightly depending on when the measurement was made. The variation was as much as 14 seconds longer when Earth was moving away from Jupiter and 14 seconds shorter when Earth was approaching Jupiter.

What might cause this discrepancy in Io's orbital period? Roemer concluded that as Earth moved away from Jupiter, the light from each new appearance of Io took longer to travel the increasing distance to Earth. Thus, the measured period increased. Likewise, as Earth approached Jupiter, Io's orbital period would seem to decrease. Based on these data, in 1676 Roemer calculated that light took 22 minutes to cross the diameter of Earth's orbit.

Roemer had successfully proved that light moved at a finite speed. Using the present value of the diameter of Earth's orbit, Roemer's value of 22 minutes gives a speed of light of about 220 million meters per second. This is only three quarters of what is now accepted as the correct value. Today we know that light takes 16 minutes, not 22, to cross Earth's orbit. Nevertheless, the speed of light was found to be finite but so fast that a light beam could circle the globe seven and a half times in one second.

# F.Y.I.

Ole Roemer made his measurements in Paris as part of a project to improve maps by calculating the longitude of locations on Earth. This is an early example of the needs of technology resulting in scientific advances.

**FIGURE 16–3** Albert A. Michelson became the first American to win a Nobel prize in science.

Although many laboratory measurements of the speed of light have been made, the most notable was a series performed by American physicist Albert A. Michelson (1852–1931), shown in **Figure 16–3.** Between 1880 and the 1920s, he developed Earth-based techniques to measure the speed of light. In 1926, Michelson measured the time required for light to make a round-trip between two California mountains 35 km apart. Michelson's best result was $2.997996 \pm 0.00004 \times 10^8$ m/s. For this work, he became the first American to receive a Nobel prize in science.

**The speed of light defined** The development of the laser in the 1960s provided new methods of measuring the speed of light. As you learned in Chapter 14, the speed of a wave is equal to the product of its frequency and wavelength. The speed of light in a vacuum is such an important and universal value that it has its own special symbol, $c$. Thus, $c = \lambda f$. The frequency of light can be counted with extreme precision using lasers and the time standard provided by atomic clocks. Measurements of its wavelength, however, are much less precise. As a result, in 1983 the International Committee on Weights and Measurements decided to make the speed of light a defined quantity. In principle, an object's length is now measured in terms of the time required by light to travel from one end of the object to the other. The committee defined the speed of light in a vacuum to be exactly $c = 299\,792\,458$ m/s. For most calculations, however, it is sufficient to use $c = 3.00 \times 10^8$ m/s.

## HELP WANTED

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Atlanta, GA 30303

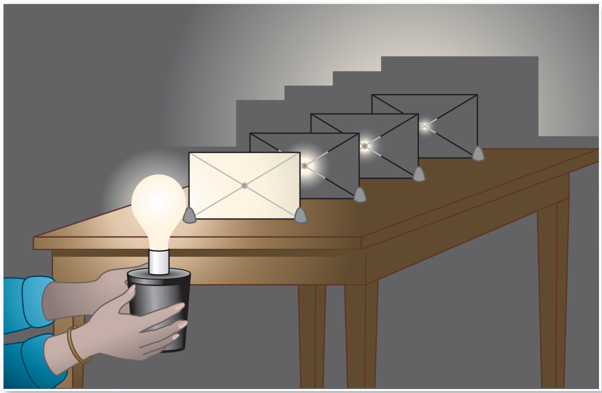
## Practice Problems

1. What is the frequency of yellow light, $\lambda = 556$ nm?
2. One nanosecond (ns) is $10^{-9}$ s. Laboratory workers often estimate the distance light travels in a certain time by remembering the approximation "light goes one foot in one nanosecond." How far, in feet, does light actually travel in exactly 1 ns?
3. Modern lasers can create a pulse of light that lasts only a few femtoseconds.
   **a.** What is the length of a pulse of violet light that lasts 6.0 fs?
   **b.** How many wavelengths of violet light ($\lambda = 400$ nm) are included in such a pulse?
4. The distance to the moon can be found with the help of mirrors left on the moon by astronauts. A pulse of light is sent to the moon and returns to Earth in 2.562 s. Using the defined speed of light, calculate the distance from Earth to the moon.
5. Use the correct time taken for light to cross Earth's orbit, 16 minutes, and the diameter of the orbit, $3.0 \times 10^{11}$ m, to calculate the speed of light using Roemer's method.



CONTENTS

# Light Ray Paths



## Problem

How do light waves travel?

## Materials

4 unlined index cards (4 × 6)
clay
40-watt lightbulb (nonfrosted) in a fixture
4–6 flat mirrors, approx. 10 cm × 15 cm
medium nail
ruler

## Procedure

1. Draw two diagonals on each index card, using the ruler. Mark the center of each card.
2. Punch the center of three of the cards with the nail.
3. Stand one of the punched cards so that its longer edge is parallel to a desk or tabletop. Use two pea-sized lumps of clay to secure the card to the table.
4. Stand the remaining cards on the table so they are about 10 cm apart. Place the card without the hole last. Use clay to secure all the cards.
5. Arrange the cards so their outside edges are in a straight line. Use the ruler to check the alignment. Once your setup is complete, dim the room lights.
6. Ask your partner to hold the light fixture so the light shines through the hole in the first card.
7. Check the alignment of the two other punched cards so you can see the light shining on the fourth card.
8. Place a mirror in front of the fourth card so the light shines on it. Give each person in your group a mirror, and have them hold it in a position that reflects the light beam to the next person's mirror. Be careful not to reflect the light beam into someone's eye.
9. When you have completed the lab, recycle the index cards and save the clay for use again.

## Data and Observations

1. Decide how to place the mirrors so that you can reflect the light onto the back of the card without the hole.
2. Draw a diagram showing your mirror setup. Use arrows to mark the path of light between the mirrors and the card.
3. Describe how the brightness of the light shining on the first mirror compares with the brightness of the light reflected from the last mirror.

## Analyze and Conclude

1. **Analyzing Data** How can you describe the path of light from one mirror to the next?
2. **Critical Thinking** What explanation can you give for your observations concerning the relative brightness of the reflections?

## Apply

1. Use your observations to draw a diagram showing how a shadow forms.

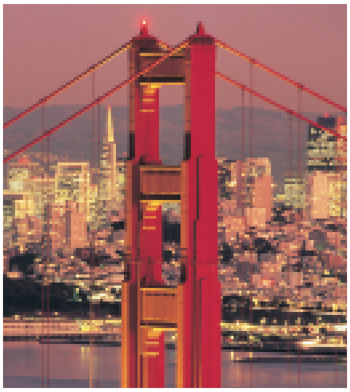


**FIGURE 16–4** The bridge is illuminated while the city lights are luminous.

## Sources of Light

What's the difference between sunlight and moonlight? Sunlight, of course, is much, much brighter. But there is an important fundamental difference between the two. The sun is a luminous body, while the moon is an illuminated body. A **luminous** body emits light waves; an **illuminated** body simply reflects light waves produced by an outside source, as illustrated in **Figure 16–4.** An incandescent lamp, such as a common lightbulb, is luminous because electrical energy heats a thin tungsten wire in the bulb and causes it to glow. An incandescent object emits light as a result of its high temperature. A bicycle reflector, on the other hand, works as an illuminated body. It is designed to reflect automobile headlights.

Humans register the sensation of light when electromagnetic waves of the appropriate wavelength(s) reach our eyes. Our eyes have different sensitivities to different wavelengths.

## Physics & Technology

### Digital Versatile Discs

In 1982, when CDs (compact discs) were introduced, they revolutionized the audio electronics industry. A few years later, CD-ROMs (CD-read only memory) began to do the same thing for the personal computer industry. The high-quality sound and images, large storage capacity, durability, and ease of use made CDs and CD-ROMs popular with consumers.

CDs, CD-ROMS, and DVDs are all examples of optical storage technology. Information is stored on the disc in a spiral of microscopic pits. These pits store a digital code that is read by a laser. The primary difference between CD and DVDs is the amount of information that each can hold. Today's CD can store 0.68 gigabytes of data whereas DVDs have the ability to store from 4.7 to 17 gigabytes.

How are DVDs made to obtain a higher storage capacity? Storage capacity depends on the number of pits. Manufacturers of DVDs increase the number of pits by shrinking pit size and by recording data on as many as four layers. Reducing pit size allows the pits to be closer together and the spiral track to be tighter. Thus, more pits can fit on the surface providing DVDs with more than six times the storage capability of a CD. Because the smaller pits are shallower on a DVD than a CD, a shorter wavelength laser is required. DVDs use a red, 640-nm laser as opposed to CDs with an infrared, 780-nm laser.

Another boost to storage is layering technology. Advances in aiming and focusing of the laser allow data to be recorded on two layers. To read the second layer, the laser is simply focused a little deeper into the disc where the second layer of data is stored. Not only are the two layer discs possible, but so are double-sided discs. The possibility of four layers gives DVDs a storage capability of 17 gigabytes.

**Thinking Critically** What would be the result of using even smaller pits and even shorter-wavelength blue or green lasers to read optical storage discs? Evaluate the impact that research to improve DVDs has on society.

**Luminous flux** The rate at which visible light is emitted from a source is called the **luminous flux,** $P$. The unit of luminous flux is the **lumen,** lm. A typical 100-watt incandescent lightbulb emits approximately 1750 lm. Imagine placing the bulb at the center of a sphere, as shown in **Figure 16–5.** The bulb emits light in almost all directions. The 1750 lm of luminous flux characterize all of the light that strikes the inside surface of the sphere in a given unit of time.

Often, we may not be interested in the total amount of light emitted by a luminous object. We are more likely to be interested in the amount of illumination the object provides on a book, a sheet of paper, or a highway. The illumination of a surface is called the **illuminance,** $E$, and is the rate at which light falls on a surface. Illuminance is measured in lumens per square meter, lm/m$^2$, or **lux,** lx.

Consider the 100-watt lightbulb in the middle of the sphere. What is the illumination of the sphere's surface? The area of the surface of a sphere is $4\pi r^2$. **Figure 16–5** shows that the luminous flux striking each square meter of the sphere is as follows.

$$\frac{1750 \text{ lm}}{4\pi r^2 \text{ m}^2} = \frac{1750}{4\pi r^2} \text{ lx}$$

At a distance of 1 m from the bulb, the illumination is approximately 140 lx.

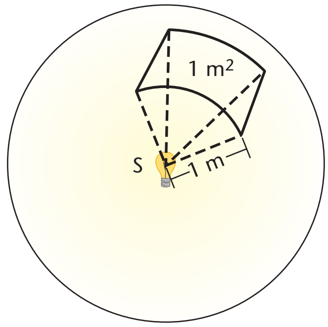



**FIGURE 16–5** Luminous flux is the rate that light is emitted from a bulb, whereas illuminance is the rate that light falls on some surface.

**An inverse-square relationship** What would happen if the sphere surrounding the lamp were larger? If the sphere had a radius of 2 m, the luminous flux would still total 1750 lm, but the area of the sphere would then be $4\pi(2 \text{ m})^2 = 16\pi \text{ m}^2$, four times larger. Consequently, the illumination on the surface would be reduced by a factor of four to 35 lx. Thus, if the distance of a surface from a point source of light is doubled, the illumination provided by the source on that surface is reduced by a factor of four. In the same way, if the distance is increased to 3 m, the illumination would be only $(1/3)^2$ or 1/9 as large as it was when the light source was 1 m away. Notice that illumination is proportional to $1/r^2$. This inverse-square relationship, as shown in **Figure 16–6,** is similar to that of gravitational force, which you studied in Chapter 8.

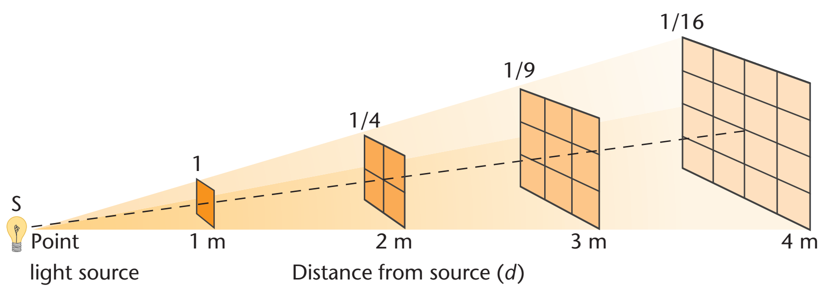



**FIGURE 16–6** The illuminance of a surface varies inversely as the square of its distance from a light source.

## Pocket Lab

### An Illuminating Matter

Which is more efficient, or has the highest lm/W, a lower- or higher-power lightbulb? To find out, look at your lightbulbs at home and record the power and lumens for at least three different bulbs.

**Graph Your Results** Make a graph of power (horizontal axis) versus lumens (vertical axis). Summarize your results.

**Luminous intensity** Some light sources are specified in **candela,** cd, or candle power. A candela is not a measure of luminous flux, but of luminous intensity. The **luminous intensity** of a point source is the luminous flux that falls on 1 $m^2$ of a sphere 1 m in radius. Thus, luminous intensity is luminous flux divided by $4\pi$. A bulb with 1750 lm flux has an intensity of $(1750 \text{ lm})/4\pi = 139$ cd. A flashlight bulb labeled 1.5 cd emits a flux of $4\pi\,(1.5 \text{ cd}) = 19$ lm. The candela is the official SI unit from which all light intensity units are calculated.

**How to illuminate a surface** There are two ways to increase the illumination on a surface. You can use a brighter bulb, which increases luminous flux, or you can move the surface closer to the bulb, decreasing the distance. Mathematically, the illuminance, $E$, directly under a small light source is represented by the following equation.

**Illuminance** $$E = \frac{P}{4\pi d^2}$$

$P$ represents the luminous flux of the source, and $d$ represents its distance from the surface. This equation is valid only if the light from the source strikes the surface perpendicular to it. It is also valid only for sources that are small enough or far enough away to be considered point sources. Thus, the equation does not give accurate values with long fluorescent lamps, or with incandescent bulbs in large reflectors that are close to the illuminated surface.

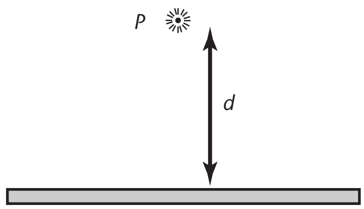
## Example Problem

### Illumination of a Surface

What is the illumination on your desktop if it is lighted by a 1750-lm lamp that is 2.50 m above your desk?

#### Sketch the Problem

- Assume that the bulb is the point source.
- Diagram the position of the bulb and desktop. Label $P$ and $d$.




#### Calculate Your Answer

**Known:**

luminous flux, $P = 1750$ lm

$d = 2.50$ m

**Unknown:**

illuminance, $E = ?$

**Strategy:**

The surface is perpendicular to the direction the light ray is traveling, so you can use the illuminance equation.

**Calculations:**

$$E = \frac{P}{4\pi d^2}$$

$$E = \frac{1750 \text{ lm}}{4\pi(2.50 \text{ m})^2} = 22.3 \text{ lm/m}^2 = 22.3 \text{ lx}$$

### Check Your Answer

- Are the units correct? $lm/m^2 = lx$, which the answer agrees with.
- Do the signs make sense? All quantities are positive, as they should be.
- Is the magnitude realistic? Answer agrees with quantities given.

## Math Handbook

To review **ratios, rates,** and **proportions,** see the Math Handbook, Appendix A, page 739.

## Practice Problems

6. A lamp is moved from 30 cm to 90 cm above the pages of a book. Compare the illumination on the book before and after the lamp is moved.
7. What is the illumination on a surface 3.0 m below a 150-watt incandescent lamp that emits a luminous flux of 2275 lm?
8. Draw a graph of the illuminance from a 150-watt incandescent lamp between 0.50 m and 5.0 m.
9. A 64-cd point source of light is 3.0 m above the surface of a desk. What is the illumination on the desk's surface in lux?
10. The illumination on a tabletop is $2.0 \times 10^1$ lx. The lamp providing the illumination is 4.0 m above the table. What is the intensity of the lamp?
11. A public school law requires a minimum illumination of 160 lx on the surface of each student's desk. An architect's specifications call for classroom lights to be located 2.0 m above the desks. What is the minimum luminous flux the lights must deliver?

## 16.1 Section Review

1. How far does light travel in the time it takes sound to go 1 cm in air at 20°C?
2. The speed of light is slower in air and water than in a vacuum. The frequency, however, does not change when light enters water. Does the wavelength change? If so, in which direction?
3. Research and describe the history of the measurement of the speed of light.
4. Which provides greater illumination of a surface, placing two equal bulbs instead of one at a given distance or moving one bulb to half that distance?
5. **Critical Thinking** A bulb illuminating your desk provides only half the illumination it should. If it is currently 1.0 m away, how far should it be to provide the correct illumination?

# 16.2 Light and Matter

Objects can be seen clearly through air, glass, some plastics, and other materials. These materials, which transmit light waves without distorting images, are **transparent** materials. Materials that transmit light but do not permit objects to be seen clearly through them are **translucent** materials. Lamp shades and frosted lightbulbs are examples of translucent objects. Materials such as brick, which transmit no light but absorb or reflect all light incident upon them, are **opaque** materials. All three types of materials are illustrated in **Figure 16–7.**

## OBJECTIVES

- **Explain** the formation of color by light and by pigments or dyes.
- **Explain** the cause and **give examples** of interference in thin films.
- **Describe** methods of producing polarized light.

**FIGURE 16–7** Materials can be transparent, translucent, or opaque.

## Color

One of the most beautiful phenomena in nature is a rainbow. Artificial rainbows can be produced when light passes through water or glass. How is the color pattern of a rainbow produced? In 1666, the 24-year-old Isaac Newton did his first scientific experiments on the colors produced when a narrow beam of sunlight passed through a prism, shown in **Figure 16–8.** Newton called the ordered arrangement of colors from violet to red a **spectrum.** He thought that some unevenness in the glass might be producing the spectrum.

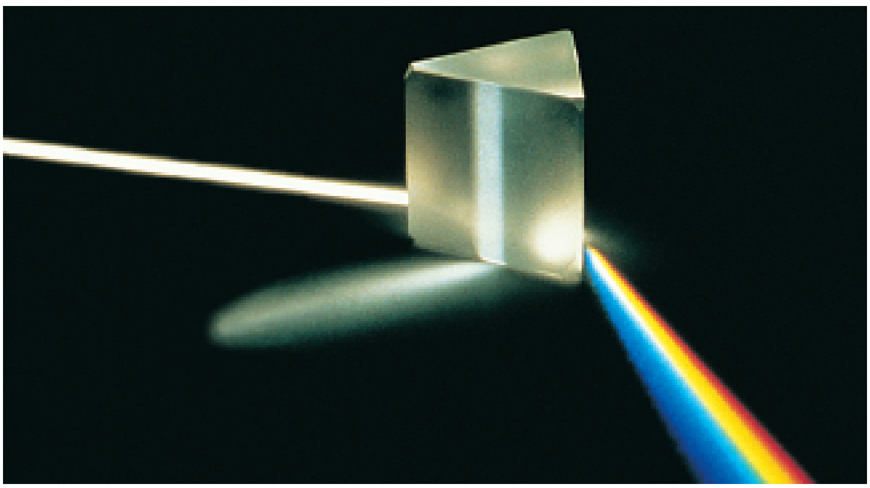


**FIGURE 16–8** White light, when passed through a prism, is separated into a spectrum of colors.



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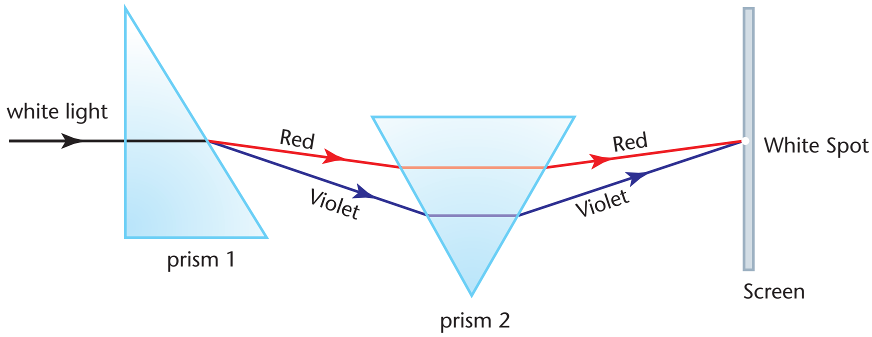



**FIGURE 16–9** A second prism can recombine the colors separated by the first prism into white light again.

To test this assumption, he allowed the spectrum from one prism to fall on a second prism. If the spectrum were caused by irregularities in the glass, he reasoned, then the second prism should have increased the spread in colors. Instead, the second prism reversed the spreading of colors and recombined them to form white light, as shown in **Figure 16–9.** After more experiments, Newton concluded that white light is composed of colors. We now know that each color in the spectrum is associated with a specific wavelength of light, as represented in **Figure 16–1,** page 374.

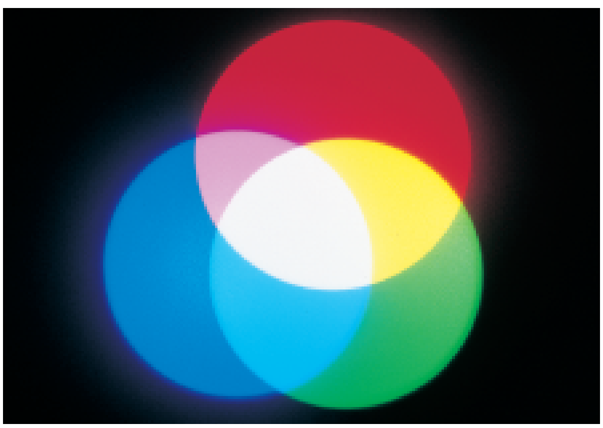
**Color by addition** White light can be formed from colored light in a variety of ways. For example, if correct intensities of red, green, and blue light are projected onto a white screen, as in **Figure 16–10,** the screen will appear to be white. Thus, red, green, and blue light added together form white light. This is called the additive color process. A color television tube uses the additive process. It has tiny dotlike sources of red, green, and blue light. When all have the correct intensities, the screen appears to be white. For this reason, red light, green light, and blue light are called the **primary colors** of light. The primary colors can be mixed by pairs to form three different colors. Red and green light together produce yellow light, blue and green light produce cyan, and red and blue light produce magenta. The three colors yellow, cyan, and magenta are called the **secondary colors** of light.

## Pocket Lab

### Hot and Cool Colors

Some artists refer to red and orange as hot colors and green and blue as cool colors. But does emitting red or orange light really indicate that an object is hotter than one emitting blue or green? Try this to find out. Obtain a pair of prism glasses or a piece of diffraction grating from your teacher. Find a lamp with a dimmer switch and turn off the light. Next, slowly turn the dimmer so that the light gets brighter and brighter. To get the best effect, turn off all the other lights in the room.

**Analyze and Conclude** Which colors appeared first when the light was dim? Which colors were the last to appear? How do these colors relate to the temperature of the filament?



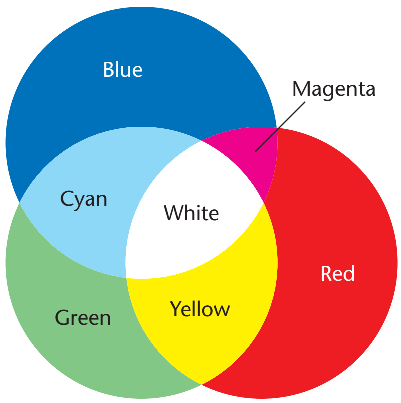



**FIGURE 16–10** The additive mixture of blue, green, and red light produces white light.

## Colors to Mix and Match

➥ *Answers question from page 372.*

In the chapter-opening photograph, each shadow occurs when the girl blocks one color of light, leaving the secondary colors. Thus, in order from the right, the yellow shadow is illuminated by red and green lights, the cyan shadow by blue and green lights, and the magenta shadow by red and blue lights. Smaller shadows showing the primary light colors appear where two lights are blocked. Where there is a black shadow, all three lights are blocked.

Yellow light can be made from red light and green light. If yellow light and blue light are projected onto a white screen with the correct intensities, the surface will appear to be white. Thus, yellow and blue light combine to form white light, and consequently, yellow light is called the **complementary color** to blue light. Yellow light is made up of the two other primary colors. In the same way, cyan and red are complementary colors, as are magenta and green.

**Colors by subtraction** A **dye** is a molecule that absorbs certain wavelengths of light and transmits or reflects others. A tomato is red because it reflects red light to our eyes. When white light falls on the red block in **Figure 16–11,** dye molecules in the red block absorb the blue and green light and reflect the red. When only blue light falls on the block, very little light is reflected and the block appears to be almost black.

CHEMISTRY CONNECTION

Like a dye, a **pigment** is a colored material that absorbs certain colors and transmits or reflects others. The difference is that a pigment particle is larger than a molecule and can be seen with a microscope. Often, a pigment is a finely ground inorganic compound such as titanium(IV) oxide (white), chromium(III) oxide (green), or cadmium sulfide (yellow). Pigments mix in a medium to form suspensions rather than solutions.

The absorption of light forms colors by the subtractive process. Pigments and dyes absorb certain colors from white light. A pigment that absorbs only one primary color from white light is called a **primary pigment.** Yellow pigment absorbs blue light and reflects red and green light. Yellow, cyan, and magenta are the primary pigments. A pigment that absorbs two primary colors and reflects one is a **secondary pigment.** The secondary pigments are red (which absorbs green and blue light), green (which absorbs red and blue light), and blue (which absorbs red and green light). Note that the primary pigment colors are the secondary light colors. In the same way, the secondary pigment colors are the primary light colors.


a b c

**FIGURE 16–11** The dyes in the blocks selectively absorb and reflect various wavelengths of light. Illumination is by white light in **(a),** red light in **(b),** and blue light in **(c).**

**FIGURE 16–12** The primary pigment colors are yellow, cyan, and magenta. In each case, the pigment absorbs one of the primary light colors and reflects the other two.

The primary pigment yellow absorbs blue light. If it is mixed with the secondary pigment blue, which absorbs green and red light, all light will be absorbed. No light will be reflected, so the result will be black. Thus, yellow and blue are complementary pigments. Cyan and red, as well as magenta and green, are also complementary pigments. The primary pigments and their complementary pigments are shown in **Figure 16–12.**

## Formation of Colors in Thin Films

Have you ever seen a spectrum of colors produced by a soap bubble or by the oily film on a water puddle in a parking lot? These colors are not the result of separation of white light by a prism or of absorption of colors in a pigment. In fact, the colors you see cannot be explained in terms of a ray model of light; they are a result of the constructive and destructive interference of light waves, or **thin-film interference.**

If a soap film is held vertically, as in **Figure 16–13,** its weight makes it thicker at the bottom than at the top. The thickness varies gradually from top to bottom. When a light wave strikes the film, part of it is reflected, as shown by $R_1$, and part is transmitted. The transmitted wave travels through the film to the back surface, where, again, part is reflected, as shown by $R_2$. If the thickness of the film is one fourth of the wavelength of the wave in the film ($\lambda/4$), the round-trip path length in

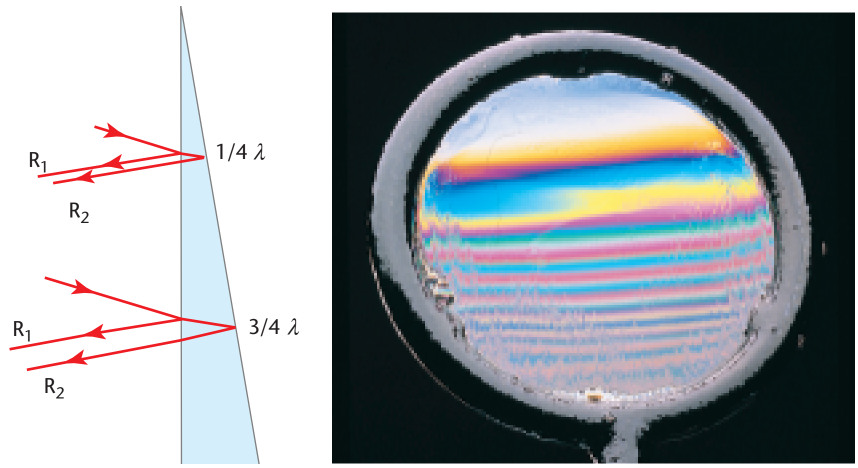



**FIGURE 16–13** Each color is reinforced where the soap film is 1/4, 3/4, 5/4, and so on of the wavelength for that color. Because each color has a different wavelength, a series of color bands is reflected from the soap films.

## Pocket Lab

### Soap Solutions

Dip a ring into soap solution and hold it at a 45° angle to the horizontal. Look for color bands to form in horizontal stripes.

**Analyze and Conclude** Why do the bands move? Why are the bands horizontal? What type of pattern would you see if you looked through the soap with a red filter? Try it. Describe and explain your results.

the film is $\lambda/2$. In this case, it would appear that the wave returning from the back surface would reach the front surface one-half wavelength behind the first reflected wave and that the two waves would cancel by the superposition principle. But, as you learned in Chapter 14, when a transverse wave is reflected from a more optically dense medium, it is inverted. As a result, the first reflected wave, $R_1$, is inverted on reflection. The second reflected wave, $R_2$, is reflected from a less-dense medium and is not inverted. Thus, when the film has a thickness of $\lambda/4$, the wave reflected from the back surface returns to the front surface in sync with the first reflected wave. The two waves reinforce each other as they leave the film. Light with other wavelengths suffers partial or complete destructive interference. At any point on the film, the light most strongly reflected has a wavelength satisfying the requirement that the film thickness equals $\lambda/4$.

Different colors of light have different wavelengths. As the thickness of the film changes, the $\lambda/4$ requirement will be met at different locations for different colors. As the thickness increases, the light with the shortest wavelength, violet, will be most strongly reflected, then blue, green, yellow, orange, and finally red, which has the longest wavelength. A rainbow of color results.

Notice in **Figure 16–13** that the spectrum repeats. When the thickness is $3\lambda/4$, the round-trip distance is $3\lambda/2$, and constructive interference occurs again. Any thickness equal to an odd multiple of quarter wavelengths—$\lambda/4$, $3\lambda/4$, $5\lambda/4$, $7\lambda/4$, and so on—satisfies the conditions for reinforcement for a given color. At the top of the film, there is no color; the film appears to be black. Here, the film is too thin to produce constructive interference for any color. Shortly after the top of the film becomes thin enough to appear black, it breaks.

## Polarization of Light

Have you ever looked at light reflected off a road through Polaroid sunglasses? As you rotate the glasses, the road first appears to be dark, then light, and then dark again. Light from a lamp, however, changes very little as the glasses are rotated. Why is there a difference? Part of the reason is that the light coming from the road is reflected. A second part is that the reflected light has become polarized.

Polarization can be understood by considering the rope model of light waves, as shown in **Figure 16–14.** The transverse mechanical waves in the rope represent the transverse electromagnetic waves of light. The slots represent what is referred to as the polarizing axis of the Polaroid material. When the rope waves are parallel to the slots, they pass through. When they are perpendicular to the slots, the waves are blocked. Polaroid material contains long molecules that allow electromagnetic waves of one direction to pass through while absorbing the waves vibrating in the other direction. One direction of the Polaroid material is called the polarizing axis. Only waves vibrating parallel to that axis can pass through.

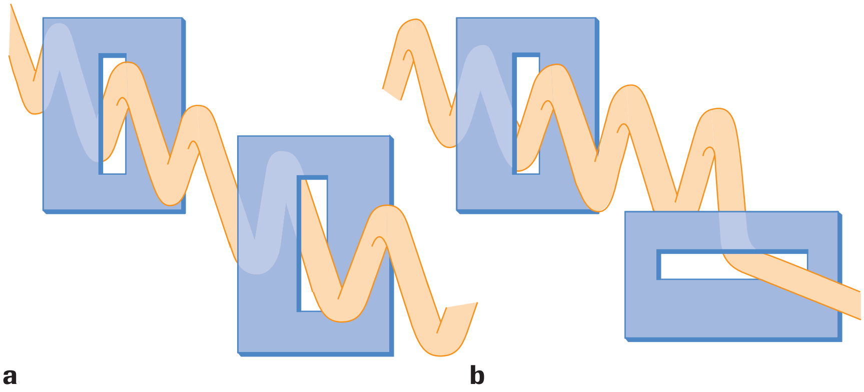



**FIGURE 16–14** In the wave model of light, waves are polarized in relation to the vertical plane **(a).** Vertically polarized waves cannot pass through a horizontal polarizer **(b).**

## Pocket Lab

### Light Polarization

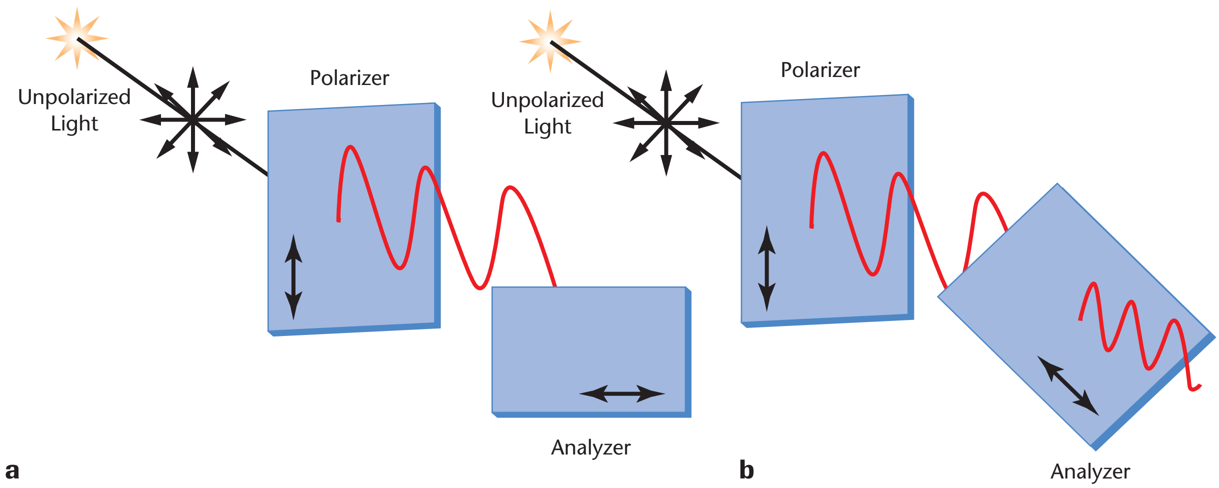
Obtain a polarizing filter from your teacher to take home. Look through the filter at various objects as you rotate the filter. Make a record of those objects that seem to change in brightness as the filter is rotated.

**Recognize Cause and Effect** What seems to be the pattern?

Ordinary light contains electromagnetic waves vibrating in every direction perpendicular to its direction of travel. Each wave can be resolved into two perpendicular components in a manner similar to an acceleration or velocity vector. On the average, therefore, half the waves vibrate in one plane, while the other half vibrate in a plane perpendicular to the first. If polarizing material is placed in a beam of ordinary light, only those waves vibrating in one plane pass through. Half the light, passes through, and the intensity of the light is reduced by half. The polarizing material produces light that is **polarized** in a particular plane of vibration. The material is said to be a polarizer of light and is called a polarizing filter.

Suppose a second polarizing filter is placed in the path of the polarized light. If the polarizing axis of the second filter is perpendicular to the direction of vibration of the polarized light, no light will pass through, as shown in **Figure 16–15a.** If the filter, however, is at an angle, the component of light parallel to the polarizing axis of the filter will be transmitted, as shown in **Figure 16–15b.** Thus, a polarizing filter can determine the orientation of polarization of light and is often called an "analyzer."

**FIGURE 16–15** The arrows show that unpolarized light vibrates in many planes. Polarized light from a polarizer is absorbed by an analyzer that is perpendicular to the plane of the polarized light **(a).** Polarized light from a polarizer is only partially absorbed by an analyzer that is at an angle to the plane of the polarized light **(b).**



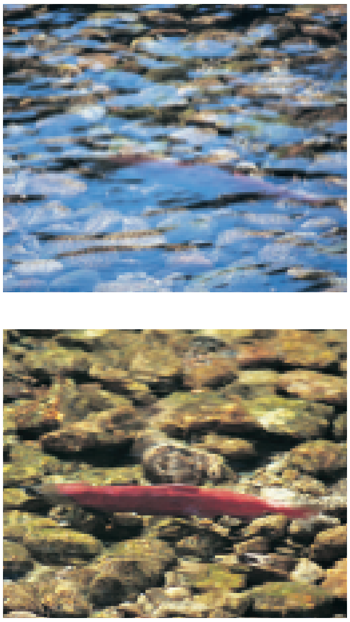


**FIGURE 16–16** A polarizing filter over the lens of a camera can block the glare from reflecting surfaces.

Light also can be polarized by reflection. If you look through a polarizing filter at the light reflected by a sheet of glass and rotate the filter, you will see the light brighten and dim. The light was partially polarized when it was reflected. That is, the reflected ray contains a great deal of light vibrating in one direction. The polarization of light reflected by roads is the reason why polarizing sunglasses reduce glare. The fact that the intensity of light reflected off a road varies as Polaroid sunglasses are rotated suggests that the reflected light is partially polarized. Photographers can use polarizing filters to block reflected light, as shown in **Figure 16–16.** Light also is polarized when it is scattered by molecules in the air. If you look through Polaroid sunglasses along the horizon when the sun is overhead and rotate the glasses, you will see the brightness change, showing that the light is polarized.

## The Ray and Wave Models of Light

You have learned that many characteristics of light can be explained with a simple ray model. An understanding of the interaction of light with thin films that produce colors, however, requires the use of a model of light that involves waves. This model also is used to explain polarization. In the next chapter, you'll find that the ray model is suitable for explaining how lenses and mirrors form images. In Chapter 18 you'll learn about other aspects of light that can be understood only through the use of the wave model. But both the ray and wave models of light have been found to be inadequate to explain some other interactions of light with matter. For such phenomena, we will need yet another model, which is much closer to the ray model than to the wave model. This model, often referred to as the particle theory of light, will be discussed in Chapter 27.

## 16.2 Section Review

1. Why might you choose a window shade that is translucent? Opaque?
2. What light color do you add to blue light to obtain white light?
3. What primary pigment colors must be mixed to get red?
4. What color will a yellow banana appear to be when illuminated by
   **a.** white light?
   **b.** green and red light?
   **c.** blue light?
5. **Critical Thinking** Describe a simple experiment you could do to determine whether sunglasses in a store were polarizing. How does the ability of light to be polarized impact the photography industry?

# CHAPTER 16 REVIEW

## Key Terms

**16.1**
- light
- ray model
- luminous
- illuminated
- luminous flux
- lumen
- illuminance
- lux
- candela
- luminous intensity

**16.2**
- transparent
- translucent
- opaque
- spectrum
- primary color
- secondary color
- complementary color
- dye
- pigment
- primary pigment
- secondary pigment
- thin-film interference
- polarized

## *Summary*

### 16.1 Light Fundamentals

- Light is an electromagnetic wave that stimulates the retina of the eye. Its wavelengths are between 400 and 700 nm.
- Light travels in a straight line through any uniform medium.
- In a vacuum, light has a speed of $3.00 \times 10^8$ m/s.
- The luminous flux of a light source is the rate at which light is emitted. It is measured in lumens.
- Illuminance is the rate at which light falls on a unit area. It is measured in lux.

### 16.2 Light and Matter

- Materials may be characterized as being transparent, translucent, or opaque, depending on the amount of light they reflect, transmit, or absorb.
- White light is a combination of the spectrum of colors, each having different wavelengths.
- White light can be formed by adding together the primary light colors: red, blue, and green.
- The subtractive primary colors—cyan, magenta, and yellow—are used in pigments and dyes to produce a wide variety of colors.
- Colors in soap and oil films are caused by the interference of specific wavelengths of light reflected from the front and back surfaces of the thin films.
- Polarized light consists of waves vibrating in a particular plane.

### Key Equation

16.1

$$E = \frac{P}{4\pi d^2}$$

## *Reviewing Concepts*

### Section 16.1

1. Sound does not travel through a vacuum. How do we know that light does?
2. What is the range of wavelength, from shortest to longest, that the human eye can detect?
3. What color of visible light has the shortest wavelength?
4. What was changed in the equation $v = \lambda f$ in this chapter?
5. Distinguish between a luminous body and an illuminated body.
6. Look carefully at an ordinary, frosted, incandescent bulb. Is it a luminous or an illuminated body?
7. Explain how we can see ordinary, nonluminous classroom objects.
8. What are the units used to measure each of the following?
   **a.** luminous intensity
   **b.** illuminance
   **c.** luminous flux
9. What is the symbol that represents each of the following?
   **a.** luminous intensity
   **b.** illuminance
   **c.** luminous flux

### Section 16.2

10. Distinguish among transparent, translucent, and opaque objects.
11. Of what colors does white light consist?
12. Is black a color? Why does an object appear to be black?

13. Name each primary light color and its secondary light color.
14. Name each primary pigment and its secondary pigment.
15. Why can sound waves not be polarized?

## *Applying Concepts*

16. What happens to the wavelength of light as the frequency increases?
17. To what is the illumination of a surface by a light source directly proportional? To what is it inversely proportional?
18. A point source of light is 2.0 m from screen A and 4.0 m from screen B. How does the illumination of screen B compare with the illumination of screen A?
19. You have a small reading lamp 35 cm from the pages of a book. You decide to double the distance. Is the illumination on the book the same? If not, how much more or less is it?
20. Why are the insides of binoculars and cameras painted black?
21. The eye is most sensitive to yellow-green light. Its sensitivity to red and blue light is less than ten percent as great. Based on this knowledge, what color would you recommend that fire trucks and ambulances be painted? Why?
22. Some very efficient streetlights contain sodium vapor under high pressure. They produce light that is mainly yellow with some red. Should a community having these lights buy dark-blue police cars? Why or why not?
23. Suppose astronauts made a soap film in the space shuttle. Would you expect an orderly set of colored lines, such as those in **Figure 16–13?** Explain.
24. Photographers often put polarizing filters over the camera lens to make clouds in the sky more visible. The clouds remain white while the sky looks darker. Explain this based on your knowledge of polarized light.
25. An apple is red because it reflects red light and absorbs blue and green light. Follow these steps to decide whether a piece of transparent red cellophane absorbs or transmits blue and green light:
    **a.** Explain why the red cellophane looks red in reflected light.
    **b.** When you hold it between your eye and a white light, it looks red. Explain.
    **c.** Now, what happens to the blue and green light?
26. A soap film is transparent and doesn't absorb any color. If such a film reflects blue light, what kind of light does it transmit?
27. You put a piece of red cellophane over one flashlight and a piece of green cellophane over another. You shine the light beams on a white wall. What color will you see where the two flashlight beams overlap?
28. You now put both the red and green cellophane pieces over one of the flashlights in problem 27. If you shine the flashlight beam on a white wall, what color will you see? Explain.
29. If you have yellow, cyan, and magenta pigments, how can you make a blue pigment? Explain.
30. Describe what happens when white light interacts with a thin film. Now consider a thin film of gasoline floating on water. The speed of light is slower in gasoline than in air, and slower in water than in gasoline. Would you expect the $\lambda/4$ rule to hold in this case? Explain.

## *Problems*

### Section 16.1

31. Convert 700 nm, the wavelength of red light, to meters.
32. Light takes 1.28 s to travel from the moon to Earth. What is the distance between them?
33. The sun is $1.5 \times 10^8$ km from Earth. How long does it take for the sun's light to reach us?
34. Radio stations are usually identified by their frequency. One radio station in the middle of the FM band has a frequency of 99.0 MHz. What is its wavelength?
35. What is the frequency of a microwave that has a wavelength of 3.0 cm?
36. Find the illumination 4.0 m below a 405-lm lamp.
37. A screen is placed between two lamps so that they illuminate the screen equally. The first lamp emits a luminous flux of 1445 lm and is 2.5 m from the screen. What is the distance of the second lamp from the screen if the luminous flux is 2375 lm?

38. A three-way bulb uses 50, 100, or 150 W of electrical power to deliver 665, 1620, or 2285 lm in its three settings. The bulb is placed 80 cm above a sheet of paper. If an illumination of at least 175 lx is needed on the paper, what is the minimum setting that should be used?

39. Two lamps illuminate a screen equally. The first lamp has an intensity of 101 cd and is 5.0 m from the screen. The second lamp is 3.0 m from the screen. What is the intensity of the second lamp?

40. Ole Roemer found that the maximum increased delay in the disappearance of Io from one orbit to the next is 14 s.
   **a.** How far does light travel in 14 s?
   **b.** Each orbit of Io takes 42.5 h. Earth travels the distance calculated in **a** in 42.5 h. Find the speed of Earth in km/s.
   **c.** See if your answer for **b** is reasonable. Calculate Earth's speed in orbit using the orbital radius, $1.5 \times 10^8$ km, and the period, one year.

41. Suppose you wanted to measure the speed of light by putting a mirror on a distant mountain, setting off a camera flash, and measuring the time it takes the flash to reflect off the mirror and return to you. Without instruments, a person can detect a time interval of about 0.1 s. How many kilometers away would the mirror have to be? Compare this distance with that of some known objects.

42. A streetlight contains two identical bulbs 3.3 m above the ground. If the community wants to save electrical energy by removing one bulb, how far from the ground should the streetlight be positioned to have the same illumination on the ground under the lamp?

43. A student wants to compare the luminous flux from a bulb with that of a 1750-lm lamp. The two bulbs illuminate a sheet of paper equally. The 1750-lm lamp is 1.25 m away; the unknown bulb is 1.08 m away. What is its luminous flux?

44. A 10.0-cd point source lamp and a 60.0-cd point source lamp cast equal intensities on a wall. If the 10.0-cd lamp is 6.0 m from the wall, how far is the 60.0-cd lamp?

**Extra Practice** For more practice solving problems, go to Extra Practice Problems, Appendix B.

## *Critical Thinking Problems*

45. Suppose you illuminated a thin soap film with red light from a laser. What would you see?

46. If you were to drive at sunset in a city filled with buildings that have glass-covered walls, you might be temporarily blinded by the setting sun reflected off the building's walls. Would polarizing glasses solve this problem?

## *Going Further*

A hanging soap film **(Figure 16-13)** gets thicker at a rate of 150 nm for each centimeter from the top of the film. Use a calculator or computer to find the distances from the top of the film of the first three reflected fringes of each of the colors blue, green, yellow, and red. The color is most strongly reflected when the thickness is an odd number of quarter wavelengths of that color ($\lambda/4$, $3\,\lambda/4$, $5\,\lambda/4$, etc.) The wavelength, however, is that of the light within the soap film. This wavelength is 3/4 of the wavelength in air. Use the following wavelengths in air: blue 460 nm, green 550 nm, yellow 600 nm, red 660 nm. Plot these locations on a sheet of paper and compare with **Figure 16-13.**

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