Fundamentals of Light

What You'll Learn

- You will understand sources of light and how light illuminates the universe around us.

- You will be able to describe the wave nature of light and some phenomena that reveal this nature.

Why It's Important

Light is a primary source of information about how the universe behaves. We all use information such as color, brightness, and shadow every day to interpret the events occurring around us.

Balloon Race You can tell the difference between the competing balloons because of the different colors visible in the sunlight. You can distinguish the balloons from the backgrounds because of color differences in the grass and sky.

Think About This ▶

What causes these differences in color? How are these colors related?

Physics nline

physicspp.com

◁ CONTENTS ▷

LAUNCH Lab

How can you determine the path of light through air?

Question
What path does light take as it travels through the air?

Procedure

1. Punch a hole with a pushpin in the center of an index card.
2. Using clay, stand the index card so that its longer edge is on the table top.
3. Turn on a lamp and have one lab partner hold the lamp so that the lightbulb shines through the hole in the card. **CAUTION: Lamp can get hot over time.**
4. Hold a mirror on the opposite side of the index card so that light coming through the hole strikes the mirror. Darken the room.
5. Angle the mirror so that it reflects the beam of light onto the back of the card. **CAUTION: Be careful not to reflect the light beam into someone's eyes.**
6. Write down your observations.

Analysis
Describe the image of the reflected light beam that you see on the index card. Describe the path that the light beam takes.

Critical Thinking Can you see the light beam in the air? Why or why not?

16.1 Illumination

Light and sound are two methods by which you can receive information. 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 usually can distinguish shadows from solid objects and sometimes distinguish reflections of objects from the objects themselves. In this section, you will learn where light comes from and how it illuminates the universe around you.

One of the first things that you ever discovered about light, although you may not have been conscious of your discovery, is that it travels in a straight line. How do you know this? When a narrow beam of light, such as that of a flashlight or sunlight streaming through a small window, is made visible by dust particles in the air, you see the path of the light as a straight line. When your body blocks sunlight, you see your outline in a shadow. Also, whenever you locate an object with your eyes and walk toward it, you most likely walk in a straight path. These things are possible only because light travels in straight lines. Based on this knowledge of how light travels, models have been developed that describe how light works.
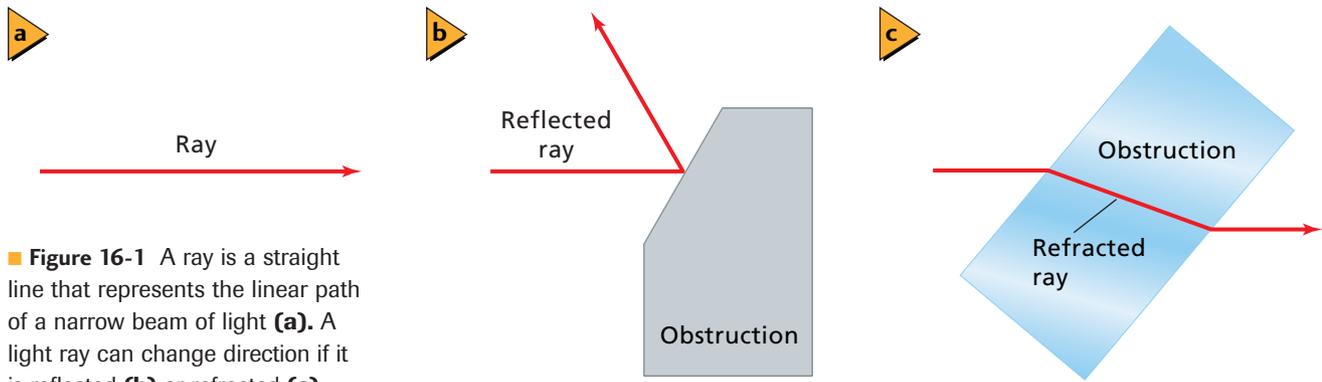
▶ **Objectives**
- **Develop** the ray model of light.
- **Predict** the effect of distance on light's illumination.
- **Solve** problems involving the speed of light.

▶ **Vocabulary**
ray model of light
luminous source
illuminated source
opaque
transparent
translucent
luminous flux
illuminance

Horizons Companies

Ray

Reflected
ray

Obstruction

Obstruction

Refracted
ray

■ **Figure 16-1** A ray is a straight line that represents the linear path of a narrow beam of light **(a).** A light ray can change direction if it is reflected **(b)** or refracted **(c).**

Ray Model of Light

Isaac Newton, whose laws of motion you studied in Chapter 6, believed that light is a stream of fast-moving, unimaginably tiny particles, which he called corpuscles. However, his model could not explain all of the properties of light. Experiments showed that light also behaves like a wave. In the **ray model of light,** light is represented as a ray that travels in a straight path, the direction of which can be changed only by placing an obstruction in the path, as shown in **Figure 16-1.** The ray model of light was introduced as a way to study how light interacts with matter, regardless of whether light is a particle or a wave. This study of light is called ray optics or geometric optics.

Sources of light Rays of light come from sources of light. Our major source of light is the Sun. Other natural sources of light include flames, sparks, and even fireflies. In the past 100 years, humans have been able to produce several other kinds of light sources. Incandescent bulbs, fluorescent lamps, television screens, lasers, and tiny, light-emitting diodes (LEDs) are each a result of humans using electricity to produce light.

What is the difference between sunlight and moonlight? Sunlight, of course, is much, much brighter. There also is an important fundamental difference between the two. The Sun is a **luminous source,** an object that emits light. In contrast, the Moon is an **illuminated source,** an object that becomes visible as a result of the light reflecting off it, as shown in **Figure 16-2.** 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 source emits light as a result of its high temperature. A bicycle reflector, on the other hand, works as an illuminated source. It is designed to become highly visible when it is illuminated by luminous automobile headlights.

Color Convention

• Light rays are **red.**

Moon

Sun

Illuminated
source

Earth
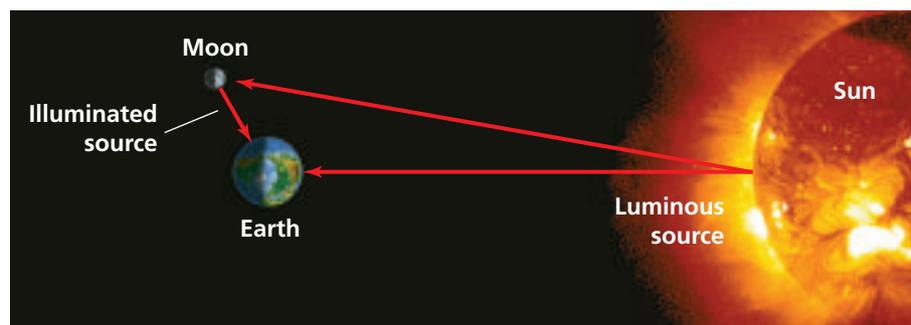
Luminous
source

■ **Figure 16-2** The Sun acts as a luminous source to Earth and the Moon. The Moon acts as an illuminated source to Earth. (Illustration not to scale)
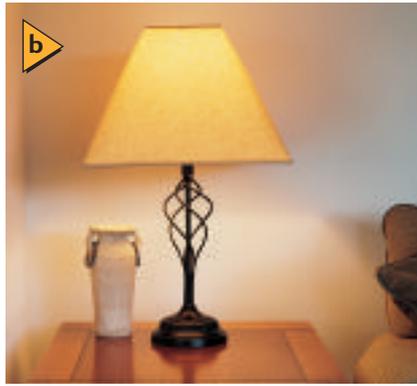
■ **Figure 16-3** The transparent glass allows objects to be seen through it **(a).** The translucent lamp shade allows light to pass through, although the lightbulb source itself is not visible **(b).** The opaque tarp covers the statue, preventing the statue from being seen **(c).**

Illuminated sources are visible to you because light is reflecting off or transmitting (passing) through the object to your eyes. Media, such as brick, that do not transmit light, but reflect some light, are **opaque** media. Media that transmit light, such as air and glass, are **transparent** media. Media that transmit light, but do not permit objects to be seen clearly through them, are **translucent** media. Lamp shades and frosted lightbulbs are examples of objects that are made of translucent media. All three types of media are illustrated in **Figure 16-3.** Transparent or translucent media not only transmit light, but they also can reflect a fraction of the light. For example, you often can see your reflection in a glass window.

Quantity of light The rate at which light energy is emitted from a luminous source is called the **luminous flux,** P. The unit of luminous flux is the lumen (lm). A typical 100-W incandescent lightbulb emits approximately 1750 lm. You can think of the luminous flux as a measure of the rate at which light rays come out of a luminous source. Imagine placing a lightbulb at the center of a 1-m-radius sphere, as shown in **Figure 16-4.** The lightbulb emits light in almost all directions. The 1750 lm of luminous flux characterizes all of the light that strikes the inside surface of the sphere in a given unit of time. Even if the sphere was 2 m in radius, the luminous flux of the lightbulb would be the same as for the 1-m-radius sphere, because the total number of light rays does not increase.

Once you know the quantity of light being emitted by a luminous source, you can determine the amount of illumination that the luminous source provides to an object, such as a book. The illumination of a surface, or the rate at which light strikes the surface, is called the **illuminance,** E. You can think of this as a measure of the number of light rays that strike a surface. Illuminance is measured in lux, lx, which is equivalent to lumens per square meter, lm/m^2.

Consider the setup shown in Figure 16-4. What is the illuminance of the sphere's inside surface? The equation for the surface area of a sphere is $4\pi r^2$, so the surface area of this sphere is $4\pi(1.00 \text{ m})^2 = 4\pi \text{ m}^2$. The luminous flux striking each square meter of the sphere is 1750 lm/$(4\pi \text{ m}^2)$ = 139 lx. At a distance of 1.00 m from the bulb, 139 lm strikes each square meter. The illuminance of the inside of the sphere is 139 lx.

■ **Figure 16-4** Luminous flux is the rate at which light is emitted from a luminous source, whereas illuminance is the rate at which light falls on a surface.
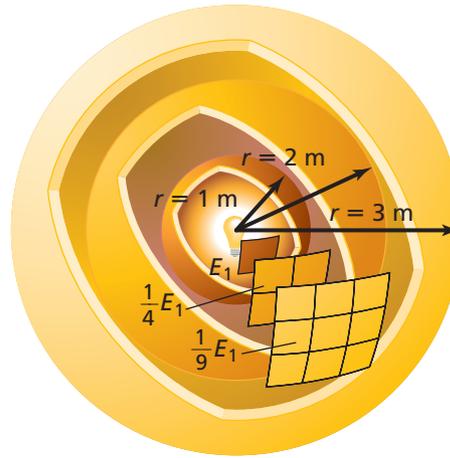
Luminous flux P = 1750 lm

$r = 1$ m

Illuminance

$$E_1 = \frac{1750}{4\pi} \text{ lx}$$

CONTENTS
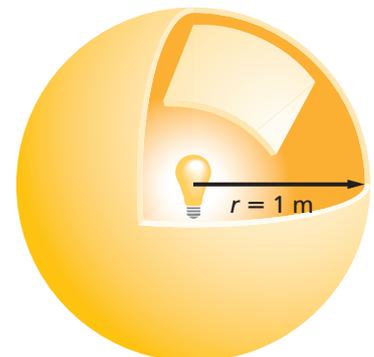
An inverse–square relationship What would happen if the sphere surrounding the lamp were larger? If the sphere had a radius of 2.00 m, the luminous flux still would total 1750 lm, but the area of the sphere would be $4\pi(2.00 \text{ m})^2 = 16.0\pi \text{ m}^2$, four times larger than the 1.00-m sphere, as shown in **Figure 16-5.** The illuminance of the inside of the 2.00-m sphere is $1750 \text{ lm}/(16.0\pi \text{ m}^2) = 34.8 \text{ lx}$, so 34.8 lm strikes each square meter.

The illuminance on the inside surface of the 2.00-m sphere is one-fourth the illuminance on the inside of the 1.00-m sphere. In the same way, the inside of a sphere with a 3.00-m radius has an illuminance only $(1/3)^2$, or 1/9, as large as the 1.00-m sphere. Figure 16-5 shows that the illuminance produced by a point source is proportional to $1/r^2$, an inverse-square relationship. As the light rays spread out in straight lines in all directions from a point source, the number of light rays available to illuminate a unit of area decreases as the square of the distance from the point source.

Luminous intensity Some luminous sources are specified in candela, cd. 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 m² of the inside of a 1-m-radius sphere. Thus, luminous intensity is luminous flux divided by 4π. A bulb with 1750 lm of flux has an intensity of $1750 \text{ lm}/4\pi = 139 \text{ cd}$.

In **Figure 16-6,** the lightbulb is twice as far away from the screen as the candle. For the lightbulb to provide the same illuminance on the lightbulb side of the screen as the candle does on the candle side of the screen, the lightbulb would have to be four times brighter than the candle, and, therefore, the luminous intensity of the lightbulb would have to be four times the luminous intensity of the candle.

CONTENTS
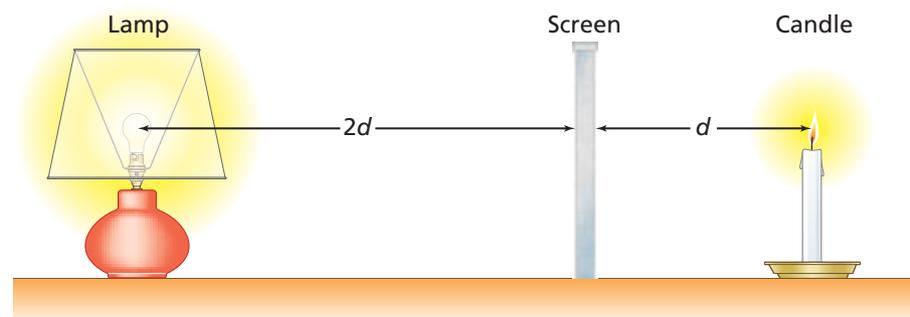
How to Illuminate a Surface

How would you increase the illuminance of your desktop? You could use a brighter bulb, which would increase the luminous flux, or you could move the light source closer to the surface of your desk, thereby decreasing the distance between the light source and the surface it is illuminating. To make the problem easier, you can use the simplification that the light source is a point source. Thus, the illuminance and distance will follow the inverse-square relationship. The problem is further simplified if you assume that light from the source strikes perpendicular to the surface of the desk. Using these simplifications, the illuminance caused by a point light source is represented by the following equation.

Point Source Illuminance $\quad E = \dfrac{P}{4\pi r^2}$

If an object is illuminated by a point source of light, then the illuminance at the object is equal to the luminous flux of the light source, divided by the surface area of the sphere, whose radius is equal to the distance the object is from the light source.

Remember that the luminous flux of the light source is spreading out spherically in all directions, so only a fraction of the luminous flux is available to illuminate the desk. Use of this equation is valid only if the light from the luminous source strikes perpendicular to the surface it is illuminating. It is also only valid for luminous sources that are small enough or far enough away to be considered point sources. Thus, the equation does not give accurate values of illuminance for long, fluorescent lamps or incandescent lightbulbs that are close to the surfaces that they illuminate.

▶ Connecting **Math to Physics**

Direct and Inverse Relationships The illuminance provided by a source of light has both a direct and an inverse relationship.

Math	Physics
$y = \dfrac{x}{az^2}$	$E = \dfrac{P}{4\pi r^2}$
If z is constant, then y is directly proportional to x.	If r is constant, then E is directly proportional to P.
• When x increases, y increases. • When x decreases, y decreases.	• When P increases, E increases. • When P decreases, E decreases.
If x is constant, then y is inversely proportional to z^2.	If P is constant, then E is inversely proportional to r^2.
• When z^2 increases, y decreases. • When z^2 decreases, y increases.	• When r^2 increases, E decreases. • When r^2 decreases, E increases.

▶ EXAMPLE Problem 1

Illumination of a Surface What is the illuminance at on your desktop if it is lighted by a 1750-lm lamp that is 2.50 m above your desk?

$P = 1.75 \times 10^3$ lm

2.50 m

1 Analyze and Sketch the Problem

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

Known:
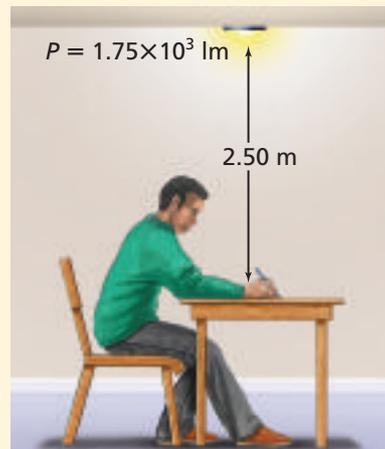
$P = 1.75 \times 10^3$ lm

$r = 2.50$ m

Unknown:

$E = ?$

2 Solve for the Unknown

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

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

$$= \frac{1.75 \times 10^3 \text{ m}}{4\pi(2.50 \text{ m})^2} \qquad \text{Substitue } P = 1.75 \times 10^3 \text{ lm, } r = 2.50 \text{ m}$$

$$= 22.3 \text{ lm/m}^2$$

$$= 22.3 \text{ lx}$$

> **Math Handbook**
>
> Operations with
> Significant Digits
> pages 835–836

3 Evaluate the Answer

- **Are the units correct?** The units of luminance are 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?** The illuminance is less than the luminous flux, which it should be at this distance.

▶ PRACTICE Problems

1. 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.

2. What is the illumination on a surface that is 3.0 m below a 150-W incandescent lamp that emits a luminous flux of 2275 lm?

3. Draw a graph of the illuminance produced by a 150-W incandescent lamp between 0.50 m and 5.0 m.

4. 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?

5. A public school law requires a minimum illuminance of 160 lx at 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 that the lights must produce?

6. A screen is placed between two lamps so that they illuminate the screen equally, as shown in **Figure 16-7.** 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?

Screen

$P = 2375$ lm

$\leftarrow$ 2.5 m $\rightarrow$

$P = 1445$ lm
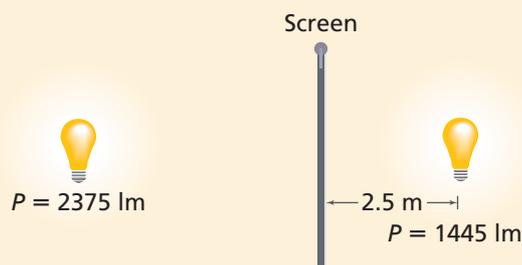
■ **Figure 16-7** (Not to scale)

Engineers who design lighting systems must understand how the light will be used. If an even illumination is needed to prevent dark areas, the common practice is to evenly space normal lights over the area to be illuminated, as was most likely done with the lights in your classroom. Because such light sources do not produce truly even light, however, engineers also design special light sources that control the spread of the light, such that they produce even illuminations over large surface areas. Much work has been done in this field with automobile headlights.

The Speed of Light

For light to travel from a source to an object to be illuminated, it must travel across some distance. According to classical mechanics, if you can measure the distance and the time it takes to travel that distance, you can calculate a speed. Before the seventeenth century, most people believed that light traveled instantaneously. Galileo was the first to hypothesize that light has a finite speed, and to suggest a method of measuring its speed using distance and time. His method, however, was not precise enough, and he was forced to conclude that the speed of light is too fast to be measured over a distance of a few kilometers.

Danish astronomer Ole Roemer was the first to determine that light does travel with a measurable speed. Between 1668 and 1674, Roemer made 70 measurements of the 1.8-day orbital period of Io, one of Jupiter's moons. He recorded the times when Io emerged from Jupiter's shadow, as shown in **Figure 16-8.** He made his measurements 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 driving scientific advances.

After making many measurements, Roemer was able to predict when the next eclipse of Io would occur. He compared his predictions with the actual measured times and found that Io's orbital period increased on average by about 13 s per orbit when Earth was moving away from Jupiter and decreased on average by about 13 s per orbit when Earth was approaching Jupiter. Roemer believed that Jupiter's moons were just as regular in their orbits as Earth's moon; thus, he wondered what might cause this discrepancy in the measurement of Io's orbital period.
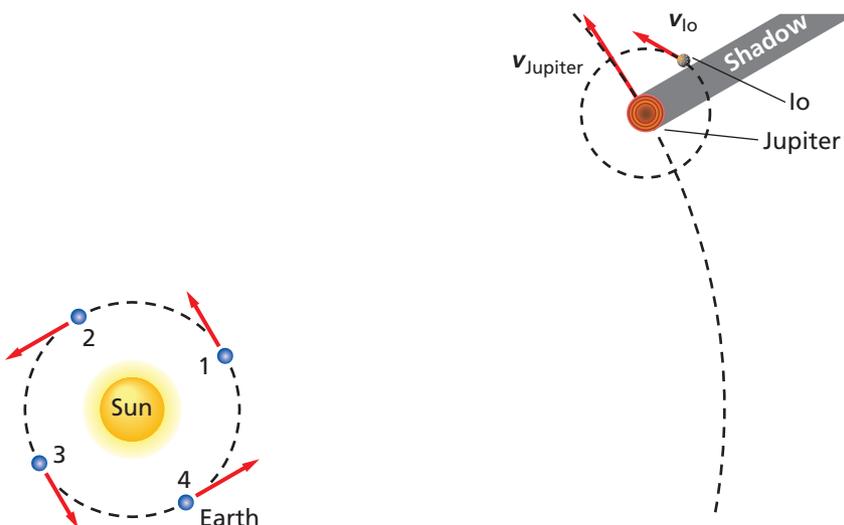
■ **Figure 16-8** Roemer measured the time between eclipses as Io emerged from Jupiter's shadow. During successive eclipses, Io's measured orbital period became increasingly smaller or larger depending on whether Earth was moving toward (from position 3 to 1) or away from (from position 1 to 3) Jupiter. (Illustration not to scale)

Measurements of the speed of light Roemer concluded that as Earth moved away from Jupiter, the light from each new appearance of Io took longer to travel to Earth because of the increasing distance to Earth. Likewise, as Earth approached Jupiter, Io's orbital period seemed to decrease. Roemer noted that during the 182.5 days that it took Earth to travel from position 1 to position 3, as shown in Figure 16-8, there were (185.2 days)(1 Io eclipse/1.8 days) = 103 Io eclipses. Thus, for light to travel the diameter of Earth's orbit, he calculated that it takes (103 eclipses)(13 s/eclipse) = 1.3×10^3 s, or 22 min.

Using the presently known value of the diameter of Earth's orbit (2.9×10^{11} m), Roemer's value of 22 min gives a value for the speed of light of 2.9×10^{11} m/((22 min)(60 s/min)) = 2.2×10^8 m/s. Today, the speed of light is known to be closer to 3.0×10^8 m/s. Thus, light takes 16.5 min, not 22 min, to cross Earth's orbit. Nevertheless, Roemer had successfully proved that light moves at a finite speed.

Although many measurements of the speed of light have been made, the most notable were performed by American physicist Albert A. Michelson. 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 used a set of rotating mirrors to measure such small time intervals. 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 in a vacuum is a very important and universal value; thus it has its own special symbol, c. Based on the wave nature of light, which you will study in the next section, the International Committee on Weights and Measurements has measured and defined the speed of light in a vacuum to be c = 299,792,458 m/s. For many calculations, the value $c = 3.00 \times 10^8$ m/s is precise enough. At this speed, light travels 9.46×10^{12} km in a year. This amount of distance is called a light-year.

16.1 Section Review

7. Use of Material Light Properties Why might you choose a window shade that is translucent? Opaque?

8. Illuminance Does one lightbulb provide more illuminance than two identical lightbulbs at twice the distance? Explain.

9. Luminous Intensity Two lamps illuminate a screen equally—lamp A at 5.0 m, lamp B at 3.0 m. If lamp A is rated 75 cd, what is lamp B rated?

10. Distance of a Light Source Suppose that a lightbulb illuminating your desk provides only half the illuminance that it should. If it is currently 1.0 m away, how far should it be to provide the correct illuminance?

11. Distance of Light Travel How far does light travel in the time it takes sound to travel 1 cm in air at 20°C?

12. Distance of Light Travel 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 measured value of the speed of light to the same precision, calculate the distance from Earth to the Moon.

13. Critical Thinking Use the correct time taken for light to cross Earth's orbit, 16.5 min, and the diameter of Earth's orbit, 2.98×10^{11} m, to calculate the speed of light using Roemer's method. Does this method appear to be accurate? Why or why not?
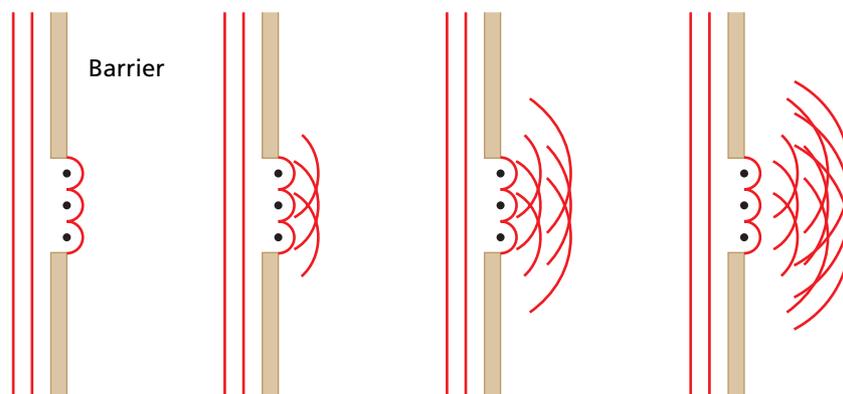
16.2 The Wave Nature of Light

You probably have heard that light is composed of waves, but what evidence do you have that this is so? Suppose that you walk by the open door of the band-rehearsal room at school. You hear the music as you walk toward the rehearsal-room door long before you can see the band members through the door. Sound seems to have reached you by bending around the edge of the door, whereas the light that enables you to see the band members has traveled only in a straight line. If light is composed of waves, why doesn't light seem to act in the same way as sound does? In fact, light does act in the same way; however, the effect is much less obvious with light than with sound.

Diffraction and the Wave Model of Light

In 1665, Italian scientist Francesco Maria Grimaldi observed that the edges of shadows are not perfectly sharp. He introduced a narrow beam of light into a dark room and held a rod in front of the light such that it cast a shadow on a white surface. The shadow cast by the rod on the white surface was wider than the shadow should have been if light traveled in a straight line past the edges of the rod. Grimaldi also noted that the shadow was bordered by colored bands. Grimaldi recognized this phenomenon as **diffraction,** which is the bending of light around a barrier.

In 1678, Dutch scientist Christiaan Huygens argued in favor of a wave model to explain diffraction. According to Huygens' principle, all the points of a wave front of light can be thought of as new sources of smaller waves. These wavelets expand in every direction and are in step with one another. A flat, or plane, wave front of light consists of an infinite number of point sources in a line. As this wave front passes by an edge, the edge cuts the wave front such that each circular wavelet generated by each Huygens' point will propagate as a circular wave in the region where the original wave front was bent, as shown in **Figure 16-9.** This is diffraction.

■ **Figure 16-9** According to Huygens' principle, the crest of each wave can be thought of as a series of point sources. Each point source creates a circular wavelet. All the wavelets combine to make a flat wave front, except at the edge where circular wavelets of the Huygens' points move away from the wave front.

Barrier

CONTENTS

Color

In 1666, possibly prompted by Grimaldi's publication of his diffraction results, Newton performed experiments on the colors produced when a narrow beam of sunlight passed through a glass prism, as shown in **Figure 16-10.** Newton called the ordered arrangement of colors a spectrum. Using his corpuscle model of light, he believed that particles of light were interacting with some unevenness in the glass to produce the spectrum.

To test this assumption, Newton allowed the spectrum from one prism to fall on a second prism. If the spectrum was caused by irregularities in the glass, he reasoned that the second prism would increase the spread in colors. Instead, the second prism reversed the spreading of colors and recombined them to form white light. After more experiments, Newton concluded that white light is composed of colors, and that a property of the glass other than unevenness caused the light to separate into colors.

Based on the work of Grimaldi, Huygens, and others, we know that light has wave properties and that each color of light is associated with a wavelength. Light falls within the range of wavelengths from about 400 nm (4.00×10^{-7} m) to 700 nm (7.00×10^{-7} m), as shown in **Figure 16-11.** The longest wavelengths are seen as red light. As wavelength decreases, the color changes to orange, yellow, green, blue, indigo, and finally, violet.

■ **Figure 16-10** White light, when passed through a prism, is separated into a spectrum of colors.

Red (7.00×10^{-7} m)   Violet (4.00×10^{-7} m)
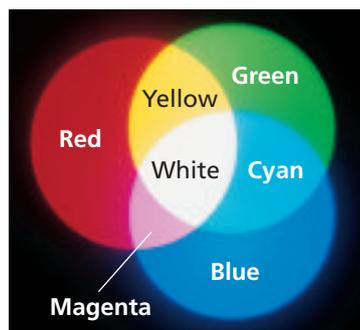

■ **Figure 16-11** The spectrum of light ranges from the long, red wavelength to the short, violet wavelength.

As white light crosses the boundary from air into glass and back into air in Figure 16-11, its wave nature causes each different color of light to be bent, or refracted, at a different angle. This unequal bending of the different colors causes the white light to be spread into a spectrum. This reveals that different wavelengths of light interact in different but predictable ways with matter.

Color by addition of light White light can be formed from colored light in a variety of ways. For example, when the correct intensities of red, green, and blue light are projected onto a white screen, as in **Figure 16-12,** the region where these three colors overlap on the screen will appear to be white. Thus, red, green, and blue light form white light when they are combined. This is called the additive color process, which is used in color-television tubes. A color-television tube contains tiny, dotlike sources of red, green, and blue light. When all three colors of light have the correct intensities, the screen appears to be white. For this reason, red, green, and blue are each called a **primary color.** The primary colors can be mixed in pairs to form three additional colors, as shown in Figure 16-12. Red and green light together produce yellow light, blue and green light produce cyan, and red and blue light produce magenta. The colors yellow, cyan, and magenta are each called a **secondary color,** because each is a combination of two primary colors.

■ **Figure 16-12** Different combinations of blue, green, and red light can produce yellow, cyan, magenta, or white light.

(b)Matt Meadows, (t)Kodak

As shown in Figure 16-12, 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. **Complementary colors** are two colors of light that can be combined to make white light. Thus, yellow is a complementary color of blue, and vice versa, because the two colors of light combine to make white light. In the same way, cyan and red are complementary colors, as are magenta and green. Yellowish laundry can be whitened with a bluing agent added to detergent.

Color by subtraction of light As you learned in the first section of this chapter, objects can reflect and transmit light. They also can absorb light. Not only does the color of an object depend on the wavelengths present in the light that illuminates the object, but an object's color also depends on what wavelengths are absorbed by the object and what wavelengths are reflected. The natural existence or artificial placement of dyes in the material of an object, or pigments on its surface, give the object color.

A dye is a molecule that absorbs certain wavelengths of light and transmits or reflects others. When light is absorbed, its energy is taken into the object that it strikes and is turned into other forms of energy. A red shirt is red because the dyes in it reflect red light to our eyes. When white light falls on the red object shown in **Figure 16-13,** the dye molecules in the object absorb the blue and green light and reflect the red light. When only blue light falls on the red object, very little light is reflected and the object appears to be almost black.

The difference between a dye and a pigment is that pigments usually are made of crushed minerals, rather than plant or insect extracts. Pigment particles can be seen with a microscope. A pigment that absorbs only one primary color and reflects two 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 colors of primary pigments. A pigment that absorbs two primary colors and reflects one color is called a **secondary pigment.** The colors of 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 colors. In the same way, the secondary pigment colors are the primary colors.

■ **Figure 16-13** The dyes in the dice selectively absorb and reflect various wavelengths of light. The dice are illuminated by white light **(a),** red light **(b),** and blue light **(c).**

The primary and secondary pigments are shown in **Figure 16-14.** When the primary pigments yellow and cyan are mixed, the yellow absorbs blue light and the cyan absorbs red light. Thus, Figure 16-14 shows yellow and cyan combining to make green pigment. When yellow pigment is mixed with the secondary pigment, blue, which absorbs green and red light, all of the primary colors are absorbed, so the result is black. Thus, yellow and blue are complementary pigments. Cyan and red, as well as magenta and green, are also complementary pigments.

A color printer uses yellow, magenta, and cyan dots of pigment to make a color image on paper. Often, pigments that are used are finely ground compounds, such as titanium(IV) oxide (white), chromium(III) oxide (green), and cadmium sulfide (yellow). Pigments mix to form suspensions rather than solutions. Their chemical form is not changed in a mixture, so they still absorb and reflect the same wavelengths.

Chemistry Connection

Biology Connection

Results in color You can now begin to understand the colors that you see in the photo at the beginning of this chapter. The plants on the hillside look green because of the chlorophyll in them. One type of chlorophyll absorbs red light and the other absorbs blue light, but they both reflect green light. The energy in the red and blue light that is absorbed is used by the plants for photosynthesis, which is the process by which green plants make food.

In the same photo, the sky is bluish. Violet and blue light are scattered (repeatedly reflected) much more by molecules in the air than are other wavelengths of light. Green and red light are not scattered much by the air, which is why the Sun looks yellow or orange, as shown in **Figure 16-15.** However, violet and blue light from the Sun are scattered in all directions, illuminating the sky in a bluish hue.

■ **Figure 16-15** The Sun can appear to be a shade of yellow or orange because of the scattering of violet and blue light.
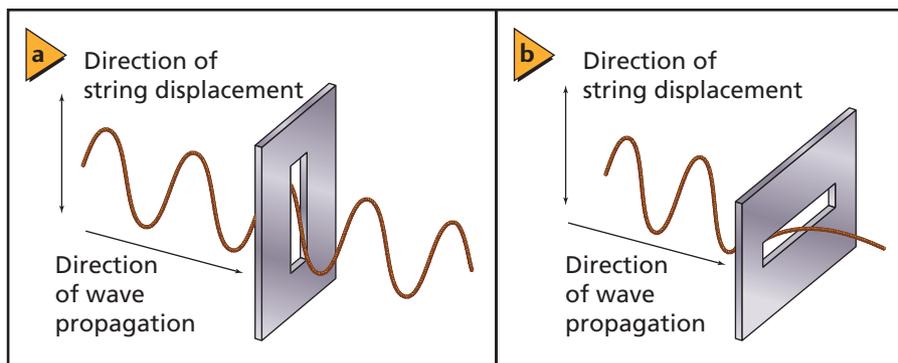
(t)Laura Sifferlin, (b)file photo

◄ **CONTENTS** ►

Polarization of Light

Have you ever looked at light reflected off a road through polarizing 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? Normal lamplight is not polarized. However, the light that is coming from the road is reflected and has become polarized. **Polarization** is the production of light in a single plane of oscillation.

**Polarization by filtering** Polarization can be understood by considering a rope model of light waves, as shown in **Figure 16-16.** The transverse mechanical waves in the rope represent transverse light waves. The slot represents what is referred to as the polarizing axis of a polarizing medium. When the rope waves are parallel to the slot, they pass through. When they are perpendicular to the slot, the waves are blocked. Polarizing media contain long molecules in which electrons can oscillate, or move back and forth, all in the same direction. As light travels past the molecules, the electrons can absorb light waves that oscillate in the same direction as the electrons. This process allows light waves vibrating in one direction to pass through, while the waves vibrating in the other direction are absorbed. The direction of a polarizing medium perpendicular to the long molecules is called the polarizing axis. Only waves oscillating parallel to that axis can pass through.

Ordinary light actually contains waves vibrating in every direction perpendicular to its direction of travel. If a polarizing medium is placed in a beam of ordinary light, only the components of the waves in the same direction as the polarizing axis can pass through. On average, half of the total light amplitude passes through, thereby reducing the intensity of the light by half. The polarizing medium produces light that is polarized. Such a medium is called a polarizing filter.

Polarization by reflection When 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 is partially polarized along the plane of the glass when it is reflected. That is, the reflected ray contains a great deal of light vibrating parallel to the surface of the glass. 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 polarizing sunglasses are rotated suggests that the reflected light is partially polarized. Photographers can use polarizing filters over camera lenses to block reflected light, as shown in **Figure 16-17.**
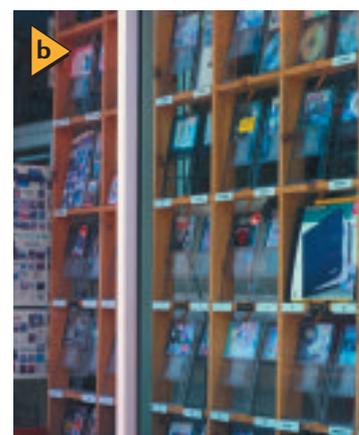
■ **Figure 16-17** This photo of a music store, taken without a polarizing filter, contains the glare of light off of the surface of the window **(a).** This photo of the same scene was taken with a polarizing filter **(b).**

CONTENTS

■ **Figure 16-18** When two polarizing filters are arranged with their polarizing axes in parallel, a maximum amount of light passes through **(a).** When two polarizing filters are arranged with perpendicular axes, no light passes through **(b).**
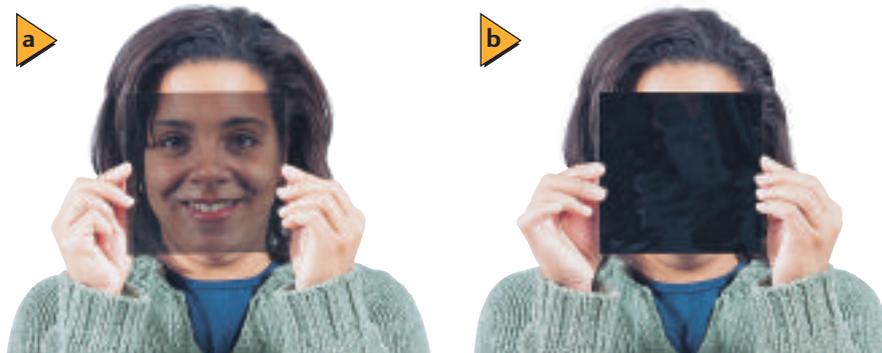
Polarization analysis Suppose that you produce polarized light with a polarizing filter. What would happen if you place a second polarizing filter in the path of the polarized light? If the polarizing axis of the second filter is parallel to that of the first, the light will pass through, as shown in **Figure 16-18a.** If the polarizing axis of the second filter is perpendicular to that of the first, no light will pass through, as shown in **Figure 16-18b.**

The law that explains the reduction of light intensity as it passes through a second polarizing filter is called **Malus's law.** If the light intensity after the first polarizing filter is I_1, then a second polarizing filter, with its polarizing axis at an angle, θ, relative to the polarizing axis of the first, will result in a light intensity, I_2, that is equal to or less than I_1.

Malus's Law $I_2 = I_1 \cos^2\theta$

The intensity of light coming out of a second polarizing filter is equal to the intensity of polarized light coming out of a first polarizing filter multiplied by the cosine, squared, of the angle between the polarizing axes of the two filters.

Using Malus's law, you can compare the light intensity coming out of the second polarizing filter to the light intensity coming out of the first polarizing filter, and thereby determine the orientation of the polarizing axis of the first filter relative to the second filter. A polarizing filter that uses Malus's law to accomplish this is called an analyzer. Analyzers can be used to determine the polarization of light coming from any source.

● CHALLENGE **PROBLEM**

You place an analyzer filter between the two cross-polarized filters, such that its polarizing axis is not parallel to either of the two filters, as shown in the figure to the right.

1. You observe that some light passes through filter 2, though no light passed through filter 2 previous to inserting the analyzer filter. Why does this happen?

2. The analyzer filter is placed at an angle of θ relative to the polarizing axes of filter 1. Derive an equation for the intensity of light coming out of filter 2 compared to the intensity of light coming out of filter 1.

**444**   Chapter 16 Fundamentals of Light
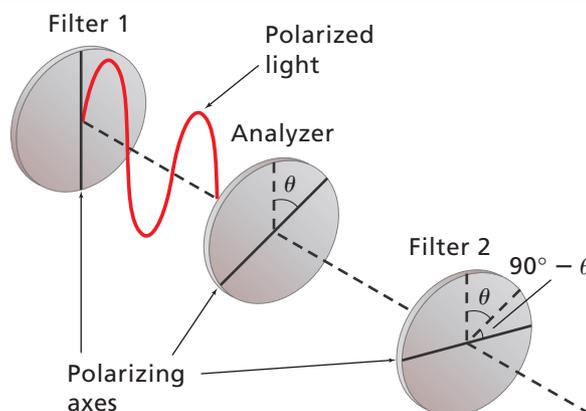
The Speed of a Light Wave

As you learned in Chapter 14, the wavelength, λ, of a wave is a function of its speed in the medium in which it is traveling and its constant frequency, f. Because light has wave properties, the same mathematical models used to describe waves in general can be used to describe light. For light of a given frequency traveling through a vacuum, wavelength is a function of the speed of light, c, which can be written as $\lambda_0 = c/f$. The development of the laser in the 1960s provided new methods of measuring the speed of light. The frequency of light can be counted with extreme precision using lasers and the time standard provided by atomic clocks. Measurements of wavelengths of light, however, are much less precise.

Different colors of light have different frequencies and wavelengths, but in a vacuum, they all travel at c. Because all wavelengths of light travel at the same speed in a vacuum, when you know the frequency of a light wave in a vacuum, you can calculate its wavelength, and vice versa. Thus, using precise measurements of light frequency and light speed, you can calculate a precise value of light wavelength.

Relative motion and light What happens if a source of light is traveling toward you or you are moving toward the light source? You learned in Chapter 15 that the frequency of a sound heard by the listener changes if either the source or the listener of the sound is moving. The same is true for light. However, when you consider the velocities of a source of sound and the observer, you are really considering each one's velocity relative to the medium through which the sound travels.

Because light waves are not vibrations of the particles of a mechanical medium, unlike sound waves, the Doppler effect of light can involve only the velocities of the source and the observer relative to each other. The magnitude of the difference between the velocities of the source and observer is called the relative speed. Remember that the only factors in the Doppler effect are the velocity components along the axis between the source and observer, as shown in **Figure 16-19.**

■ **Figure 16-19** The observer and the light source have different velocities **(a).** The magnitude of the vector subtraction of the velocity components along the axis between the source of light and the observer of the light is referred to as the relative speed along the axis between the source and observer, v **(b).**
(Illustration not to scale)

$$v = |v_{s,\ axis} - v_{o,\ axis}|$$

CONTENTS
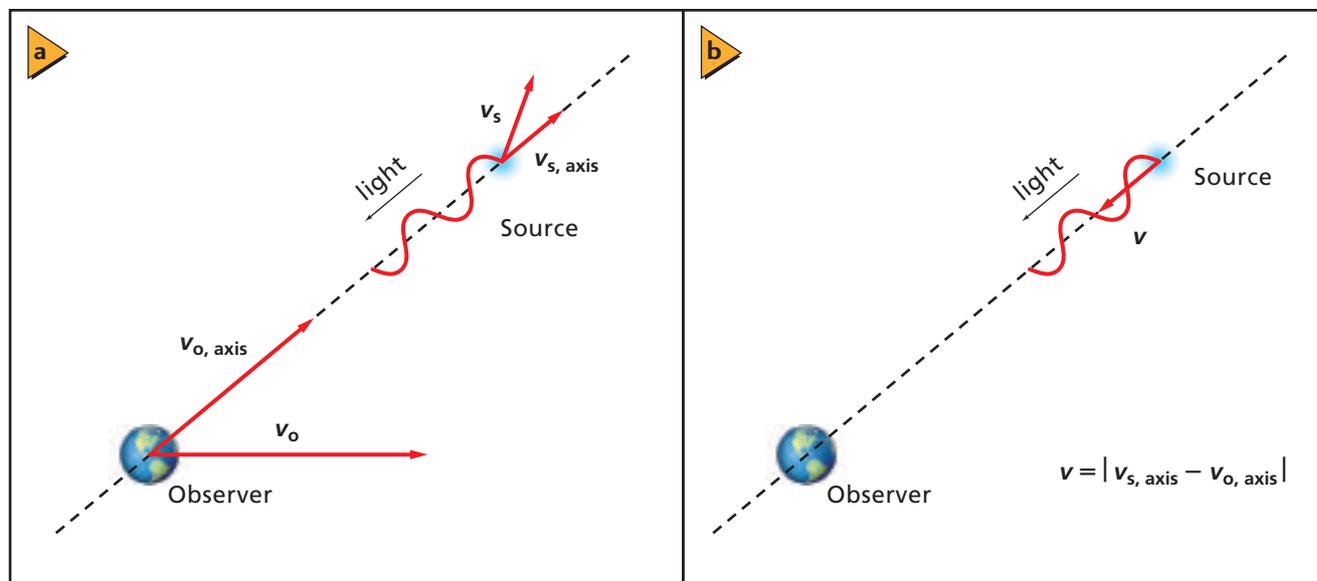
The Doppler effect To study the Doppler effect for light, the problem can be simplified by considering axial relative speeds that are much less than the speed of light ($v << c$). This simplification is used to develop the equation for the obseved light frequency, f_{obs}, which is the frequency of light as seen by an observer.

Observed Light Frequency $\quad f_{obs} = f\left(1 \pm \dfrac{v}{c}\right)$

The observed frequency of light from a source is equal to the actual frequency of the light generated by the source, times the quantity 1 plus the relative speed along the axis between the source and the observer if they are moving toward each other, or 1 minus the relative speed if they are moving away from each other.

Because most observations of the Doppler effect for light have been made in the context of astronomy, the equation for the Doppler effect for light generally is written in terms of wavelength rather than frequency. Using the relationship $\lambda = c/f$ and the $v << c$ simplification, the following equation can be used for the Doppler shift, $\Delta\lambda$, which is the difference between the observed wavelength of light and the actual wavelength.

Doppler Shift $\quad (\lambda_{obs} - \lambda) = \Delta\lambda = \pm\dfrac{v}{c}\lambda$

The difference between the observed wavelength of light and the actual wavelength of light generated by a source is equal to the actual wavelength of light generated by the source, times the relative speed of the source and observer, divided by the speed of light. This quantity is positive if they are moving away from each other or negative if they are moving toward each other.

A positive change in wavelength means that the light is red-shifted. This occurs when the relative velocity of the source is in a direction away from the observer. A negative change in wavelength means that the light is blue-shifted. This occurs when the relative velocity of the source is in a direction toward the observer. When the wavelength is red-shifted (lengthens), the observed frequency is lower as a result of the inverse relationship between the two variables, because the speed of light remains constant. When the wavelength is blue-shifted, the observed frequency is higher.

Researchers can determine how astronomical objects, such as galaxies, are moving relative to Earth by observing the Doppler shift of light. This is done by observing the spectrum of light coming from stars in the galaxy using a spectrometer, as shown in **Figure 16-20.** Elements that are present in the stars of galaxies emit specific wavelengths in the lab. A spectrometer is able to measure the Doppler shift of these wavelengths.

■ **Figure 16-20** Three emission lines of hydrogen are visibly redshifted in the spectrum of quasar 3C 273, as indicated by the taglines outside the spectra. Their wavelengths are shifted approximately 16% of what they are in a laboratory setting.

3C 273

Comparison spectrum

Maarten Schmidt

CONTENTS
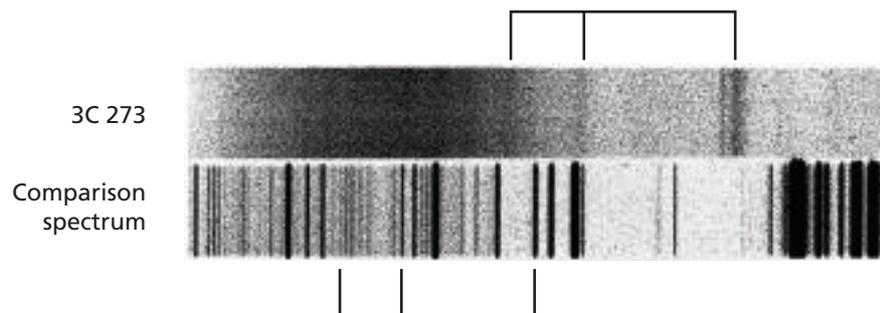
14. What is the frequency of oxygen's spectral line if its wavelength is 513 nm?

15. A hydrogen atom in a galaxy moving with a speed of 6.55×10^6 m/s away from Earth emits light with a frequency of 6.16×10^{14} Hz. What frequency of light from that hydrogen atom would be observed by an astronomer on Earth?

16. A hydrogen atom in a galaxy moving with a speed of 6.55×10^{16} m/s away from Earth emits light with a wavelength of 4.86×10^{-7} m. What wavelength would be observed on Earth from that hydrogen atom?

17. An astronomer is looking at the spectrum of a galaxy and finds that it has an oxygen spectral line of 525 nm, while the laboratory value is measured at 513 nm. Calculate how fast the galaxy would be moving relative to Earth. Explain whether the galaxy is moving toward or away from Earth and how you know.

In 1929, Edwin Hubble suggested that the universe is expanding. Hubble reached his conclusion of the expanding universe by analyzing emission spectra from many galaxies. Hubble noticed that the spectral lines of familiar elements were at longer wavelengths than expected. The lines were shifted toward the red end of the spectrum. No matter what area of the skies he observed, the galaxies were sending red-shifted light to Earth. What do you think caused the spectral lines to be red-shifted? Hubble concluded that all galaxies are moving away from Earth.

Astronomy Connection

You have learned that some characteristics of light can be explained with a simple ray model of light, whereas others require a wave model of light. In Chapters 17 and 18, you will use both of these models to study how light interacts with mirrors and lenses. In Chapter 19, you will learn about other aspects of light that can be understood only through the use of the wave model of light.

16.2 Section Review

18. **Addition of Light Colors** What color of light must be combined with blue light to obtain white light?

19. **Combination of Pigments** What primary pigment colors must be mixed to produce red? Explain how red results using color subtraction for pigment colors.

20. **Light and Pigment Interaction** What color will a yellow banana appear to be when illuminated by each of the following?
    a. white light
    b. green and red light
    c. blue light

21. **Wave Properties of Light** The speed of red light is slower in air and water than in a vacuum. The frequency, however, does not change when red light enters water. Does the wavelength change? If so, how?

22. **Polarization** Describe a simple experiment that you could do to determine whether sunglasses in a store are polarizing.

23. **Critical Thinking** Astronomers have determined that Andromeda, a neighboring galaxy to our own galaxy, the Milky Way, is moving toward the Milky Way. Explain how they determined this. Can you think of a possible reason why Andromeda is moving toward our galaxy?

◀ **CONTENTS** ▶

PHYSICS LAB •

Polarization of Light

A light source that produces transverse light waves that are all in the same fixed plane is said to be polarized in that plane. A polarizing filter can be used to find light sources that produce polarized light. Some media can rotate the plane of polarization of light as it transmits the light. Such media are said to be optically active. In this activity, you will investigate these concepts of polarized light.

QUESTION

What types of luminous and illuminated light sources produce polarized light?

Objectives

- **Experiment** with various sources of light and polarizing filters.
- **Describe** the results of your experiment.
- **Recognize** possible uses of polarizing filters in everyday life.

Safety Precautions

- **Minimize the length of time you look directly at bright light sources.**
- **Do not do this lab with laser light sources.**
- **Do not look at the Sun, even if you are using polarizing filters.**
- **Light sources can get hot and burn skin.**

Materials

two polarizing filter sheets
incandescent light source
fluorescent light source
pieces of white and black paper
calculator with a liquid crystal display
clear, plastic protractor
mirror

Procedure

1. Take a polarizing filter and look at an incandescent light source. Rotate the filter. Write your observations in the data table.

2. Use a polarizing filter to look at a fluorescent light source. Rotate the filter. Write your observations in the data table.

3. Use a polarizing filter to observe light reflected off the surface of a mirror at approximately a 45° angle. Rotate the filter. Record your observations in the data table.

Horizons Companies

Data Table

Light Source	Observations
1	
2	
3	
4	
5	
6	
7	
8	

4. Use a polarizing filter to observe light reflected off a white piece of paper at approximately a 45° angle. Rotate the filter. Record your observations in the data table.

5. Use a polarizing filter to observe light reflected off a piece of black paper at approximately a 45° angle. Rotate the filter. Record your observations in the data table.

6. Use a polarizing filter to observe a liquid crystal display on a calculator. Rotate the filter. Write your observations in the data table.

7. Place one polarizing filter on top of the other filter. Look at an incandescent light source through this set of the filters. Rotate one of the filters with respect to the other. Make a complete rotation. Record your observations in the data table.

8. Place a clear, plastic protractor between the two polarizing filters. Look at an incandescent light source with this. Do a complete rotation of one of the filters. Position the two filters the same way that produced no light in step 7. Record your observations in the data table.

Analyze

1. **Interpret Data** Does incandescent light produce polarized light? How do you know?

2. **Interpret Data** Does fluorescent light produce polarized light? How do you know?

3. **Interpret Data** Does reflection from a mirrored surface produce polarized light? How do you know?

4. **Compare and Contrast** How does reflected light from white paper compare to reflected light from black paper in terms of polarized light? Why are they different?

5. **Interpret Data** Is the light from liquid crystal displays polarized? How do you know?

Conclude and Apply

1. **Analyze and Conclude** How can two polarizing filters be used to prevent any light from passing through them?

2. **Analyze and Conclude** Why can the clear, plastic protractor between the polarizing filters be seen even though nothing else can be seen through the polarizing filters?

3. **Draw Conclusions** In general, what types of situations produce polarized light?

Going Further

1. On a sunny day, look at the polarization of blue sky near and far from the Sun using a polarizing filter. *CAUTION: Do not look directly at the Sun.* What characteristics of polarized light do you observe?

2. Is reflected light from clouds polarized? Make an observation to confirm your answer.

Real-World Physics

1. Why are high quality sunglasses made with polarizing lenses?

2. Why are polarizing sunglasses a better option than tinted sunglasses when driving a car?

Physics nline

To find out more about light, visit the Web site: **physicspp.com**

Technology and Society

Advances In Lighting

History has recorded the use of oil, candles, and gas to provide illumination in the dark hours of the night. However, there has always been inherent danger with the use of open flames to provide light. The invention of electric lighting in the nineteenth century provided brighter light and improved safety to the public.

The original form of electric light, which is still in common use, is the incandescent bulb. A tungsten filament is heated by electricity until it glows white. The tungsten does not burn, but it vaporizes, which eventually breaks the filament. Because the light is a result of heating the tungsten, this is not very efficient. Recent pursuits in electric lighting have produced longer-lasting, lower-heat light sources.

Clockwise from the upper left, the photos show LEDs, a fluorescent light, a halogen light, and gas-discharge lamps in the form of neon lights.

Quartz-Halogen Lamps

To prevent a filament from breaking, the bulb can be made very small and filled with bromine or iodine gas. Tungsten ions from the filament combine with the gas molecules in the cooler parts of the lamp to make a compound, which circulates through the lamp and recombines with the filament. The light is very white and bright, but it also is very hot. An ordinary glass bulb would melt, so fused quartz, which has a very high melting point, is used.

Gas-Discharge Lamps

This type of lamp is made of a glass tube with a wire electrode sealed into each end. All of the air is extracted and replaced by a very small amount of a specially chosen gas. A high voltage is applied across the electrodes. The electricity ionizes, or strips, some electrons from the gas atoms. An ionized gas is a good conductor, so electric current flows through it, causing the gas to glow brightly.

The use of a gas-discharge lamp depends upon the type of gas: neon for advertising, xenon for searchlights and camera flashes, and sodium vapor for streetlights. Each type of gas produces a different color, but the construction of each lamp is very similar.

Fluorescent Lamps

The glow produced by mercury vapor is almost invisible because most of its spectrum is in the ultraviolet region, which is not visible. A fluorescent lamp is made by painting the inside of a mercury-discharge lamp with phosphor, a chemical that glows brightly when ultraviolet light strikes it. Fluorescent lights can be made in any color by changing the mixture of red, green, and blue phosphors. They have a long life and are economical to use, because they produce little heat and a great deal of light.

Light-Emitting Diodes

The light of the future may be the white light-emitting diode, or LED. The LED produces white light by illuminating a tiny phosphor screen inside the LED with blue light. LEDs are bright enough to read by and produce almost no heat as they operate. They are so efficient that a car battery could power the lamps in a home for days without being recharged.

Going Further

1. **Observe** Novelty stores sell many devices that use lights. Examine some of them to see what types of lamp technology are used.
2. **Research** Find out about the inner construction, characteristic color, and typical uses of a few types of gas-discharge lamps.

CONTENTS

16.1 Illumination

Vocabulary

- ray model of light (p. 432)
- luminous source (p. 432)
- illuminated source (p. 432)
- opaque (p. 433)
- transparent (p. 433)
- translucent (p. 433)
- luminous flux (p. 433)
- illuminance (p. 433)

Key Concepts

- Light travels in a straight line through any uniform medium.
- Materials can be characterized as being transparent, translucent, or opaque, depending on the amount of light that they reflect, transmit, or absorb.
- The luminous flux of a light source is the rate at which light is emitted. It is measured in lumens (lm).
- Illuminance is the luminous flux per unit area. It is measured in lux (lx), or lumens per square meter (lm/m^2).
- For a point source, illuminance follows an inverse-square relationship with distance and a direct relationship with luminous flux.

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

- In a vacuum, light has a constant speed of $c = 3.00\times10^8$ m/s.

16.2 The Wave Nature of Light

Vocabulary

- diffraction (p. 439)
- primary color (p. 440)
- secondary color (p. 440)
- complementary colors (p. 441)
- primary pigment (p. 441)
- secondary pigment (p. 441)
- polarization (p. 443)
- Malus's law (p. 444)

Key Concepts

- Light can have wavelengths between 400 and 700 nm.
- White light is a combination of the spectrum of colors, each color having a different wavelength.
- Combining the primary colors, red, blue, and green, forms white light. Combinations of two primary colors form the secondary colors, yellow, cyan, and magenta.
- The primary pigments, cyan, magenta, and yellow, are used in combinations of two to produce the secondary pigments, red, blue, and green.
- Polarized light consists of waves oscillating in the same plane.
- When two polarizing filters are used to polarize light, the intensity of the light coming out of the last filter is dependent on the angle between the polarizing axes of the two filters.

$$I_2 = I_1\cos^2\theta$$

- Light waves traveling through a vacuum can be characterized in terms of frequency, wavelength, and the speed of light.
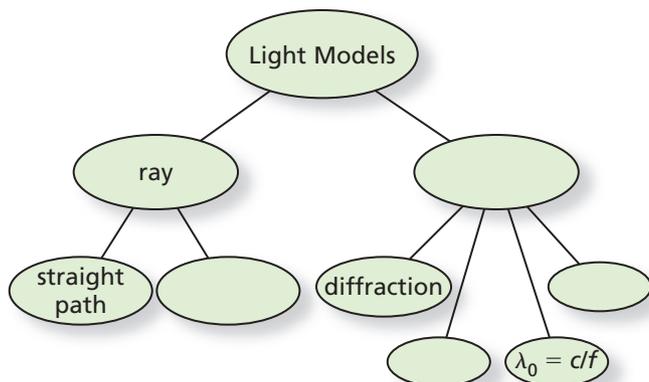
$$\lambda_0 = \frac{c}{f}$$

- Light waves are Doppler shifted based upon the relative speed along the axis of the observer and the source of light.

$$f_{\text{obs}} = f\left(1 \pm \frac{v}{c}\right)$$

$$\Delta\lambda = (\lambda_{\text{obs}} - \lambda) = \pm\frac{v}{c}\lambda$$

CONTENTS

Concept Mapping

24. Complete the following concept map using the following terms: *wave, c, Doppler effect, polarization.*

Light Models

ray

straight path

diffraction

$\lambda_0 = c/f$

Mastering Concepts

25. Sound does not travel through a vacuum. How do we know that light does? (16.1)

26. Distinguish between a luminous source and an illuminated source. (16.1)

27. Look carefully at an ordinary, frosted, incandescent bulb. Is it a luminous or an illuminated source? (16.1)

28. Explain how you can see ordinary, nonluminous classroom objects. (16.1)

29. Distinguish among transparent, translucent, and opaque objects. (16.1)

30. To what is the illumination of a surface by a light source directly proportional? To what is it inversely proportional? (16.1)

31. What did Galileo assume about the speed of light? (16.1)

32. Why is the diffraction of sound waves more familiar in everyday experience than is the diffraction of light waves? (16.2)

33. What color of light has the shortest wavelength? (16.2)

34. What is the range of the wavelengths of light, from shortest to longest? (16.2)

35. Of what colors does white light consist? (16.2)

36. Why does an object appear to be black? (16.2)

37. Can longitudinal waves be polarized? Explain. (16.2)

38. If a distant galaxy were to emit a spectral line in the green region of the light spectrum, would the observed wavelength on Earth shift toward red light or toward blue light? Explain. (16.2)

39. What happens to the wavelength of light as the frequency increases? (16.2)

Applying Concepts

40. A point source of light is 2.0 m from screen A and 4.0 m from screen B, as shown in **Figure 16-21.** How does the illuminance at screen B compare with the illuminance at screen A?

Screen A

Screen B

Source

←— 2 m —→|←—— 4 m ——→
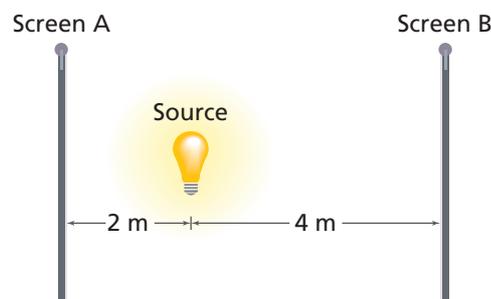
■ **Figure 16-21**

41. **Reading Lamp** You have a small reading lamp that is 35 cm from the pages of a book. You decide to double the distance.
 a. Is the illuminance at the book the same?
 b. If not, how much more or less is it?

42. Why are the insides of binoculars and cameras painted black?

43. **Eye Sensitivity** The eye is most sensitive to yellow-green light. Its sensitivity to red and blue light is less than 10 percent as great. Based on this knowledge, what color would you recommend that fire trucks and ambulances be painted? Why?

44. **Streetlight Color** Some very efficient streetlights contain sodium vapor under high pressure. They produce light that is mainly yellow with some red. Should a community that has these lights buy dark blue police cars? Why or why not?

Refer to **Figure 16-22** *for problems 45 and 46.*
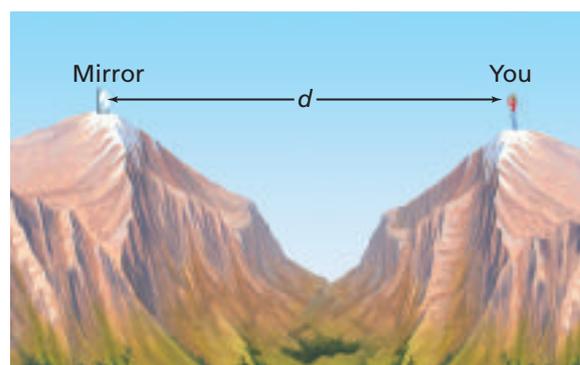
■ **Figure 16-22**

45. What happens to the illuminance at a book as the lamp is moved farther away from the book?

46. What happens to the luminous intensity of the lamp as it is moved farther away from the book?

452 Chapter 16 Fundamentals of Light For more problems, go to Additional Problems, Appendix B.

◀ **CONTENTS** ▶

47. Polarized Pictures Photographers often put polarizing filters over camera lenses 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.

48. An apple is red because it reflects red light and absorbs blue and green light.
   a. Why does red cellophane look red in reflected light?
   b. Why does red cellophane make a white lightbulb look red when you hold the cellophane between your eye and the lightbulb?
   c. What happens to the blue and green light?

49. 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?

50. You now put both the red and green cellophane pieces over one of the flashlights in Problem 49. If you shine the flashlight beam on a white wall, what color will you see? Explain.

51. If you have yellow, cyan, and magenta pigments, how can you make a blue pigment? Explain.

52. Traffic Violation Suppose that you are a traffic officer and you stop a driver for going through a red light. Further suppose that the driver draws a picture for you (**Figure 16-23**) and explains that the light looked green because of the Doppler effect when he went through it. Explain to him using the Doppler shift equation just how fast he would have had to be going for the red light ($\lambda = 645$ nm), to appear green ($\lambda = 545$ nm). *Hint: For the purpose of this problem, assume that the Doppler shift equation is valid at this speed.*
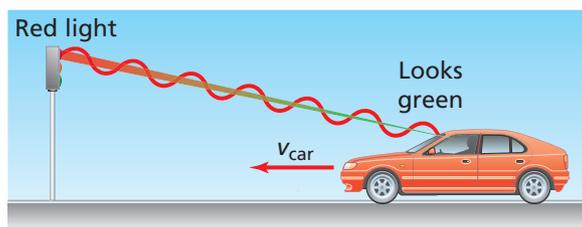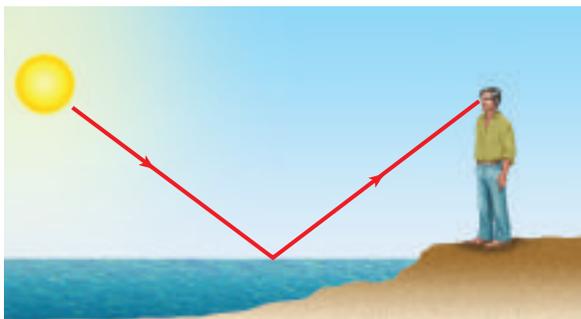

Figure 16-23

Mastering Problems

16.1 Illumination

53. Find the illumination 4.0 m below a 405-lm lamp.

54. Light takes 1.28 s to travel from the Moon to Earth. What is the distance between them?

55. 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?

56. Earth's Speed Ole Roemer found that the average increased delay in the disappearance of Io from one orbit around Jupiter to the next is 13 s.
   a. How far does light travel in 13 s?
   b. Each orbit of Io takes 42.5 h. Earth travels the distance calculated in part **a** in 42.5 h. Find the speed of Earth in km/s.
   c. Check to make sure that your answer for part **b** is reasonable. Calculate Earth's speed in orbit using the orbital radius, 1.5×10^8 km, and the period, 1.0 yr.

57. A student wants to compare the luminous flux of a lightbulb with that of a 1750-lm lamp. The lightbulb and the lamp illuminate a sheet of paper equally. The 1750-lm lamp is 1.25 m away from the sheet of paper; the lightbulb is 1.08 m away. What is the lightbulb's luminous flux?

58. Suppose that 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, as shown in **Figure 16-24.** Without instruments, a person can detect a time interval of about 0.10 s. How many kilometers away would the mirror have to be? Compare this distance with that of some known distances.

Figure 16-24

16.2 The Wave Nature of Light

59. Convert 700 nm, the wavelength of red light, to meters.

60. Galactic Motion How fast is a galaxy moving relative to Earth if a hydrogen spectral line of 486 nm is red-shifted to 491 nm?

61. Suppose that you are facing due east at sunrise. Sunlight is reflected off the surface of a lake, as shown in **Figure 16-25.** Is the reflected light polarized? If so, in what direction?

■ **Figure 16-25**

62. Polarizing Sunglasses In which direction should the transmission axis of polarizing sunglasses be oriented to cut the glare from the surface of a road: vertically or horizontally? Explain.

63. Galactic Motion A hydrogen spectral line that is known to be 434 nm is red-shifted by 6.50 percent in light coming from a distant galaxy. How fast is the galaxy moving away from Earth?

64. For any spectral line, what would be an unrealistic value of the apparent wavelength for a galaxy moving away from Earth. Why?

Mixed Review

65. Streetlight Illumination A streetlight contains two identical bulbs that are 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?

66. An octave in music is a doubling of frequency. Compare the number of octaves that correspond to the human hearing range to the number of octaves in the human vision range.

67. 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 from the wall is the 60.0-cd lamp?

68. Thunder and Lightning Explain why it takes 5 s to hear thunder when lightning is 1.6 km away.

69. Solar Rotation Because the Sun rotates on its axis, one edge of the Sun moves toward Earth and the other moves away. The Sun rotates approximately once every 25 days, and the diameter of the Sun is 1.4×10^9 m. Hydrogen on the Sun emits light of frequency 6.16×10^{14} Hz from the two sides of the Sun. What changes in wavelength are observed?

Thinking Critically

70. Research Why did Galileo's method for measuring the speed of light not work?

71. Make and Use Graphs A 110-cd light source is 1.0 m from a screen. Determine the illumination on the screen originally and for every meter of increasing distance up to 7.0 m. Graph the data.
 a. What is the shape of the graph?
 b. What is the relationship between illuminance and distance shown by the graph?

72. Analyze and Conclude If you were to drive at sunset in a city filled with buildings that have glass-covered walls, the setting Sun reflected off the building's walls might temporarily blind you. Would polarizing glasses solve this problem?

Writing in Physics

73. Write an essay describing the history of human understanding of the speed of light. Include significant individuals and the contribution that each individual made.

74. Look up information on the SI unit *candela, cd,* and explain in your own words the standard that is used to set the value of 1 cd.

Cumulative Review

75. A 2.0-kg object is attached to a 1.5-m long string and swung in a vertical circle at a constant speed of 12 m/s. (Chapter 7)
 a. What is the tension in the string when the object is at the bottom of its path?
 b. What is the tension in the string when the object is at the top of its path?

76. A space probe with a mass of 7.600×10^3 kg is traveling through space at 125 m/s. Mission control decides that a course correction of 30.0° is needed and instructs the probe to fire rockets perpendicular to its present direction of motion. If the gas expelled by the rockets has a speed of 3.200 km/s, what mass of gas should be released? (Chapter 9)

77. When a 60.0-cm-long guitar string is plucked in the middle, it plays a note of frequency 440 Hz. What is the speed of the waves on the string? (Chapter 14)

78. What is the wavelength of a sound wave with a frequency of 17,000 Hz in water at 25°C? (Chapter 15)

454   Chapter 16 Fundamentals of Light   For more problems, go to Additional Problems, Appendix B.

◀ **CONTENTS** ▶

Standardized Test Practice

Multiple Choice

1. In 1987, a supernova was observed in a neighboring galaxy. Scientists believed the galaxy was 1.66×10^{21} m away. How many years prior to the observation did the supernova explosion actually occur?

   Ⓐ 5.53×10^3 yr Ⓒ 5.53×10^{12} yr

   Ⓑ 1.75×10^5 yr Ⓓ 1.74×10^{20} yr

2. A galaxy is moving away at 5.8×10^6 m/s. Its light appears to observers to have a frequency of 5.6×10^{14} Hz. What is the emitted frequency of the light?

   Ⓐ 1.1×10^{13} Hz Ⓒ 5.7×10^{14} Hz

   Ⓑ 5.5×10^{14} Hz Ⓓ 6.2×10^{14} Hz

3. Which of the following light color combinations is incorrect?

   Ⓐ Red plus green produces yellow.

   Ⓑ Red plus yellow produces magenta.

   Ⓒ Blue plus green produces cyan.

   Ⓓ Blue plus yellow produces white.

4. The illuminance of direct sunlight on Earth is about 1×10^5 lx. A light on a stage has an intensity in a certain direction of 5×10^6 cd. At what distance from the stage does a member of the audience experience an illuminance equal to that of sunlight?

   Ⓐ 1.4×10^{-1} m Ⓒ 10 m

   Ⓑ 7 m Ⓓ 5×10^1 m

5. What is meant by the phrase *color by subtraction of light*?

   Ⓐ Adding green, red, and blue light produces white light.

   Ⓑ Exciting phosphors with electrons in a television produces color.

   Ⓒ Paint color is changed by subtracting certain colors, such as producing blue paint from green by removing yellow.

   Ⓓ The color that an object appears to be is a result of the material absorbing specific light wavelengths and reflecting the rest.

6. The illuminance due to a 60.0-W lightbulb at 3.0 m is 9.35 lx. What is the total luminous flux of the bulb?

   Ⓐ 8.3×10^{-2} lm Ⓒ 1.2×10^2 lm

   Ⓑ 7.4×10^{-1} lm Ⓓ 1.1×10^3 lm

7. Light from the Sun takes about 8.0 min to reach Earth. How far away is the Sun?

   Ⓐ 2.4×10^9 m Ⓒ 1.4×10^8 km

   Ⓑ 1.4×10^{10} m Ⓓ 2.4×10^9 km

8. What is the frequency of 404 nm of light in a vacuum?

   Ⓐ 2.48×10^{-3} Hz Ⓒ 2.48×10^6 Hz

   Ⓑ 7.43×10^5 Hz Ⓓ 7.43×10^{14} Hz

Extended Answer

9. A celestial object is known to contain an element that emits light at a wavelength of 525 nm. The observed spectral line for this element is at 473 nm. Is the object approaching or receding, and at what speed?

10. Nonpolarized light of intensity I_o is incident on a polarizing filter, and the emerging light strikes a second polarizing filter, as shown in the figure. What is the light intensity emerging from the second polarizing filter?

Non-polarized light

45°

Polarizing filters
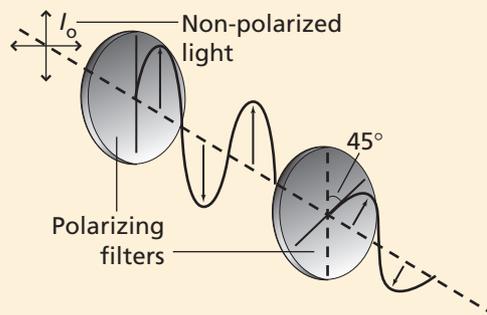
✓ **Test-Taking TIP**

Ask Questions

When you have a question about what will be on a test, the way a test is scored, the time limits placed on each section, or anything else, ask the instructor or the person giving the test.

CONTENTS

Reflection and Mirrors

What You'll Learn

- You will learn how light reflects off different surfaces.
- You will learn about the different types of mirrors and their uses.
- You will use ray tracing and mathematical models to describe images formed by mirrors.

Why It's Important

How light reflects off a surface into your eyes determines the reflection that you see. When you look down at the surface of a lake, you see an upright reflection of yourself.

Mountain Scene When you look across a lake, you might see a scene like the one in this photo. The image of the trees and mountains in the lake appears to you to be upside-down.

Think About This ▶

Why would the image you see of yourself in the lake be upright, while the image of the mountain is upside-down?

Physics nline

physicspp.com

George Matchneer

CONTENTS