CHAPTER 18 The Electromagnetic Spectrum and Light

CONCEPTS in Action

How do science concepts apply to your world? Here are some questions you'll be able to answer after you read this chapter.

- Why does a lamp seem brighter the closer you are to it? *(Section 18.1)*
- How does a microwave oven cook food? *(Section 18.2)*
- How is a mirage formed? *(Section 18.3)*
- How can you make millions of colors from only three? *(Section 18.4)*
- Why are fluorescent lights commonly used in large buildings? *(Section 18.5)*

Discovery Channel School

Video Field Trip

Finding the Fakes

- How can you tell if a painting is a forgery? *(Page 554)*

Colorful neon lights brighten up a walkway in Chicago's O'Hare Airport.

Chapter Preview

Inquiry Activity

How Do Color Filters Work?

Procedure

1. Place a piece of cardboard that has a slit cut into it in sunlight so that a beam of light passes through the slit. **CAUTION** *Never look directly at the sun.*
2. Create a rainbow by positioning a prism in the beam of light that has passed through the slit. Project the rainbow onto white paper.
3. Use colored markers to draw the colors in the order in which they appear on the paper.
4. Replace the paper. Place a red filter between the slit and the prism and draw the colors you see projected onto the paper.
5. Repeat Step 4 with a blue filter and then with a green filter.

Think About It

1. **Inferring** What happens to sunlight when it passes through a prism?
2. **Observing** Which colors did you see projected onto the paper while using each filter? Which colors didn't you see while using each filter?
3. **Drawing Conclusions** What can you conclude about what happens to sunlight as it passes through a filter?

18.1 Electromagnetic Waves

Reading Focus

Key Concepts

- How are electromagnetic waves different from mechanical waves?
- What is the maximum speed of light?
- How do electromagnetic waves differ from one another?
- What is the dual nature of electromagnetic radiation?
- What happens as light travels farther from its source?

Vocabulary

- electromagnetic waves
- electric field
- magnetic field
- electromagnetic radiation
- photoelectric effect
- photons
- intensity

Reading Strategy

Comparing and Contrasting Copy the table below. As you read about electromagnetic waves, fill in the table to compare them with mechanical waves. Use E for properties of electromagnetic waves, M for mechanical waves, and B for both.

Travels through vacuum	E
Travels through medium	a. ?
Fits wave model	B
Fits particle model	b. ?
Transverse wave	c. ?
Longitudinal wave	d. ?

What do X-ray machines, microwave ovens, and heat lamps have in common with police radar, television, and radiation therapy? They all use waves. You are surrounded by such waves all the time. But you may not realize it, because most waves are invisible.

With X-rays, you can take pictures of your bones. Your dentist uses X-rays to examine the inner structure of your teeth. Microwaves cook or reheat your meals and carry cell phone conversations between you and your friends. Radio waves bring your favorite music to your radio from the radio station. Ultraviolet rays can give you a sunburn. Without waves, the girl in Figure 1 wouldn't be able to talk with her friends on a cell phone. Without waves, you wouldn't be able to watch your favorite TV show. You wouldn't be able to see colors. In fact, without waves you wouldn't be able to see anything at all.

Figure 1 The waves that carry this girl's cell phone conversation are not visible. The girl may not even know they exist. But their existence is what makes cell phone technology possible.

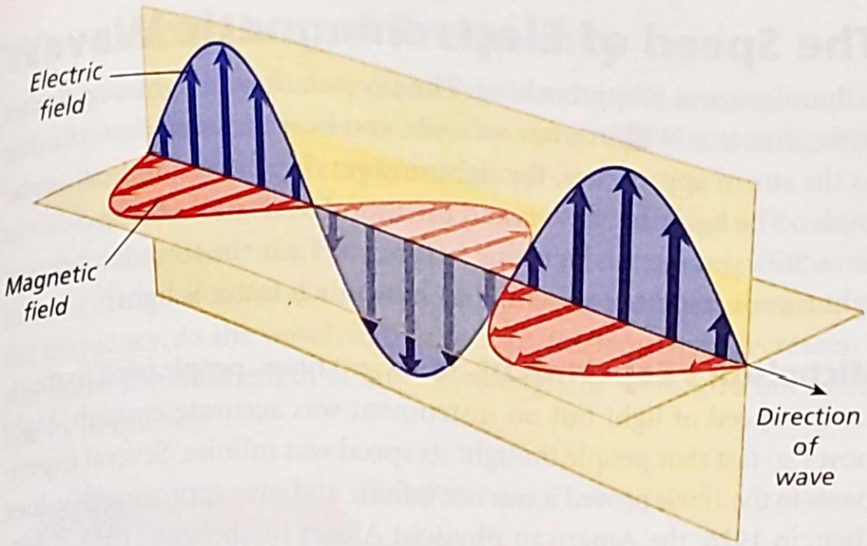

Figure 2 Electromagnetic waves consist of changing electric fields and magnetic fields. The fields are at right angles to each other and to the direction of the wave. **Interpreting Diagrams** *How can you tell that electromagnetic waves are transverse waves?*

What Are Electromagnetic Waves?

The visible and invisible waves you will learn about in this chapter exhibit some of the same behaviors as mechanical waves. Other behaviors are unique to electromagnetic waves. **Electromagnetic waves** are transverse waves consisting of changing electric fields and changing magnetic fields. Like mechanical waves, electromagnetic waves carry energy from place to place. Electromagnetic waves differ from mechanical waves in how they are produced and how they travel.

How They Are Produced Electromagnetic waves are produced by constantly changing fields. An **electric field** in a region of space exerts electric forces on charged particles. Electric fields are produced by electrically charged particles and by changing magnetic fields. A **magnetic field** in a region of space produces magnetic forces. Magnetic fields are produced by magnets, by changing electric fields, and by vibrating charges. **Electromagnetic waves are produced when an electric charge vibrates or accelerates.** Figure 2 shows that the fields are at right angles to each other. You can tell this is a transverse wave because the fields are also at right angles to the direction in which the wave travels.

How They Travel Because changing electric fields produce changing magnetic fields, and changing magnetic fields produce changing electric fields, the fields regenerate each other. As the fields regenerate, their energy travels in the form of a wave. Unlike mechanical waves, electromagnetic waves do not need a medium. **Electromagnetic waves can travel through a vacuum, or empty space, as well as through matter.** The transfer of energy by electromagnetic waves traveling through matter or across space is called **electromagnetic radiation.**

Reading Checkpoint *What are electromagnetic waves?*

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The Speed of Electromagnetic Waves

A thunderstorm is approaching. The sky is dark, and lightning flashes in the distance. Within a few seconds, you hear thunder's low rumble. As the storm approaches, the lightning gets brighter and the thunder louder. The lightning flashes and the sound of thunder come closer in time. Still, you see the lightning before you hear the thunder, because light travels faster than sound. But how much faster is light?

Michelson's Experiment In ancient times, people tried to measure the speed of light but no instrument was accurate enough. Light moves so fast that people thought its speed was infinite. Several experiments in the 1800s proved it was not infinite and gave approximate values. Then, in 1926, the American physicist Albert Michelson (1852–1931) measured the speed of light more accurately than ever before.

Figure 3 shows an experimental setup similar to Michelson's. On top of Mount Wilson in California, Michelson placed an eight-sided rotating mirror. He placed another mirror, this one stationary, on Mount San Antonio, 35.4 kilometers away. Michelson shined a bright light at one face of the rotating mirror. The light reflected to the stationary mirror on the other mountain and then back to Mount Wilson, where it struck another face of the rotating mirror. Michelson knew how fast the eight-sided mirror was rotating and how far the light traveled from mountain to mountain and back again. With those values he was able to calculate the speed of light quite accurately. His findings were similar to modern measurements.

The Speed of Light Since Michelson, many other scientists have measured the speed of light. Their experiments have confirmed that light and all electromagnetic waves travel at the same speed when in a vacuum, regardless of the observer's motion. **The speed of light in a vacuum, c, is 3.00×10^8 meters per second.**

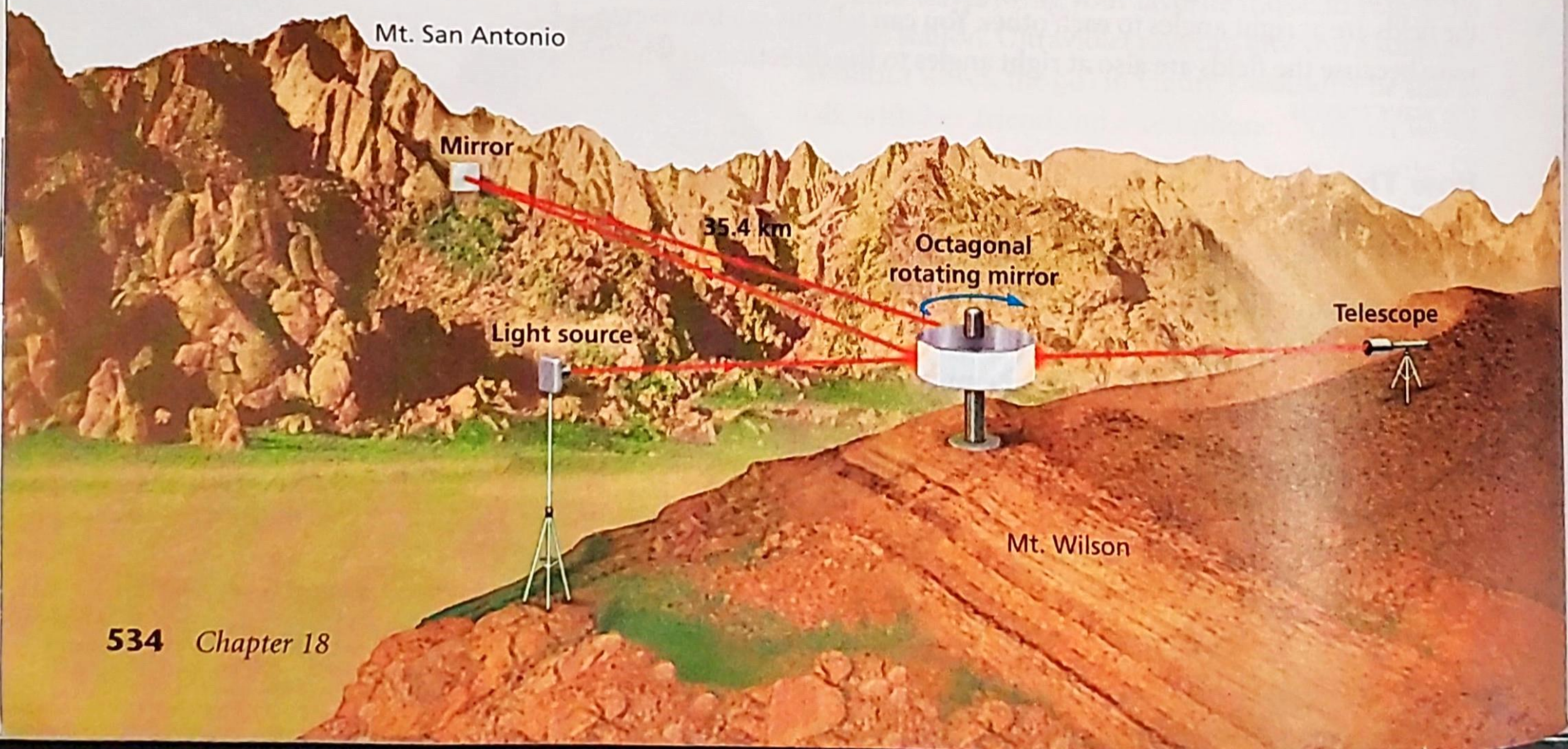


Figure 3 Michelson timed a light beam as it traveled from one mountain to another and back again. His experiment measured the speed of light more accurately than it had been measured before. **Inferring** ***Why must the light beam travel so far for its speed to be measurable?***

Wavelength and Frequency

In a vacuum, all electromagnetic waves travel at the same speed. But not all electromagnetic waves are the same. **Electromagnetic waves vary in wavelength and frequency.**

The speed of an electromagnetic wave is the product of its wavelength and its frequency. Because the speed of electromagnetic waves in a vacuum is constant, the wavelength is inversely proportional to the frequency. As the wavelength increases, the frequency decreases. If you know the wavelength of an electromagnetic wave, you can calculate its frequency.

Math Skills

Calculating Wave Speed

A radio station broadcasts a radio wave with a wavelength of 3.0 meters. What is the frequency of the wave?

1 Read and Understand

What information are you given?

$$\text{Speed} = c = 3.00 \times 10^8 \text{ m/s}$$

$$\text{Wavelength} = 3.0 \text{ m}$$

2 Plan and Solve

What unknown are you trying to calculate?

$$\text{Frequency} = ?$$

What formula contains the given quantities and the unknown?

$$\text{Speed} = \text{Wavelength} \times \text{Frequency}$$

$$\text{or, Frequency} = \frac{\text{Speed}}{\text{Wavelength}}$$

Replace each variable with its known value.

$$\text{Frequency} = \frac{3.00 \times 10^8 \text{ m/s}}{3.0 \text{ m}}$$

$$= 1.0 \times 10^8 \text{ Hz}$$

3 Look Back and Check

Is your answer reasonable?

Check that product of wavelength and frequency gives a speed of 3.0×10^8 m/s.

$$\text{Speed} = 3.0 \text{ m} \times (1.0 \times 10^8 \text{ Hz}) = 3.0 \times 10^8 \text{ m/s}$$

Math Practice

1. A global positioning satellite transmits a radio wave with a wavelength of 19 cm. What is the frequency of the radio wave? (*Hint:* Convert the wavelength to meters before calculating the frequency.)
2. The radio waves of a particular AM radio station vibrate 680,000 times per second. What is the wavelength of the wave?
3. Radio waves that vibrate 160,000,000 times per second are used on some train lines for communications. If radio waves that vibrate half as many times per second were used instead, how would the wavelength change?

Figure 4 The fact that light casts a shadow has been used as evidence for both the wave model of light and the particle model of light.

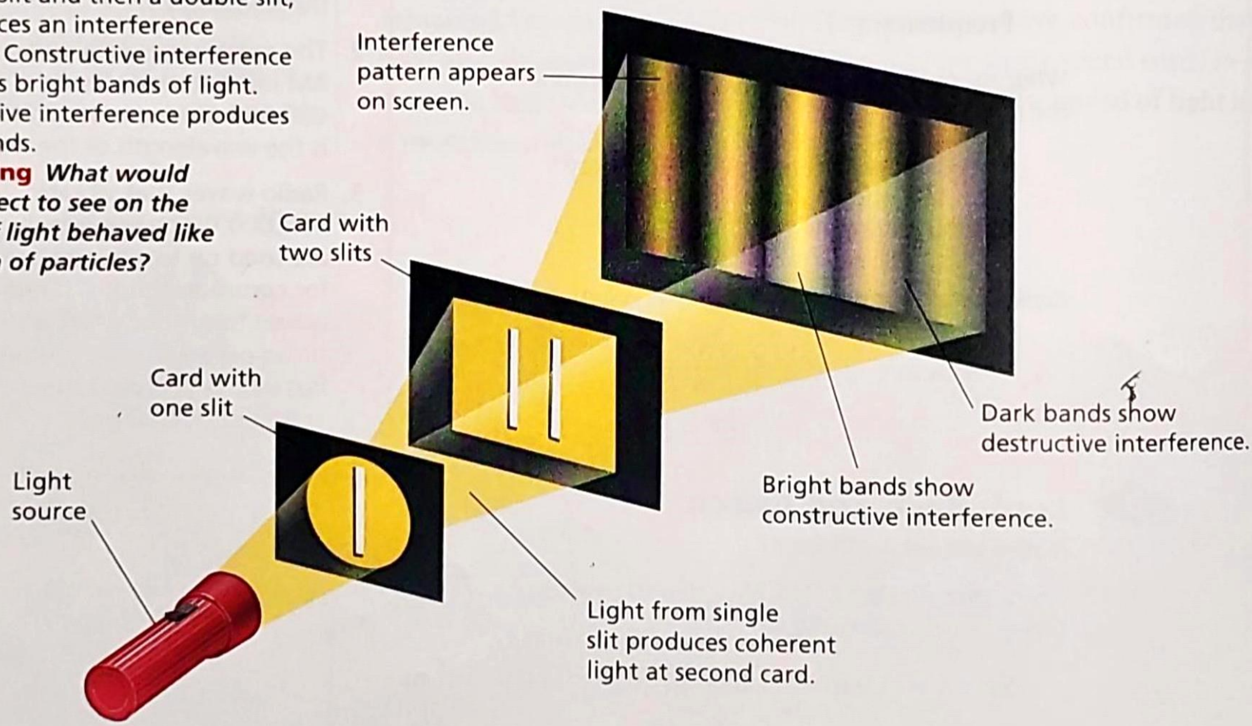
Wave or Particle?

Scientists know that electromagnetic radiation travels as a wave. Scientists also have evidence that electromagnetic radiation behaves like a stream of particles. In the late 1600s, the English physicist Isaac Newton was the first to propose a particle explanation. He based this hypothesis on two pieces of evidence: light travels in a straight line and it casts a shadow, as shown in Figure 4. But not all evidence supports Newton's hypothesis. So which is light, wave or particle? It is both. **Electromagnetic radiation behaves sometimes like a wave and sometimes like a stream of particles.**

Evidence for the Wave Model In 1801, the English physicist Thomas Young (1773–1829) showed that light behaves like a wave. Look at Figure 5. Young passed a beam of light first through a single slit and then through a double slit. Where light from the two slits reached a darkened screen, Young observed alternating bright and dark bands. The bands were evidence that the light had produced an interference pattern. Bright bands indicated constructive interference, and dark bands indicated destructive interference. Interference occurs only when two or more waves overlap. Therefore, Young's experiment showed that light behaves like a wave.

Reading Checkpoint *What is the evidence that light travels like a wave?*

Figure 5 This diagram illustrates Young's experiment, which showed that light behaves like a wave. When light passes through a single slit and then a double slit, it produces an interference pattern. Constructive interference produces bright bands of light. Destructive interference produces dark bands.
Predicting ***What would you expect to see on the screen if light behaved like a stream of particles?***



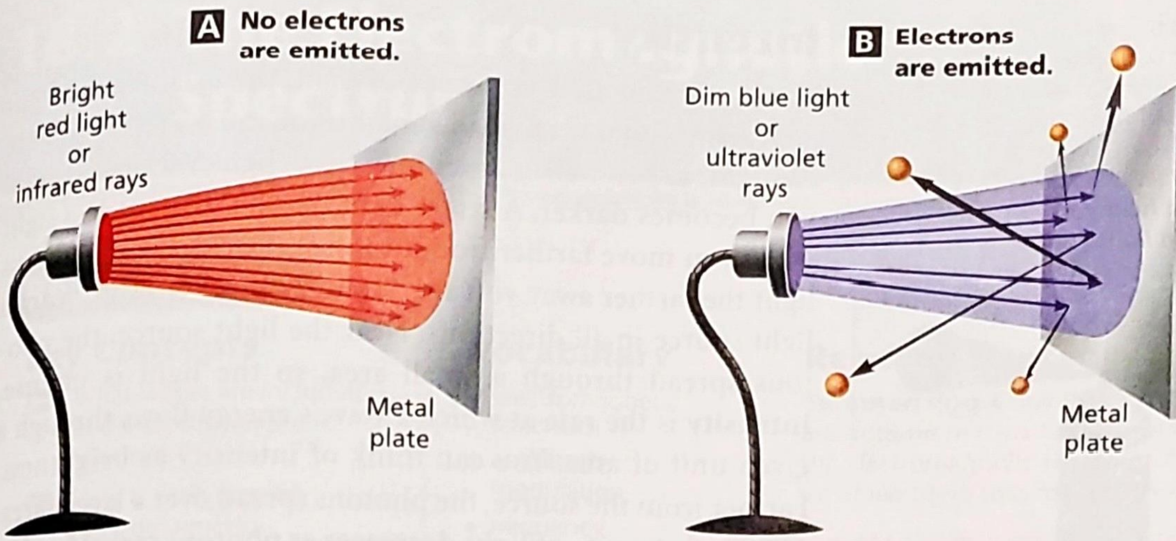


Figure 6 The emissions of electrons from a metal caused by light striking the metal is called the photoelectric effect. **A** Red light or infrared rays, no matter how bright, does not cause electrons to be emitted from this metal surface. **B** When blue light or ultraviolet rays strike the metal surface, electrons are emitted, even if the light is dim.

Evidence for the Particle Model When dim blue light hits the surface of a metal such as cesium, an electron is emitted. A brighter blue light causes even more electrons to be emitted, as you can see in Figure 6. But red light, no matter how bright it is, does not cause the emission of any electrons in this particular metal.

The emission of electrons from a metal caused by light striking the metal is called the **photoelectric effect.** Discovered in 1887, the photoelectric effect was puzzling. Scientists did not understand why dim blue light caused electrons to be emitted from metal but even bright red light did not.

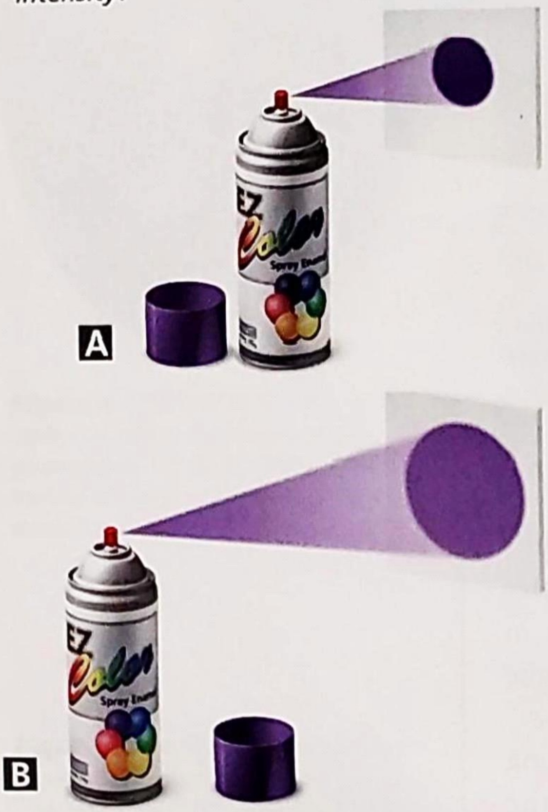
In 1905, Albert Einstein (1879–1955) proposed that light, and all electromagnetic radiation, consists of packets of energy. These packets of electromagnetic energy are now called **photons** (FOH tawnz). Each photon's energy is proportional to the frequency of the light. The greater the frequency of an electromagnetic wave, the more energy each of its photons has.

Blue light has a higher frequency than red light, so photons of blue light have more energy than photons of red light. Blue light consists of photons that have enough energy to cause electrons to be emitted from a metal surface. So blue light can cause emission of electrons.

Red light has a lower frequency than blue light, so photons of red light have less energy than photons of blue light. Red light consists of photons that have too little energy to cause any electrons to be emitted from a metal surface. So red light does not cause emission of electrons.

Reading Checkpoint ***What is the photoelectric effect?***

Figure 7 The closer you are to a surface when you spray paint it, the smaller the area the paint covers and the more intense the paint color looks. **Using Models** ***How does a can of spray paint help you model a change in light intensity?***



Intensity

The closer you are to a source of light, the brighter the light appears. If you want to read at night, you must sit near a lamp. At night, as you walk away from a street light, the area around you becomes darker. A street light doesn't give off less light when you move farther from it. It just provides you with less light the farther away you are. Photons travel outward from a light source in all directions. Near the light source, the photons spread through a small area, so the light is intense. **Intensity** is the rate at which a wave's energy flows through a given unit of area. You can think of intensity as brightness. Farther from the source, the photons spread over a larger area. **The intensity of light decreases as photons travel farther from the source.**

A can of spray paint can help you model a change in light intensity. Look at Figure 7. When the nozzle is close to a piece of paper, the paint forms a small, dense spot. When the nozzle is farther from the paper, the paint forms a larger, fainter spot because the paint is sprayed over a larger area. Like paint on paper, light intensity decreases as distance from the light source increases.

A wave model for light also explains how intensity decreases with distance from a source. As waves travel away from the source, they pass through a larger and larger area. Because the total energy does not change, the wave's intensity decreases.

Section 18.1 Assessment

Reviewing Concepts

1. What produces electromagnetic waves?
2. How fast does light travel in a vacuum?
3. What makes electromagnetic waves different from one another?
4. Explain how light behaves like a stream of particles.
5. What happens to the intensity of light as photons move away from the light source?
6. How does photon energy relate to frequency?

Critical Thinking

7. **Applying Concepts** Why does blue light cause emission of electrons from metal while red light does not?
8. **Observing** Describe what happens as you get closer to a light source. Explain this observation.

Math Practice

9. What is the wavelength of an AM radio wave in a vacuum if its frequency is 810 kilohertz?
10. A global positioning satellite (GPS) transmits a signal at a frequency of 1575 megahertz. What is the wavelength? (*Hint:* Assume the wave speed is the same as in a vacuum.)