c. only a magnetic field, but no electric field
d. only an electric field, but no magnetic field

# 15.2 The Behavior of Electromagnetic Radiation

### Section Learning Objectives

*By the end of this section, you will be able to do the following:*

- Describe the behavior of electromagnetic radiation
- Solve quantitative problems involving the behavior of electromagnetic radiation

## Section Key Terms

| | | | | | |
|---|---|---|---|---|---|
| illuminance | interference | lumens | luminous flux | lux | polarized light |

## Types of Electromagnetic Wave Behavior

In a vacuum, all electromagnetic radiation travels at the same incredible speed of $3.00 \times 10^8$ m/s, which is equal to 671 million miles per hour. This is one of the fundamental physical constants. It is referred to as the speed of light and is given the symbol $c$. The space between celestial bodies is a near vacuum, so the light we see from the Sun, stars, and other planets has traveled here at the speed of light. Keep in mind that all EM radiation travels at this speed. All the different wavelengths of radiation that leave the Sun make the trip to Earth in the same amount of time. That trip takes 8.3 minutes. Light from the nearest star, besides the Sun, takes 4.2 years to reach Earth, and light from the nearest galaxy—a dwarf galaxy that orbits the Milky Way—travels 25,000 years on its way to Earth. You can see why we call very long distances *astronomical*.

When light travels through a physical medium, its speed is always less than the speed of light. For example, light travels in water at three-fourths the value of $c$. In air, light has a speed that is just slightly slower than in empty space: 99.97 percent of $c$. Diamond slows light down to just 41 percent of $c$. When light changes speeds at a boundary between media, it also changes direction. The greater the difference in speeds, the more the path of light bends. In other chapters, we look at this bending, called *refraction*, in greater detail. We introduce refraction here to help explain a phenomenon called thin-film interference.

Have you ever wondered about the rainbow colors you often see on soap bubbles, oil slicks, and compact discs? This occurs when light is both refracted by and reflected from a very thin film. The diagram shows the path of light through such a thin film. The symbols $n_1$, $n_2$, and $n_3$ indicate that light travels at different speeds in each of the three materials. Learn more about this topic in the chapter on diffraction and interference.

Figure 15.9 shows the result of thin film interference on the surface of soap bubbles. Because ray 2 travels a greater distance, the two rays become *out of phase*. That is, the crests of the two emerging waves are no longer moving together. This causes **interference**, which reinforces the intensity of the wavelengths of light that create the bands of color. The color bands are separated because each color has a different wavelength. Also, the thickness of the film is not uniform, and different thicknesses cause colors of different wavelengths to interfere in different places. Note that the film must be very, very thin—somewhere in the vicinity of the wavelengths of visible light.

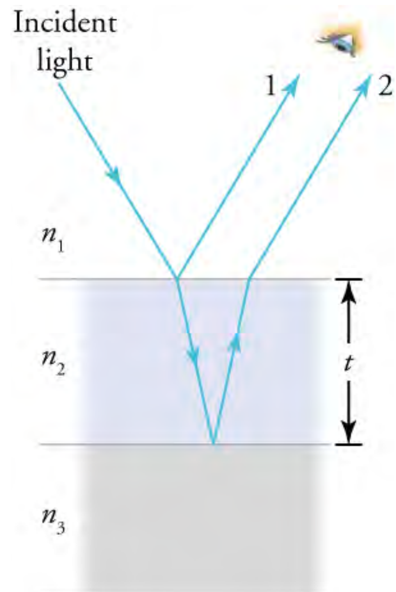


**Figure 15.9** Light striking a thin film is partially reflected (ray 1) and partially refracted at the top surface. The refracted ray is partially reflected at the bottom surface and emerges as ray 2. These rays will interfere in a way that depends on the thickness of the film and the indices of refraction of the various media.

You have probably experienced how polarized sunglasses reduce glare from the surface of water or snow. The effect is caused by the wave nature of light. Looking back at , we see that the electric field moves in only one direction perpendicular to the direction of propagation. Light from most sources vibrates in all directions perpendicular to propagation. Light with an electric field that vibrates in only one direction is called *polarized*. A diagram of **polarized light** would look like .

Polarized glasses are an example of a polarizing filter. These glasses absorb most of the horizontal light waves and transmit the vertical waves. This cuts down glare, which is caused by horizontal waves. Figure 15.10 shows how waves traveling along a rope can be used as a model of how a polarizing filter works. The oscillations in one rope are in a vertical plane and are said to be vertically polarized. Those in the other rope are in a horizontal plane and are horizontally polarized. If a vertical slit is placed on the first rope, the waves pass through. However, a vertical slit blocks the horizontally polarized waves. For EM waves, the direction of the electric field oscillation is analogous to the disturbances on the ropes.

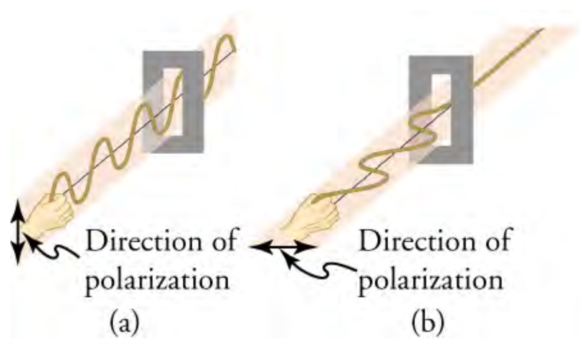


**Figure 15.10** The transverse oscillations in one rope are in a vertical plane, and those in the other rope are in a horizontal plane. The first is said to be vertically polarized, and the other is said to be horizontally polarized. Vertical slits pass vertically polarized waves and block horizontally polarized waves.

Light can also be polarized by reflection. Most of the light reflected from water, glass, or any highly reflective surface is polarized horizontally. Figure 15.11 shows the effect of a polarizing lens on light reflected from the surface of water.


**Figure 15.11** These two photographs of a river show the effect of a polarizing filter in reducing glare in light reflected from the surface of water. Part (b) of this figure was taken with a polarizing filter and part (a) was taken without. As a result, the reflection of clouds and sky observed in part (a) is not observed in part (b). Polarizing sunglasses are particularly useful on snow and water.

## WATCH PHYSICS

### Polarization of Light, Linear and Circular

This video explains the polarization of light in great detail. Before viewing the video, look back at the drawing of an electromagnetic wave from the previous section. Try to visualize the two-dimensional drawing in three dimensions.

Click to view content (https://www.openstax.org/l/28Polarization)

**GRASP CHECK**

How do polarized glasses reduce glare reflected from the ocean?

a. They block horizontally polarized and vertically polarized light.
b. They are transparent to horizontally polarized and vertically polarized light.
c. They block horizontally polarized rays and are transparent to vertically polarized rays.
d. They are transparent to horizontally polarized light and block vertically polarized light.

## Snap Lab

### Polarized Glasses

- EYE SAFETY—Looking at the Sun directly can cause permanent eye damage. Avoid looking directly at the Sun.

- two pairs of polarized sunglasses
  OR
- two lenses from one pair of polarized sunglasses

Procedure

1. Look through both or either polarized lens and record your observations.
2. Hold the lenses, one in front of the other. Hold one lens stationary while you slowly rotate the other lens. Record your observations, including the relative angles of the lenses when you make each observation.
3. Find a reflective surface on which the Sun is shining. It could be water, glass, a mirror, or any other similar smooth surface. The results will be more dramatic if the sunlight strikes the surface at a sharp angle.
4. Observe the appearance of the surface with your naked eye and through one of the polarized lenses.
5. Observe any changes as you slowly rotate the lens, and note the angles at which you see changes.

## GRASP CHECK

If you buy sunglasses in a store, how can you be sure that they are polarized?

a. When one pair of sunglasses is placed in front of another and rotated in the plane of the body, the light passing through the sunglasses will be blocked at two positions due to refraction of light.
b. When one pair of sunglasses is placed in front of another and rotated in the plane of the body, the light passing through the sunglasses will be blocked at two positions due to reflection of light.
c. When one pair of sunglasses is placed in front of another and rotated in the plane of the body, the light passing through the sunglasses will be blocked at two positions due to the polarization of light.
d. When one pair of sunglasses is placed in front of another and rotated in the plane of the body, the light passing through the sunglasses will be blocked at two positions due to the bending of light waves.

## Quantitative Treatment of Electromagnetic Waves

We can use the speed of light, $c$, to carry out several simple but interesting calculations. If we know the distance to a celestial object, we can calculate how long it takes its light to reach us. Of course, we can also make the reverse calculation if we know the time it takes for the light to travel to us. For an object at a very great distance from Earth, it takes many years for its light to reach us. This means that we are looking at the object as it existed in the distant past. The object may, in fact, no longer exist. Very large distances in the universe are measured in light years. One light year is the distance that light travels in one year, which is $9.46 \times 10^{12}$ kilometers or $5.88 \times 10^{12}$ miles (…and $10^{12}$ is a trillion!).

A useful equation involving $c$ is

$$c = f\lambda \tag{15.1}$$

where $f$ is frequency in Hz, and $\lambda$ is wavelength in meters.

## WORKED EXAMPLE

### Frequency and Wavelength Calculation

For example, you can calculate the frequency of yellow light with a wavelength of $6.00 \times 10^{-7}$ m.

**STRATEGY**

Rearrange the equation to solve for frequency.

$$f = \frac{c}{\lambda} \tag{15.2}$$

**Solution**

Substitute the values for the speed of light and wavelength into the equation.

$$f = \frac{3.00 \times 10^{8}\ \text{m/s}}{6.00 \times 10^{-7}\ \text{m}} = 5.00 \times 10^{14}\ \text{s}^{-1} = 5.00 \times 10^{14}\ \text{Hz} \tag{15.3}$$

**Discussion**

Manipulating exponents of 10 in a fraction can be tricky. Be sure you keep track of the + and – exponents correctly. Checking back to the diagram of the electromagnetic spectrum in the previous section shows that $10^{14}$ is a reasonable order of magnitude for the frequency of yellow light.

The frequency of a wave is proportional to the energy the wave carries. The actual proportionality constant will be discussed in a later chapter. Since frequency is inversely proportional to wavelength, we also know that wavelength is inversely proportional to energy. Keep these relationships in mind as general rules.

The rate at which light is radiated from a source is called **luminous flux**, $P$, and it is measured in **lumens** (lm). Energy-saving light bulbs, which provide more luminous flux for a given use of electricity, are now available. One of these bulbs is called a *compact fluorescent lamp*; another is an *LED* (light-emitting diode) bulb. If you wanted to replace an old incandescent bulb with an energy saving bulb, you would want the new bulb to have the same brightness as the old one. To compare bulbs accurately, you would need to compare the lumens each one puts out. Comparing wattage—that is, the electric power used—would be misleading. Both wattage and lumens are stated on the packaging.

The luminous flux of a bulb might be 2,000 lm. That accounts for all the light radiated in all directions. However, what we really need to know is how much light falls on an object, such as a book, at a specific distance. The number of lumens per square meter is called **illuminance**, and is given in units of **lux** (lx). Picture a light bulb in the middle of a sphere with a 1-m radius. The total surface of the sphere equals $4\pi r^2$ m$^2$. The illuminance then is given by

$$\text{illuminance} = \frac{P}{4\pi r^2}. \tag{15.4}$$

What happens if the radius of the sphere is increased 2 m? The illuminance is now only one-fourth as great, because the $r^2$ term in the denominator is 4 instead of 1. Figure 15.12 shows how illuminance decreases with the inverse square of the distance.

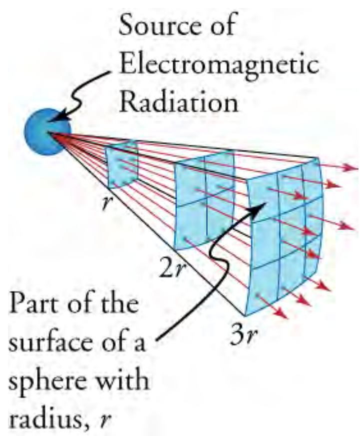


**Figure 15.12** The diagram shows why the illuminance varies inversely with the square of the distance from a source of light.

## WORKED EXAMPLE

### Calculating Illuminance

A woman puts a new bulb in a floor lamp beside an easy chair. If the luminous flux of the bulb is rated at 2,000 lm, what is the illuminance on a book held 2.00 m from the bulb?

**STRATEGY**

Choose the equation and list the knowns.

Equation: $\text{illuminance} = \frac{P}{4\pi r^2}$

$P$ = 2,000 lm

$\pi$ = 3.14

$r$ = 2.00 m

**Solution**

Substitute the known values into the equation.

$$\begin{aligned}\text{illuminance} &= \frac{P}{4\pi r^2} \\ &= \frac{2{,}000\ \text{lm}}{4(3.14)(2.00)^2\ \text{m}^2} \\ &= 39.8\ \text{lm/m}^2 \\ &= 39.8\ \text{lx}\end{aligned}$$

**Discussion**

Try some other distances to illustrate how greatly light fades with distance from its source. For example, at 3 m the illuminance is only 17.7 lux. Parents often scold children for reading in light that is too dim. Instead of shouting, “You’ll ruin your eyes!” it might be better to explain the inverse square law of illuminance to the child.

## Practice Problems

**6.** Red light has a wavelength of 7.0 × 10–7 m and a frequency of 4.3 × 1014 Hz. Use these values to calculate the speed of light in a vacuum.

a. 3 × 1020 m/s
b. 3 × 1015 m/s
c. 3 × 1014 m/s
d. 3 × 108 m/s

**7.** A light bulb has a luminous flux of 942 lumens. What is the illuminance on a surface $3.00\ \text{m}$ from the bulb when it is lit?

a. $33.32\ \text{lx}$
b. $26.15\ \text{lx}$
c. $2.77\ \text{lx}$
d. $8.33\ \text{lx}$

## Check Your Understanding

**8.** Give an example of a place where light travels at the speed of $3.00 \times 10^8$ m/s.

a. outer space
b. water
c. Earth's atmosphere
d. quartz glass

**9.** Explain in terms of distances and the speed of light why it is currently very unlikely that humans will visit planets that circle stars other than our Sun.

a. The spacecrafts used for travel are very heavy and thus very slow.
b. Spacecrafts do not have a constant source of energy to run them.
c. If a spacecraft could attain a maximum speed equal to that of light, it would still be too slow to cover astronomical distances.
d. Spacecrafts can attain a maximum speed equal to that of light, but it is difficult to locate planets around stars.