

CHAPTER 15

Light



Figure 15.1 Human eyes detect these orange *sea goldie* fish swimming over a coral reef in the blue waters of the Gulf of Eilat, in the Red Sea, using visible light. (credit: David Darom, Wikimedia Commons)

Chapter Outline

[15.1 The Electromagnetic Spectrum](#)

[15.2 The Behavior of Electromagnetic Radiation](#)

INTRODUCTION The beauty of a coral reef, the warm radiance of sunshine, the sting of sunburn, the X-ray revealing a broken bone, even microwave popcorn—all are brought to us by electromagnetic waves. The list of the various types of electromagnetic waves, ranging from radio transmission waves to nuclear gamma-ray (γ -ray) emissions, is interesting in itself.

Even more intriguing is that all of these different phenomena are manifestations of the same thing—electromagnetic waves (see [Figure 15.1](#)). What are electromagnetic waves? How are they created, and how do they travel? How can we understand their widely varying properties? What is the relationship between electric and magnetic effects? These and other questions will be explored.

15.1 The Electromagnetic Spectrum

Section Learning Objectives

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

- Define the electromagnetic spectrum, and describe it in terms of frequencies and wavelengths
- Describe and explain the differences and similarities of each section of the electromagnetic spectrum and the applications of radiation from those sections

Section Key Terms

electric field electromagnetic radiation (EMR) magnetic field Maxwell's equations

The Electromagnetic Spectrum

We generally take light for granted, but it is a truly amazing and mysterious form of energy. Think about it: Light travels to Earth across millions of kilometers of empty space. When it reaches us, it interacts with matter in various ways to generate almost all the energy needed to support life, provide heat, and cause weather patterns. Light is a form of **electromagnetic radiation (EMR)**. The term *light* usually refers to visible light, but this is not the only form of EMR. As we will see, visible light occupies a narrow band in a broad range of types of electromagnetic radiation.

Electromagnetic radiation is generated by a moving electric charge, that is, by an electric current. As you will see when you study electricity, an electric current generates both an **electric field, E** , and a **magnetic field, B** . These fields are perpendicular to each other. When the moving charge oscillates, as in an alternating current, an EM wave is propagated. [Figure 15.2](#) shows how an electromagnetic wave moves away from the source—indicated by the \sim symbol.



WATCH PHYSICS

Electromagnetic Waves and the Electromagnetic Spectrum

This video, link below, is closely related to the following figure. If you have questions about EM wave properties, the EM spectrum, how waves propagate, or definitions of any of the related terms, the answers can be found in this [video](http://www.openstax.org/l/28EMWaves) (<http://www.openstax.org/l/28EMWaves>).

[Click to view content \(https://www.openstax.org/l/28EMWaves\)](https://www.openstax.org/l/28EMWaves)

GRASP CHECK

In an electromagnetic wave, how are the magnetic field, the electric field, and the direction of propagation oriented to each other?

- All three are parallel to each other and are along the x -axis.
- All three are mutually perpendicular to each other.
- The electric field and magnetic fields are parallel to each other and perpendicular to the direction of propagation.
- The magnetic field and direction of propagation are parallel to each other along the y -axis and perpendicular to the electric field.

Virtual Physics

Radio Waves and Electromagnetic Fields

[Click to view content \(https://www.openstax.org/l/28Radiowaves\)](https://www.openstax.org/l/28Radiowaves)

This simulation demonstrates wave propagation. The EM wave is propagated from the broadcast tower on the left, just as in [Figure 15.2](#). You can make the wave yourself or allow the animation to send it. When the wave reaches the antenna on the right, it causes an oscillating current. This is how radio and television signals are transmitted and received.

GRASP CHECK

Where do radio waves fall on the electromagnetic spectrum?

- Radio waves have the same wavelengths as visible light.
- Radio waves fall on the high-frequency side of visible light.
- Radio waves fall on the short-wavelength side of visible light.
- Radio waves fall on the low-frequency side of visible light.

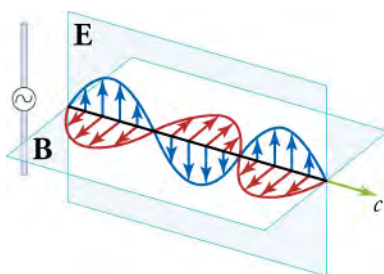


Figure 15.2 A part of the electromagnetic wave sent out from an oscillating charge at one instant in time. The electric and magnetic fields (**E** and **B**) are in phase, and they are perpendicular to each other and to the direction of propagation. For clarity, the waves are shown only along one direction, but they propagate out in other directions too.

From your study of sound waves, recall these features that apply to all types of waves:

- Wavelength—The distance between two wave crests or two wave troughs, expressed in various metric measures of distance
- Frequency—The number of wave crests that pass a point per second, expressed in hertz (Hz or s^{-1})
- Amplitude: The height of the crest above the null point

As mentioned, electromagnetic radiation takes several forms. These forms are characterized by a range of frequencies. Because frequency is inversely proportional to wavelength, any form of EMR can also be represented by its range of wavelengths. [Figure 15.3](#) shows the frequency and wavelength ranges of various types of EMR. With how many of these types are you familiar?

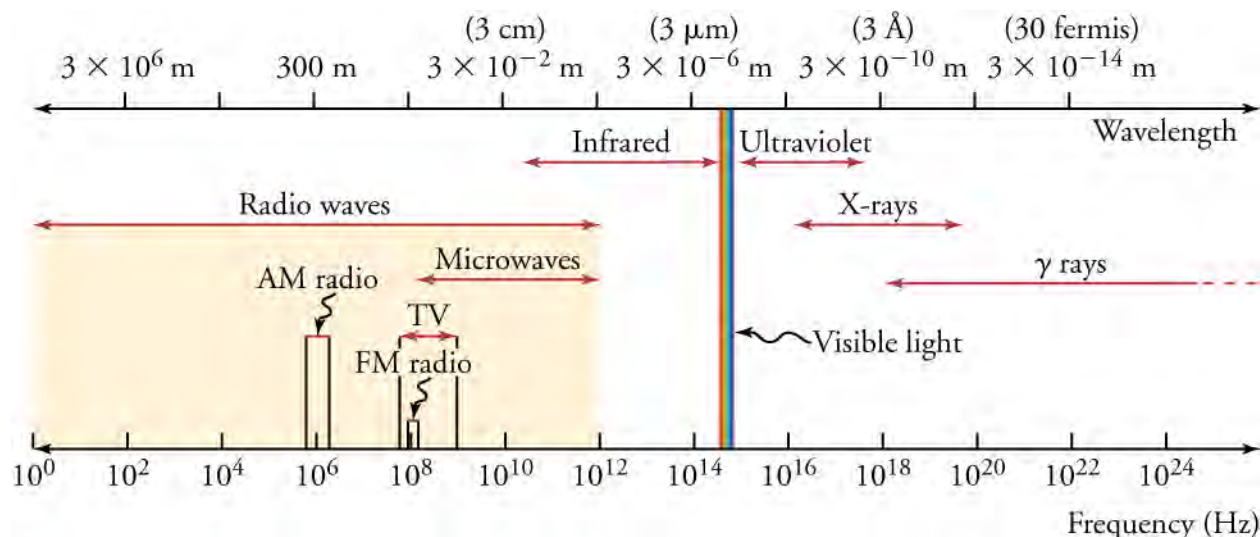


Figure 15.3 The electromagnetic spectrum, showing the major categories of electromagnetic waves. The range of frequencies and wavelengths is remarkable. The dividing line between some categories is distinct, whereas other categories overlap.

Take a few minutes to study the positions of the various types of radiation on the EM spectrum, above. Sometimes all radiation with frequencies lower than those of visible light are referred to as infrared (IR) radiation. This includes radio waves, which overlap with the frequencies used for media broadcasts of TV and radio signals. The microwave radiation that you see on the diagram is the same radiation that is used in a microwave oven. What we feel as radiant heat is also a form of low-frequency EMR.

All the high-frequency radiation to the right of visible light is sometimes referred to as ultraviolet (UV) radiation. This includes X-rays and gamma (γ) rays. The narrow band that is visible light extends from lower-frequency red light to higher-frequency violet light, thus the terms are *infrared* (below red) and *ultraviolet* (beyond violet).



BOUNDLESS PHYSICS

Maxwell's Equations

The Scottish physicist James Clerk Maxwell (1831–1879) is regarded widely to have been the greatest theoretical physicist of the

nineteenth century. Although he died young, Maxwell not only formulated a complete electromagnetic theory, represented by **Maxwell's equations**, he also developed the kinetic theory of gases, and made significant contributions to the understanding of color vision and the nature of Saturn's rings.

Maxwell brought together all the work that had been done by brilliant physicists, such as Ørsted, Coulomb, Ampere, Gauss, and Faraday, and added his own insights to develop the overarching theory of electromagnetism. Maxwell's equations are paraphrased here in words because their mathematical content is beyond the level of this text. However, the equations illustrate how apparently simple mathematical statements can elegantly unite and express a multitude of concepts—why mathematics is the language of science.

Maxwell's Equations

1. Electric field lines originate on positive charges and terminate on negative charges. The electric field is defined as the force per unit charge on a test charge, and the strength of the force is related to the electric constant, ϵ_0 .
2. Magnetic field lines are continuous, having no beginning or end. No magnetic monopoles are known to exist. The strength of the magnetic force is related to the magnetic constant, μ_0 .
3. A changing magnetic field induces an electromotive force (emf) and, hence, an electric field. The direction of the emf opposes the change, changing direction of the magnetic field.
4. Magnetic fields are generated by moving charges or by changing electric fields.

Maxwell's complete theory shows that electric and magnetic forces are not separate, but different manifestations of the same thing—the electromagnetic force. This classical unification of forces is one motivation for current attempts to unify the four basic forces in nature—the gravitational, electromagnetic, strong nuclear, and weak nuclear forces. The weak nuclear and electromagnetic forces have been unified, and further unification with the strong nuclear force is expected; but, the unification of the gravitational force with the other three has proven to be a real head-scratcher.

One final accomplishment of Maxwell was his development in 1855 of a process that could produce color photographic images. In 1861, he and photographer Thomas Sutton worked together on this process. The color image was achieved by projecting red, blue, and green light through black-and-white photographs of a tartan ribbon, each photo itself exposed in different-colored light. The final image was projected onto a screen (see [Figure 15.4](#)).

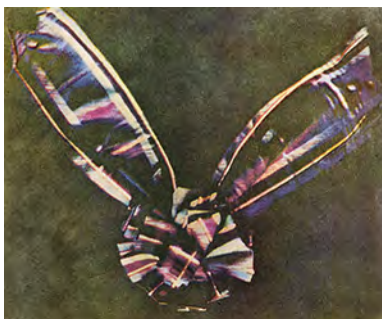


Figure 15.4 Maxwell and Sutton's photograph of a colored ribbon. This was the first durable color photograph. The plaid tartan of the Scots made a *colorful* photographic subject.

GRASP CHECK

Describe electromagnetic force as explained by Maxwell's equations.

- a. According to Maxwell's equations, electromagnetic force gives rise to electric force and magnetic force.
- b. According to Maxwell's equations, electric force and magnetic force are different manifestations of electromagnetic force.
- c. According to Maxwell's equations, electric force is the cause of electromagnetic force.
- d. According to Maxwell's equations, magnetic force is the cause of electromagnetic force.

Characteristics of Electromagnetic Radiation

All the EM waves mentioned above are basically the same form of radiation. They can all travel across empty space, and they all

travel at the speed of light in a vacuum. The basic difference between types of radiation is their differing frequencies. Each frequency has an associated wavelength. As frequency increases across the spectrum, wavelength decreases. Energy also increases with frequency. Because of this, higher frequencies penetrate matter more readily. Some of the properties and uses of the various EM spectrum bands are listed in [Table 15.1](#).

Types of EM Waves	Production	Applications	Life Sciences Aspect	Issues
Radio and TV	Accelerating charges	Communications, remote controls	MRI	Requires controls for band use
Microwaves	Accelerating charges & thermal agitation	Communications, microwave ovens, radar	Deep heating	Cell phone use
Infrared	Thermal agitation & electronic transitions	Thermal imaging, heating	Absorption by atmosphere	Greenhouse effect
Visible Light	Thermal agitation & electronic transitions	All pervasive	Photosynthesis, human vision	
Ultraviolet	Thermal agitation & electronic transitions	Sterilization, slowing abnormal growth of cells	Vitamin D production	Ozone depletion, causes cell damage
X-rays	Inner electronic transitions & fast collisions	Medical, security	Medical diagnosis, cancer therapy	Causes cell damage
Gamma Rays	Nuclear decay	Nuclear medicine, security	Medical diagnosis, cancer therapy	Causes cell damage, radiation damage

Table 15.1 Electromagnetic Waves This table shows how each type of EM radiation is produced, how it is applied, as well as environmental and health issues associated with it.

The narrow band of visible light is a combination of the colors of the rainbow. [Figure 15.5](#) shows the section of the EM spectrum that includes visible light. The frequencies corresponding to these wavelengths are $4.0 \times 10^{14} \text{ s}^{-1}$ at the red end to $7.9 \times 10^{14} \text{ s}^{-1}$ at the violet end. This is a very narrow range, considering that the EM spectrum spans about 20 orders of magnitude.

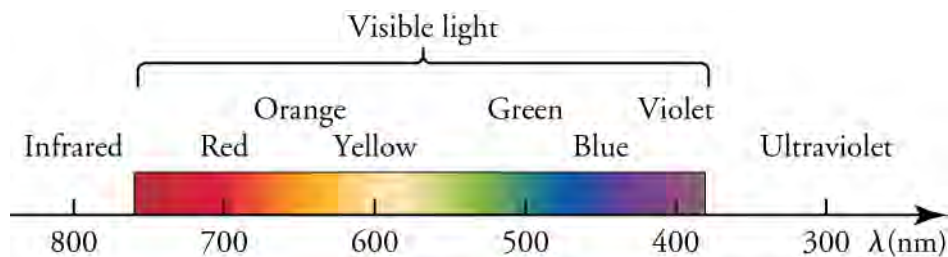


Figure 15.5 A small part of the electromagnetic spectrum that includes its visible components. The divisions between infrared, visible, and ultraviolet are not perfectly distinct, nor are the divisions between the seven rainbow colors

TIPS FOR SUCCESS

Wavelengths of visible light are often given in nanometers, nm. One nm equals 10^{-9} m . For example, yellow light has a wavelength of about 600 nm, or $6 \times 10^{-7} \text{ m}$.

As a child, you probably learned the color wheel, shown on the left in [Figure 15.6](#). It helps if you know what color results when you mix different colors of paint together. Mixing two of the primary *pigment* colors—magenta, yellow, or cyan—together results in a secondary color. For example, mixing cyan and yellow makes green. This is called *subtractive* color mixing. Mixing different colors of *light* together is quite different. The diagram on the right shows *additive* color mixing. In this case, the primary colors are red, green, and blue, and the secondary colors are cyan, magenta, and yellow. Mixing pigments and mixing light are different because materials absorb light by a different set of rules than does the perception of light by the eye. Notice that, when all colors are subtracted, the result is no color, or black. When all colors are added, the result is white light. We see the reverse of this when white sunlight is separated into the visible spectrum by a prism or by raindrops when a rainbow appears in the sky.

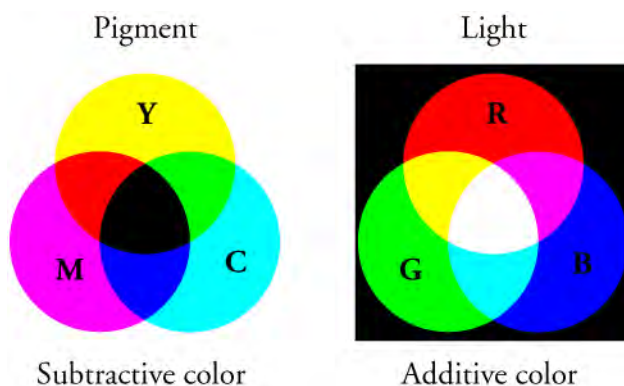


Figure 15.6 Mixing colored pigments follows the subtractive color wheel, and mixing colored light follows the additive color wheel.

Virtual Physics

Color Vision

[Click to view content \(https://www.openstax.org/l/28Colorvision\)](https://www.openstax.org/l/28Colorvision)

This video demonstrates additive color and color filters. Try all the settings except *Photons*.

GRASP CHECK

Explain why only light from a blue bulb passes through the blue filter.

- A blue filter absorbs blue light.
- A blue filter reflects blue light.
- A blue filter absorbs all visible light other than blue light.
- A blue filter reflects all of the other colors of light and absorbs blue light.



LINKS TO PHYSICS

Animal Color Perception

The physics of color perception has interesting links to zoology. Other animals have very different views of the world than humans, especially with respect to which colors can be seen. Color is detected by cells in the eye called *cones*. Humans have three cones that are sensitive to three different ranges of electromagnetic wavelengths. They are called red, blue, and green cones, although these colors do not correspond exactly to the centers of the three ranges. The ranges of wavelengths that each cone detects are red, 500 to 700 nm; green, 450 to 630 nm; and blue, 400 to 500 nm.

Most primates also have three kinds of cones and see the world much as we do. Most mammals other than primates only have two cones and have a less colorful view of things. Dogs, for example see blue and yellow, but are color blind to red and green. You might think that *simpler* species, such as fish and insects, would have less sophisticated vision, but this is not the case. Many birds, reptiles, amphibians, and insects have four or five different cones in their eyes. These species don't have a wider range of perceived colors, but they see more hues, or combinations of colors. Also, some animals, such as bees or rattlesnakes, see a

range of colors that is as broad as ours, but shifted into the ultraviolet or infrared.

These differences in color perception are generally adaptations that help the animals survive. Colorful tropical birds and fish display some colors that are too subtle for us to see. These colors are believed to play a role in the species mating rituals. [Figure 15.7](#) shows the colors visible and the color range of vision in humans, bees, and dogs.

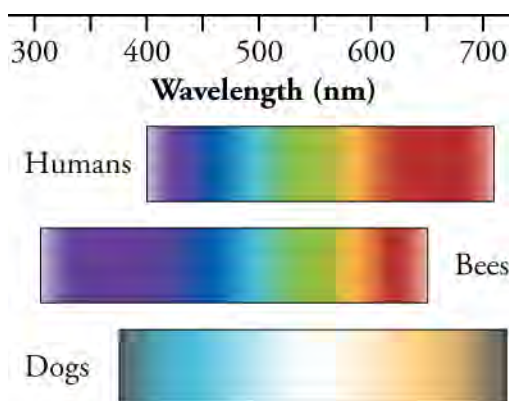


Figure 15.7 Humans, bees, and dogs see colors differently. Dogs see fewer colors than humans, and bees see a different range of colors.

GRASP CHECK

The belief that bulls are enraged by seeing the color red is a misconception. What did you read in this Links to Physics that shows why this belief is incorrect?

- Bulls are color-blind to every color in the spectrum of colors.
- Bulls are color-blind to the blue colors in the spectrum of colors.
- Bulls are color-blind to the red colors in the spectrum of colors.
- Bulls are color-blind to the green colors in the spectrum of colors.

Humans have found uses for every part of the electromagnetic spectrum. We will take a look at the uses of each range of frequencies, beginning with visible light. Most of our uses of visible light are obvious; without it our interaction with our surroundings would be much different. We might forget that nearly all of our food depends on the photosynthesis process in plants, and that the energy for this process comes from the visible part of the spectrum. Without photosynthesis, we would also have almost no oxygen in the atmosphere.

The low-frequency, infrared region of the spectrum has many applications in media broadcasting. Television, radio, cell phone, and remote-control devices all broadcast and/or receive signals with these wavelengths. AM and FM radio signals are both low-frequency radiation. They are in different regions of the spectrum, but that is not their basic difference. AM and FM are abbreviations for *amplitude modulation* and *frequency modulation*. Information in AM signals has the form of changes in *amplitude* of the radio waves; information in FM signals has the form of changes in wave *frequency*.

Another application of long-wavelength radiation is found in microwave ovens. These appliances cook or warm food by irradiating it with EM radiation in the microwave frequency range. Most kitchen microwaves use a frequency of 2.45×10^9 Hz. These waves have the right amount of energy to cause polar molecules, such as water, to rotate faster. Polar molecules are those that have a partial charge separation. The rotational energy of these molecules is given up to surrounding matter as heat. The first microwave ovens were called *Radaranges* because they were based on radar technology developed during World War II.

Radar uses radiation with wavelengths similar to those of microwaves to detect the location and speed of distant objects, such as airplanes, weather formations, and motor vehicles. Radar information is obtained by receiving and analyzing the echoes of microwaves reflected by an object. The speed of the object can be measured using the Doppler shift of the returning waves. This is the same effect you learned about when you studied sound waves. Like sound waves, EM waves are shifted to higher frequencies by an object moving toward an observer, and to lower frequencies by an object moving away from the observer. Astronomers use this same Doppler effect to measure the speed at which distant galaxies are moving away from us. In this case, the shift in frequency is called the *red shift*, because visible frequencies are shifted toward the lower-frequency, red end of the spectrum.

Exposure to any radiation with frequencies greater than those of visible light carries some health hazards. All types of radiation in this range are known to cause cell damage. The danger is related to the high energy and penetrating ability of these EM waves. The likelihood of being harmed by any of this radiation depends largely on the amount of exposure. Most people try to reduce exposure to UV radiation from sunlight by using sunscreen and protective clothing. Physicians still use X-rays to diagnose medical problems, but the intensity of the radiation used is extremely low. [Figure 15.8](#) shows an X-ray image of a patient's chest cavity.

One medical-imaging technique that involves no danger of exposure is magnetic resonance imaging (MRI). MRI is an important imaging and research tool in medicine, producing highly detailed two- and three-dimensional images. Radio waves are broadcast, absorbed, and reemitted in a resonance process that is sensitive to the density of nuclei, usually hydrogen nuclei—protons.

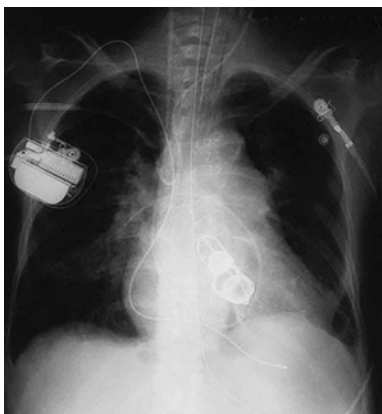


Figure 15.8 This shadow X-ray image shows many interesting features, such as artificial heart valves, a pacemaker, and wires used to close the sternum. (credit: P.P. Urone)

Check Your Understanding

- Identify the fields produced by a moving charged particle.
 - Both an electric field and a magnetic field will be produced.
 - Neither a magnetic field nor an electric field will be produced.
 - A magnetic field, but no electric field will be produced.
 - Only the electric field, but no magnetic field will be produced.
- X-rays carry more energy than visible light. Compare the frequencies and wavelengths of these two types of EM radiation.
 - Visible light has higher frequencies and shorter wavelengths than X-rays.
 - Visible light has lower frequencies and shorter wavelengths than X-rays.
 - Visible light has higher frequencies and longer wavelengths than X-rays.
 - Visible light has lower frequencies and longer wavelengths than X-rays.
- How does wavelength change as frequency increases across the EM spectrum?
 - The wavelength increases.
 - The wavelength first increases and then decreases.
 - The wavelength first decreases and then increases.
 - The wavelength decreases.
- Why are X-rays used in imaging of broken bones, rather than radio waves?
 - X-rays have higher penetrating energy than radio waves.
 - X-rays have lower penetrating energy than radio waves.
 - X-rays have a lower frequency range than radio waves.
 - X-rays have longer wavelengths than radio waves.
- Identify the fields that make up an electromagnetic wave.
 - both an electric field and a magnetic field
 - neither a magnetic field nor an electric field

- 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 3.00×10^8 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.