This short reading on the Electromagnetic Spectrum is from
Hobson (2007) *Physics: Concepts & Connections*, 4th Edition, Chapter 9.

9.3 The Complete Spectrum

The possible frequencies of light lie in a narrow range near 10^{15} Hz. We have seen that Heinrich Hertz produced electromagnetic waves, now called radio waves, having a frequency around 10^9 Hz. These are only two examples of the huge range or "spectrum" of electromagnetic waves now known. We call this range the **electromagnetic spectrum** (Figure 9.5). In the figure, wavelengths are

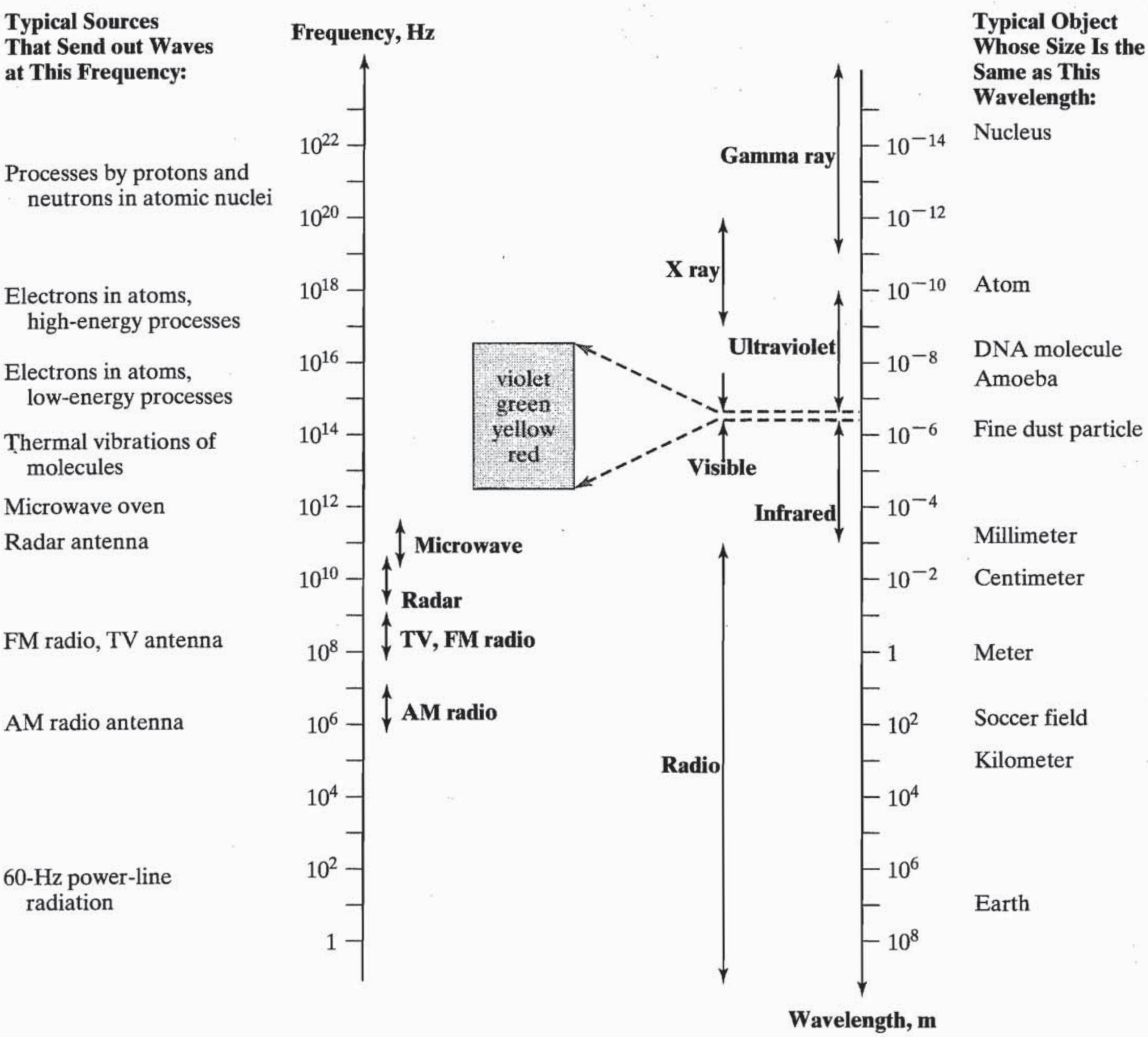

FIGURE 9.5

The electromagnetic spectrum. There are no definite ends to the spectrum and no sharp boundaries between the regions.

arranged from the longest at the bottom to the shortest at the top, with typical objects having the size of these wavelengths listed for comparison. Frequencies are shown from the lowest (smallest) at the bottom to the highest at the top, with typical sources of these frequencies listed. In order to display a large range, Figure 9.5 shows wavelengths and frequencies on a so-called "logarithmic scale" in which each increment is a factor of 10: 1, 10, 100, 1000, and so forth. A "linear scale"—such as 10, 20, 30, 40, and so forth—could not do justice to the entire range.

All these waves are basically the same phenomenon, namely, an electromagnetic field disturbance that is created by a vibrating charged object and that travels at lightspeed outward through the field. All these waves can be received by other charged objects that the wave causes to move as the wave passes by. All can travel through empty space. And they all carry energy. The energy of an electromagnetic wave is called **radiant energy**. For example, the energy in transit from the sun to Earth is radiant energy. Electromagnetic waves are often called **electromagnetic radiation** because they "radiate" out from charged objects. Since higher frequency means higher energy (provided that other things such as amplitude are not changed), energies increase as we move up the scale from bottom to top.

Let's tour the electromagnetic spectrum. It's useful to arrange it into the six regions shown in Figure 9.5, regions that correspond to different ways of either sending or receiving electromagnetic radiation. The longest wavelengths, down to about a millimeter, form the **radio waves**, comprising AM and FM radio, TV, and microwaves. Humans can create and control these waves electronically by causing electrons to vibrate in human-made electric circuits. Hertz's waves fall into this category, and so does a lot of modern technology. AM radio waves at around 1000 kilohertz (10^6 Hz) and FM radio and TV waves at around 100 megahertz (10^8 Hz) are created by electrons moving back and forth along a metal antenna that is part of an electric circuit. Radar and microwaves, with frequencies up to a trillion (10^{12}) hertz, also are created electronically.

Many natural processes also create radio waves. Radio astronomers use radio receivers or "radio telescopes" pointed at stars or other astronomical objects to learn about the universe. In fact, astronomical objects produce electromagnetic radiation in all parts of the spectrum. During the past few decades, many new sorts of receivers, stationed on or above Earth, have produced an explosion of astronomical knowledge.

Infrared radiation has wavelengths ranging from 1 millimeter to below 1/1000 of a millimeter—the size of a fine particle of baby powder. Infrared is typically created by the random thermal motion of molecules due to their thermal energy. Since all objects have thermal energy, all objects produce infrared and hotter objects produce more of it. Infrared detectors, such as certain infrared-sensitive chemicals, can detect warmer objects against a cooler background, which is the basis for night-vision devices and infrared photography. You cannot see infrared radiation but you can feel it. Since it's created by thermal motion, it's not surprising that it has the proper frequency to shake molecules into thermal motion—so it can warm the objects it hits. When you feel the warmth of a fire or a hot plate at some distance away, you are using your skin as an infrared detector, "seeing" with your skin. Some animals have evolved highly developed infrared sensors for nocturnal vision.

Many animals, including humans, have sensors that detect a narrow range of frequencies just above infrared. This range of **visible radiation** or "light" has

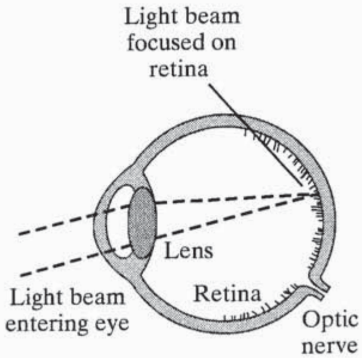

FIGURE 9.6
The human eye.

wavelengths centering on 5×10^{-7} m. This is smaller than the finest dust particles and some 5000 times larger than an atom. Light is typically created by electrons moving within individual atoms. The visible region's defining characteristic is simply that the human eye is sensitive to it. Light waves entering the pupil of the eye strike the retina at the back (Figure 9.6). The retina is covered with light-sensitive cells that act like tiny antennae to receive electromagnetic waves in the visible range. Some cells respond differently to different wavelengths, and the brain interprets these as different colors.

Suppose that you have a variable-frequency source of electromagnetic waves and that you set it to 6×10^{14} Hz—the frequency of green light. If you gradually decrease the frequency, this green light will change to yellow, then orange, and finally red. As you continue decreasing the frequency, the red becomes deeper and darker until, at about 4×10^{14} Hz, the frequency is so low that your retina can no longer respond to it. The source no longer emits visible light. The waves have crossed the boundary into *infra-* (below) red. The source still radiates, but your eye cannot detect it.

Now go in the other direction. Beginning with 6×10^{14} Hz, increase the frequency. The color changes from green to blue to violet. The violet light darkens until, around 8×10^{14} Hz, your eye can no longer detect it. The waves have crossed into the *ultra-* (above) violet region. **Ultraviolet radiation** is created in the same way that light is created, by electrons moving within individual atoms. Although similar to light, ultraviolet's higher energy has important consequences. Ultraviolet radiation has the proper frequency to shake many biological molecules, so it is readily absorbed by living things. And it has enough energy to split molecules, which can disrupt or kill living cells. If absorbed by a cell's DNA, and if the cell reproduces many copies of itself, this can lead to cancerous growth.

X-ray radiation also comes from electrons in individual atoms, but only from the highest-energy electron activities within atoms. X-ray wavelengths span a range around 10^{-10} m—about the size of an individual atom. Humans make X rays in high-energy X-ray tubes, as described in the caption of Figure 9.7. X rays have important interactions with biological matter. They have enough energy to ionize molecules within biological cells, that is, to knock the electrons right out of some molecules. Like ultraviolet, this radiation can cause cancers. Radiation energetic enough to ionize biological matter is called **ionizing radiation**. X rays and gamma rays are ionizing radiations, and so is the higher energy (higher frequency) portion of the ultraviolet region. Because X rays are able to penetrate deeply into biological matter, they can be put to the useful cause of examining the interior of the human body without surgery.

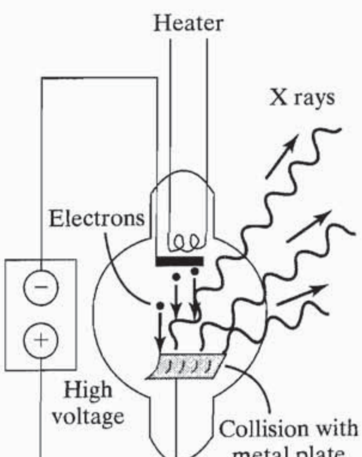

FIGURE 9.7
The operation of an X-ray tube. Electrons are boiled off a thin, heated wire filament and are accelerated toward a positively charged metal plate at the other end of the vacuum tube. When the electrons smash into this plate, their rapid deceleration causes them to emit X rays, and the collision also causes the plate's atoms to emit X rays.

There is a certain logic to our tour through the electromagnetic spectrum. As we move to smaller wavelengths, we move toward higher frequencies and hence higher-energy radiation, which in turn implies higher-energy processes to create the radiation. We also have progressed toward processes that occur in smaller and smaller regions of space: Radio waves are created in macroscopic electric circuits; infrared is created in molecules; and the next three (visible, ultraviolet, and X ray) are created in atoms.

It should come as no surprise then that the shortest-wavelength radiation, **gamma radiation**, carries the highest frequency and highest energy and comes from the highest-energy processes in the smallest regions of space. Gamma rays are created within atomic nuclei by high-energy nuclear processes caused by the strong forces that hold the nucleus together. Gamma rays are created in radioactive materials (Chapter 15) and in the nuclear reactions known as "fission" and "fusion" (Chapter 16). Like X rays, gamma rays are a form of ionizing radiation and can damage biological matter. But this very feature is often put to use to destroy diseased cells and so cure some cancers. Since gamma ray wavelengths are much smaller than individual atoms, atoms cannot readily respond to them, and so they can penetrate deeply into matter.

The room you are in is full of electromagnetic waves. Hundreds of television and radio broadcasts, radio pulsations from neutron stars, radio noise from millions of normal stars, the faint background radiation from the big bang, possibly communications from extraterrestrial life, radiations from the sun and the center of our galaxy, and much more are passing through your room right now. Your body is equipped to receive directly only the tiny visible portion of the complete spectrum of these waves. With the proper receiver, you could sense any of the other frequencies. The universe would appear far different in other wavelength ranges and would appear complex indeed if we could directly receive the entire spectrum. The reality that meets the eye is only a tiny fraction of nature's reality.

✓ concept check 3 When your radio is tuned to 100 on the FM dial, it is receiving (a) a 100 Hz sound wave; (b) a 10^8 Hz sound wave; (c) a 100 Hz electromagnetic wave with a wavelength about the size of Earth; (d) a 10^6 Hz electromagnetic wave with a wavelength of around 100 m; (e) a 10^8 Hz electromagnetic wave with a wavelength of around 100 m; (f) a 10^8 Hz electromagnetic wave with a wavelength of around 1 m.

✓ concept check 4 In the preceding question, the sound coming from the radio is (a) an electromagnetic wave traveling at 300,000 km/s; (b) an electromagnetic wave that travels far more slowly than 300,000 km/s; (c) not an electromagnetic wave of any kind, and travels far more slowly than 300,000 km/s.

MAKING ESTIMATES In the following list, which of these waves have wavelengths much bigger than your room (a few meters), which have wavelengths between a millimeter and a few meters, and which have wavelengths of less than a millimeter: AM radio; light; electromagnetic waves from the alternating current that oscillates 60 times each second in your house circuits; warming rays from a fire; rays from a microwave oven; radar; electromagnetic radiation from shaking an electrically charged blouse that you remove from the dryer?[4]

9.4 Solar Radiation: The Light from Our Star

The sun, "Sol," transmits electromagnetic waves in every region of the spectrum. Most of this **solar radiation** is in the visible, infrared, and ultraviolet parts of the spectrum and is created at the sun's visible surface. Other solar radiation

[4] Use Figure 9.5. Much bigger than a few meters: AM radio, waves from alternating current, waves from the blouse. One millimeter up to a few meters: microwaves, radar. Less than 1 mm: warming rays, light.

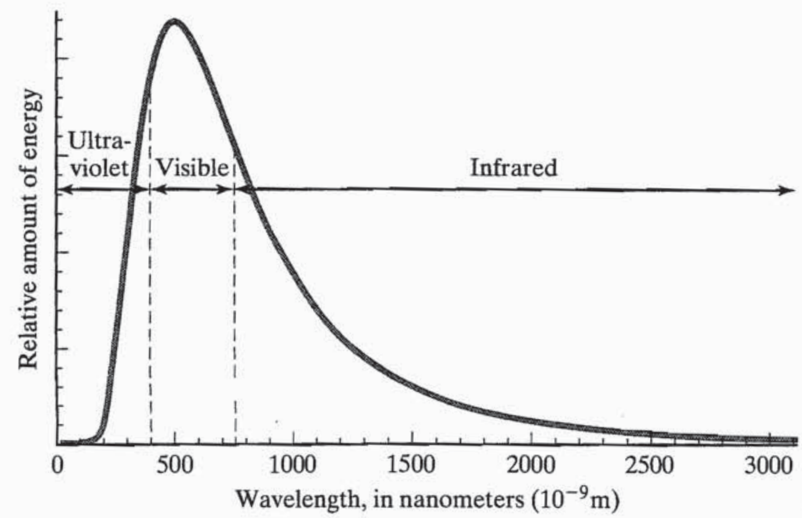

FIGURE 9.8

The relative amounts of energy at different wavelengths in the solar spectrum. Most of the sun's radiant energy is in the ultraviolet, visible, and infrared portions of the electromagnetic spectrum.

is created in the rarefied, very hot gas that surrounds the sun in the same way that Earth's atmosphere surrounds Earth. Processes within the sun's atmosphere create high-energy X rays and some gamma rays, along with radio waves. The intense radiation created by high-energy processes deep within the sun is absorbed and altered within the sun, and little of it escapes directly.

Figure 9.8 graphs the relative amounts of radiant energy emitted by the sun at different wavelengths. When you sit in the sunlight, your eyes detect the sun's visible radiation and your skin detects its infrared as warmth. Your skin also detects ultraviolet but you don't notice it until a little later, as the cellular damage that we call "sunburning." The amount of solar energy reaching Earth is different at different locations, in different seasons, in different weather conditions, and at different times of the 24 hour day. In the United States, an average 200 watts (200 joules every second) strikes every square meter.

MAKING ESTIMATES Photovoltaic cells are devices that transform solar energy into electric current. If such devices were 100% efficient, about how much area would need to be covered by these cells in order to provide the average 1 kilowatt of electric power that a typical family home uses? Actual photovoltaic cells are only about 15% (one-seventh) efficient. At this efficiency, how much area must be covered? Could you put this on your roof?[5]

✔ **concept check 5** When energy from the sun is absorbed by your skin (a) it remains there as electromagnetic energy; (b) it remains there as radiant energy; (c) it transforms into nuclear energy; (d) it transforms into kinetic energy; (e) it transforms into thermal energy; (f) it gives you the heebie-jeebies.

[5] One kilowatt (1000 watts) of solar energy falls on 5 square meters (1000/200) of surface. At an efficiency of one-seventh, it would take seven times this much area: 35 square meters. If square-shaped, this would be about 6 m on a side and would probably fit on your roof.