19 The Electromagnetic Spectrum

KEY IDEA

Light is a form of electromagnetic radiation produced whenever an electric charge accelerates.

PHYSICS AROUND US . . . Light All Around Us

You wake up when your clock radio goes off, flooding your bedroom with sound. Bright sunlight streams through the window as you jump out of bed, clean up, get dressed, and go down to make breakfast. In the kitchen, you pop a couple of slices of bread into the toaster, barely noticing how the heating coils glow a dull orange as they turn the bread brown. You also warm up a cup of coffee in your microwave oven. While you wait, you idly scan the notes held to your refrigerator by tiny magnets.

Did you realize that everything mentioned in this story, from the light of the Sun to the microwaves of your oven to the refrigerator magnets, are examples of the connection between electricity and magnetism? In particular, all these events involve electromagnetic waves.

ELECTROMAGNETIC WAVES

Physicists characterize waves by a mathematical expression called a "wave equation," which describes the movement of the medium for every wave, whether it's an ocean wave moving through water, a sound wave in air, or a seismic wave moving through Earth. Physicists have learned that whenever an equation of this (or some closely related) form appears, a corresponding wave is seen in nature.

Soon after Maxwell wrote the four equations that describe electricity and magnetism, he realized that some rather straightforward mathematical manipulation led to yet another equation, one that describes waves. The waves that Maxwell predicted are rather strange sorts of things, and we'll describe their anatomy in more detail later. However, the important point is that these are waves in which energy is transferred not through matter but through electric and magnetic fields. For example, it appears from the equations that whenever an electric charge is accelerated, one of these waves is emitted. Maxwell called them **electromagnetic waves** or **electromagnetic radiation.** An electromagnetic wave is a wave that incorporates electric and magnetic fields that fluctuate together; once it starts, the wave keeps itself going, even in a vacuum.

Maxwell's equations also predicted exactly how fast the waves would move—the wave velocity depends only on known constants such as the universal electrostatic (Coulomb) constant in Coulomb's law (see Chapter 16). These constants were known from experiments, and when Maxwell put the numbers into his expression for the velocity of his new waves, he found a very surprising answer. The predicted velocity of the wave turned out to be 300,000 kilometers per second (186,000 miles per second).

If you just had an "aha!" moment, you can imagine how Maxwell felt. The number that he calculated is the speed of light, which means that the waves described by his equations are actually the familiar (but mysterious) waves of **light.**

This result was astonishing. For centuries, scientists had puzzled over the origin and nature of light. Newton and others had discovered natural laws that describe the connections between forces and motion, as well as the behavior of matter and energy. But light remained an enigma. How did radiation from the Sun travel to Earth? What caused the light produced by a candle?

There is no obvious reason why static cling, refrigerator magnets, or the workings of an electric generator should be connected in any way to the behavior of visible light. Yet Maxwell discovered that light and other kinds of radiation are a type of wave that is generated whenever electric charges are accelerated.

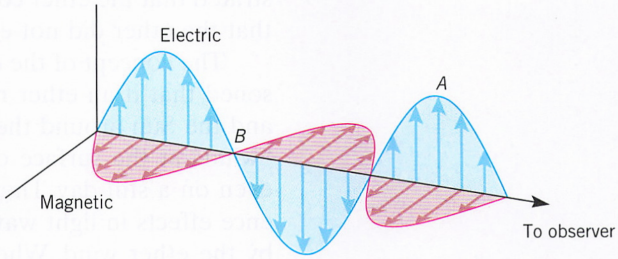


FIGURE 19-1. A diagram of an electromagnetic wave shows the interdependence of the changing electric field, the changing magnetic field, and the direction of the moving wave. *A* and *B* indicate points of maximum and minimum field strength.

Anatomy of an Electromagnetic Wave

A typical electromagnetic wave, shown in Figure 19-1, consists of electric and magnetic fields arranged at right angles to one another and perpendicular to the direction the wave is moving. To understand how the waves work, go back to Maxwell's equations that describe the behavior of electric and magnetic fields.

Recall that a changing electric field generates a magnetic field, while a changing magnetic field generates an electric field. So what happens when an electric charge such as an electron in a wire vibrates? The vibrating electric field produces a changing magnetic field, which in turn generates a changing electric field, back and forth. In other words, once one kind of field starts to change, it automatically changes the other kind of field, and that change, in turn, affects the original field.

Once you understand that the electromagnetic wave has this kind of ping-pong arrangement between electricity and magnetism, you can understand one of the most puzzling aspects of it—the fact that the wave can travel through a vacuum. Every other wave we have talked about is easy to visualize because the wave moves through a medium. We know that the motion of the wave is not the same as the motion of the medium, but in every other way the medium is there to give the wave tangible support. The electromagnetic wave is different. It is a wave that needs no medium whatsoever, but simply keeps itself going through its own internal mechanisms.

Electromagnetic waves, then, carry radiant energy, or radiation, created when electric charges accelerate. Once the waves start moving, however, they no longer depend on the source that emitted them.

Physics in the Making

The Ether

When Maxwell first proposed his idea of electromagnetic radiation, he was not prepared to deal with a wave that required no medium whatsoever. Previous scientists who had studied light, including such luminaries as Isaac Newton, assumed that light must travel through a hypothetical substance called the "ether" that permeates all space. The ether, they thought, served as the medium for light, and so Maxwell assumed that the ether provided the medium for his electromagnetic waves. In Maxwell's picture, the ether was a tenuous, transparent substance, perhaps like Jell-O, that filled all space. An accelerating charge shook the Jell-O at one point, causing electromagnetic waves to move outward at the speed of light.

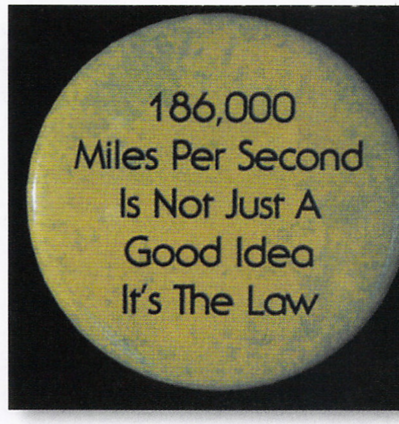
The idea of an ether goes back to the ancient Greeks, and for most of recorded history scholars imagined that the vacuum of space was filled with this invisible substance. Not until 1887 did two U.S. scientists, Albert A. Michelson (1852–1931) and Edward W. Morley (1838–1923), working at what is now Case Western Reserve University in Cleveland, perform experiments that demonstrated that the ether could not be detected. This failure was interpreted to mean that the ether did not exist.

The concept of the experiments was very simple. Michelson and Morley reasoned that if an ether really existed, then the motion of Earth around the Sun and the Sun around the center of our galaxy would produce an apparent ether "wind" at the surface of Earth, much as someone riding in a car feels a wind even on a still day. They used very sensitive instruments to search for interference effects in light waves, effects that would result from the deflection of light by the ether wind. When their experiments turned up no such deflection, they concluded that the ether does not exist.

In 1907, Albert Michelson became the first U.S. scientist to win a Nobel Prize, an honor that recognized his pioneering experimental studies of light. ●

Light

Once Maxwell understood the connection between electromagnetism and light, his equations allowed him to draw several important conclusions. For one thing, because the speed of the electromagnetic waves depends entirely on the nature of the interactions between electric charges and magnetic fields, it cannot depend on the wavelength or frequency of the wave itself. Thus, all electromagnetic waves, regardless of their wavelength or frequency, have to move at exactly the same speed. This speed—the **speed of light**—turns out to be so important in science that we give it a special symbol, *c*. The speed of electromagnetic waves in a vacuum is one of the fundamental constants of nature.



For electromagnetic waves, the relation among speed, wavelength, and frequency takes on the familiar form

$$\begin{aligned}\text{Wavelength} \times \text{Frequency} &= c \\ &= 300{,}000 \text{ km/s } (=186{,}000 \text{ miles/s})\end{aligned}$$

In other words, if you know the wavelength of an electromagnetic wave, you can calculate its frequency, and vice versa.

Figuring Frequency

EXAMPLE 19-1

The wavelength of yellow light is about 580 nanometers, or 5.8×10^{-7} m. What is the frequency of a yellow light wave?

REASONING: We know that for all electromagnetic waves,

$$\text{Wavelength} \times \text{Frequency} = 300{,}000 \text{ km/s} = 3 \times 10^8 \text{ m/s}$$

We want to determine frequency, so rearrange this equation:

$$\text{Frequency} = \frac{3 \times 10^8 \text{ m/s}}{\text{Wavelength}}$$

SOLUTION: This equation reveals that for yellow light with a wavelength of 5.8×10^{-7} m,

$$\begin{aligned}\text{Frequency} &= \frac{3 \times 10^8 \text{ m/s}}{5.8 \times 10^{-7} \text{ m}} \\ &= 0.52 \times 10^{15} \text{ Hz} \\ &= 5.2 \times 10^{14} \text{ Hz}\end{aligned}$$

(Remember, 1 hertz equals 1 cycle per second.) In order to generate yellow light by vibrating a charged comb, you would have to wiggle it more than 5 hundred trillion (520,000,000,000,000) times per second. ●

The Energy of Electromagnetic Waves

Think about how you might produce an electromagnetic wave with a simple comb. Electromagnetic waves are generated any time a charged object is accelerated, so imagine combing your hair on a dry winter day when the comb picks up a static charge. Each time you move the comb back and forth, an electromagnetic wave traveling 300,000 kilometers per second is sent out from the comb.

If you wave the electrically charged comb up and down slowly, once every second, you create electromagnetic radiation, but you're not putting much energy into it. You produce a low-frequency, low-energy wave with a wavelength of about 300,000 kilometers. (Remember, each wave moves outward 300,000 kilometers in a second, which is the separation between wave crests.)

If, on the other hand, you could vibrate the comb vigorously—say at 300,000 times per second—you would produce a higher-energy, high-frequency wave with a 1-kilometer wavelength. By putting more energy into accelerating the electric charge, you wind up with more energy in the electromagnetic wave.

Visible light, the first example of an electromagnetic wave known to humans, bears out this kind of reasoning. A glowing ember has a dull red color, corresponding to relatively low energy. Hotter, more energetic fires show a progression of more energetic colors, from the yellow of a candle flame to the blue-white flame of a blowtorch. These colors are merely different frequencies, and therefore different energies, of light. High-frequency visible light corresponds to a blue color, whereas low-frequency visible light appears red.

Red light has a wavelength corresponding to the distance across about 7000 atoms or about 700 nanometers (a nanometer is 10^{-9} meter, about 40 billionths of an inch). Red light is the longest wavelength that the eye can see and is the least energetic of the visible electromagnetic waves. Violet light, on the other hand, has a shorter wavelength, corresponding to the distance across about 4000 atoms, or about 400 nanometers, and is the most energetic of the visible electromagnetic waves. All other colors have wavelengths and energies between those of red and violet. We explore this important relationship between frequency and energy in the next chapter.

THE PARTS OF THE ELECTROMAGNETIC SPECTRUM

A profound puzzle accompanied Maxwell's original discovery that light is an electromagnetic wave. Waves can be of almost any wavelength. Water waves on the ocean, for example, range from tiny ripples to globe-spanning tides. Yet visible light spans an extremely narrow range of wavelengths, only about 400 to 700 nanometers. According to the equations that Maxwell derived, electromagnetic waves could exist at any wavelength (and, consequently, any frequency) whatsoever. The only constraint is that the wavelength times the frequency must be equal to the speed of light. Yet when Maxwell looked into the universe, he saw visible light as the only example of electromagnetic waves. It was as if a splendid symphony was playing, ranging from the deep bass of the tuba to the sharp shrill of the piccolo, but you could hear only a couple of notes from a single violin.

In such a situation it would be natural to wonder what had happened to the rest of the waves. Physicists looked at Maxwell's equations, looked at nature, and realized that something was missing. The equations predicted that there ought to be more kinds of electromagnetic waves than visible light; waves that no one had seen up to that time; waves performing the waltz between electricity and magnetism, but with frequencies and wavelengths different from those of visible light. These as-yet-unseen waves would have exactly the same structure as the one shown for the electromagnetic wave in Figure 19-1, but they could have either longer or shorter wavelengths than visible light, depending on the acceleration of the electric charge that created them. These waves would move at the speed of light and would be exactly the same as visible light except for the differences in the wavelength and frequency.

Between 1885 and 1889, German physicist Heinrich Rudolf Hertz (1857–1894), after whom the unit of frequency is named, performed the first experiments that confirmed these predictions. He discovered the waves that we now know as radio waves. Since that time, all manner of electromagnetic waves have been discovered, from those with wavelengths longer than the radius of Earth to those with wavelengths shorter than the size of the nucleus of the atom. They

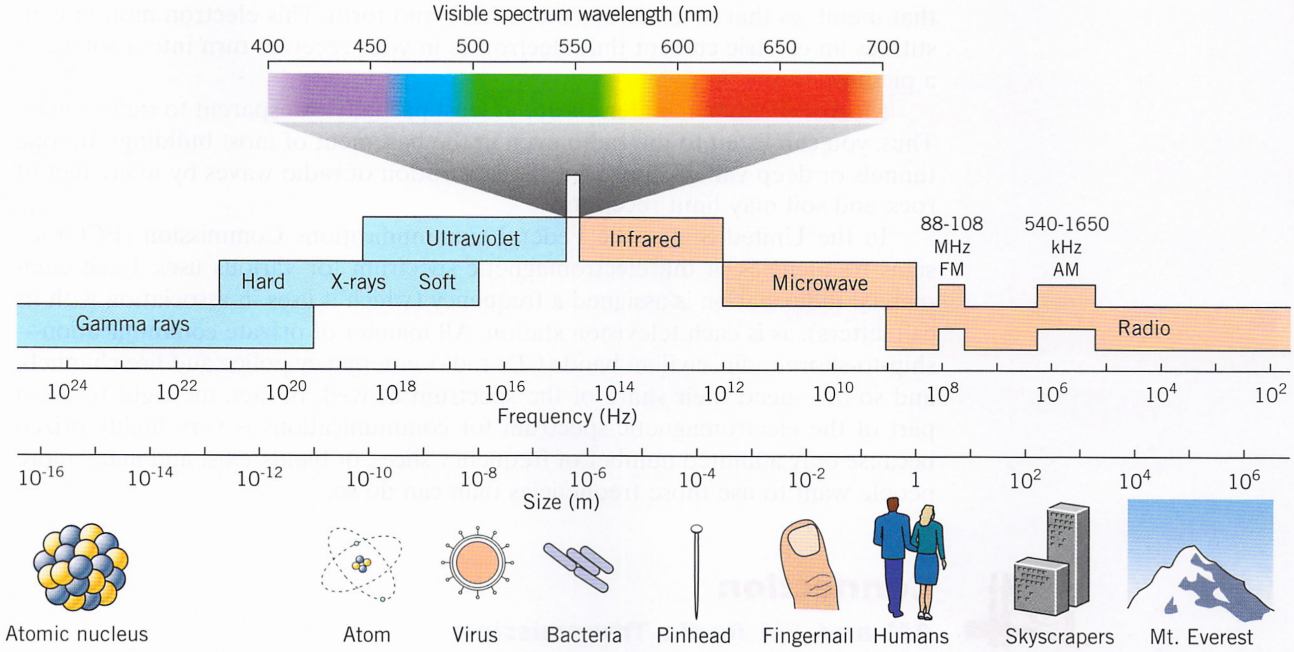


FIGURE 19-2. The electromagnetic spectrum includes all kinds of waves that travel at the speed of light, including radiowaves, microwaves, infrared radiation, visible light, ultraviolet radiation, X rays, and gamma rays. Note that sound waves, water waves, seismic waves, and other kinds of waves that require matter in order to move travel much slower than light speed.

include radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X rays, and gamma rays. This entire collection of waves is called the **electromagnetic spectrum** (Figure 19-2). Remember that every one of these waves, no matter what its wavelength or frequency, is the result of an accelerating electric charge.

Radio Waves

The **radio wave** part of the electromagnetic spectrum ranges from the longest waves, those whose wavelength is longer than the size of Earth, to waves a few meters long. The corresponding frequencies, from roughly a kilohertz (1000 cycles per second, or kHz) to several hundred megahertz (1 million cycles per second, or MHz), correspond to the familiar numbers on your radio dial. There are various subdivisions of radio waves, but the most important fact about them is that, like light, they can penetrate long distances through the atmosphere. This characteristic makes radio waves very useful in communication systems.

Have you ever been driving at night and picked up a radio signal from a station 1000 miles away? If so, you have had firsthand experience of the ability of radio waves to travel long distances through the atmosphere. Pushing electrons back and forth rapidly in a tall metal antenna can produce a typical radio wave of the type used for communication. This acceleration of electrons produces outgoing radio waves, just as throwing a rock in a pond produces outgoing ripples. When these waves encounter another piece of metal (for example, the antenna in your radio or TV set), the electric fields in the waves accelerate electrons in that metal, so that its electrons move back and forth. This electron motion constitutes an electric current that electronics in your receiver turn into a sound or a picture.

Most construction materials are at least partially transparent to radio waves. Thus, you can listen to the radio even in the basement of most buildings. In long tunnels or deep valleys, however, the absorption of radio waves by many feet of rock and soil may limit reception.

In the United States, the Federal Communications Commission (FCC) assigns frequencies in the electromagnetic spectrum for various uses. Each commercial radio station is assigned a frequency (which it uses in association with its call letters), as is each television station. All manner of private communication—ship-to-shore radio, civilian band (CB) radio, emergency police and fire channels, and so on—need their share of the spectrum as well. In fact, the right to use a part of the electromagnetic spectrum for communications is very highly prized because only a limited number of frequency slices, or bands, exist and many more people want to use those frequencies than can do so.

Connection

AM and FM Radio Transmission

Radio waves carry signals in one of two ways: AM or FM. Broadcasters can send out their programs at only one narrow range of frequencies, a situation very different from music or speech, which uses a wide range of frequencies. Thus radio stations cannot simply transform a range of sound-wave frequencies into a similar range of radio-wave frequencies. Instead, the information to be transmitted must be compressed in some way on the narrow frequency range of the station's radio waves.

This problem is similar to one you might experience if you had to send a message across a lake with a flashlight at night. You could adopt either of two strategies. You could send a coded message by turning the flashlight on and off, thus varying the brightness (the amplitude) of the light. Alternatively, you could change the color (the frequency) of the light by passing blue or red filters in front of the beam.

Radio stations also adopt these two strategies (see Figure 19-3). All stations begin with a carrier wave of fixed frequency. This is the broadcast frequency of the station. AM radio stations typically broadcast at frequencies between about 530 and 1600 kHz, whereas the carrier frequencies of FM radio stations range from about 88 to 110 MHz.

The process called *amplitude modulation* (AM) depends on varying the strength (or amplitude) of the radio's carrier wave according to the sound signal to be transmitted (Figure 19-3*a*). Thus the shape of the sound wave is impressed on the radio's carrier wave signal. When this signal is received by your radio, its interior electronics recover the original sound signal and use it to run the speakers. This original sound signal is what you hear when you turn on your radio.

Alternatively, you can slightly vary the frequency of the radio's wave according to the signal you want to transmit, a process called *frequency modulation* (FM), as shown in Figure 19-3*b*. A radio that receives this particular signal can unscramble the changes in frequency and convert them into electric signals that run the speakers so that you can hear the original signal. TV broadcasts,

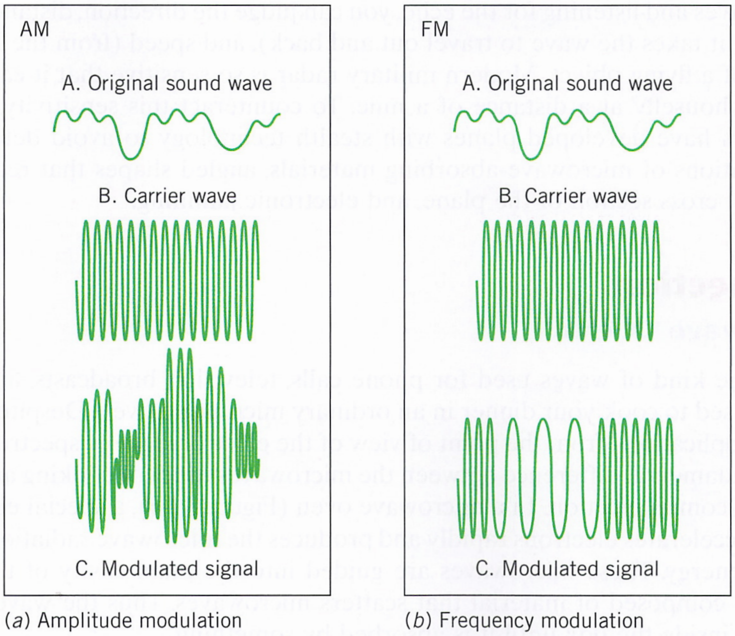


FIGURE 19-3. AM (amplitude modulation) and FM (frequency modulation) transmission differ in the way that a sound wave (A) is superimposed on a carrier wave (B) of constant amplitude and frequency. The carrier wave can be varied, or modulated, to carry information (C) by altering its amplitude or its frequency.

which use carrier frequencies about a thousand times higher than FM radio, typically transmit the picture on an AM signal and the sound on an FM signal at a slightly different frequency.

Another important difference between AM and FM radio stations is that the lower-frequency waves of AM broadcasts may partially reflect off layers of the atmosphere, which allows them to be heard at great distances (especially at night). However, higher-frequency FM transmissions require line-of-sight reception, which restricts their range to about 50 miles. ●

Microwaves

A stealth fighter relies on combinations of microwave-absorbing materials and angled shapes to reduce the apparent cross section of the plane.

Microwaves include electromagnetic waves whose wavelengths range from about 1 meter (a few feet) to 1 millimeter (1 thousandth of a meter, or about 0.04 inch). The longer wavelengths of microwaves travel easily through the atmosphere, like their cousins in the radio part of the spectrum, although rock and building materials absorb most microwaves. Therefore, microwaves are used extensively for line-of-sight communications. Most satellites broadcast signals to Earth in microwave channels, and these waves also commonly carry long-distance telephone calls and TV broadcasts. The satellite dish antennas that you see on private homes and businesses are designed primarily to receive microwave transmissions, as are the large cone-shaped receivers attached to the microwave relay towers found on many hills or tall buildings.

The distinctive transmission and absorption properties of microwaves make them ideal for use in aircraft radar. Solid objects, especially those made of metal, reflect most of the microwaves that hit them. By sending out timed pulses of microwaves and listening for the echo, you can judge the direction, distance (from the time it takes the wave to travel out and back), and speed (from the Doppler effect) of a flying object. Modern military radar is so sensitive that it can detect a single housefly at a distance of a mile. To counteract this sensitivity, aircraft designers have developed planes with stealth technology to avoid detection—combinations of microwave-absorbing materials, angled shapes that reduce the apparent cross section of the plane, and electronic jamming.

Connection

Microwave Ovens

The same kind of waves used for phone calls, television broadcasts, and radar can be used to cook your dinner in an ordinary microwave oven. Despite the different applications, from the point of view of the electromagnetic spectrum there is no fundamental difference between the microwaves used for cooking and those used for communication. In a microwave oven (Figure 19-4), a special electronic device accelerates electrons rapidly and produces the microwave radiation, which carries energy. These microwaves are guided into the main cavity of the oven, which is composed of material that scatters microwaves. Thus the wave energy remains inside the box until it is absorbed by something.

It turns out that microwaves are absorbed quickly by water molecules. This means that the energy used to create microwaves is carried by those waves to food inside the oven, where the energy is absorbed by water molecules inside the food and converted into heat. This absorption of microwave energy results

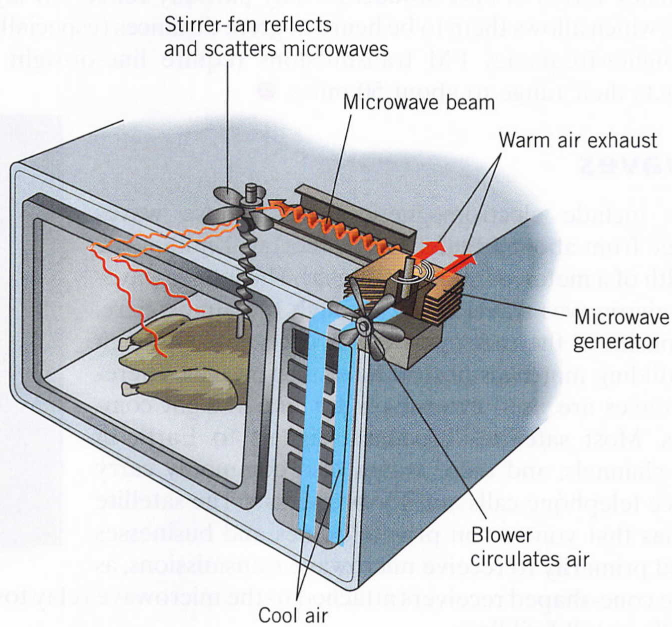


FIGURE 19-4. Every microwave oven contains a device that generates microwaves by accelerating electrons. The walls scatter the microwaves until they are absorbed, usually by water molecules in the food.

in a very rapid rise in temperature and rapid cooking. In a microwave oven, then, food is heated from the inside, unlike an ordinary oven, where heat travels from the surface to the interior. Microwaves do not heat paper and glass, which don't contain many water molecules.

Metal is a good reflector of microwaves; a metal fan is often contained in a microwave oven to help scatter the beam around the oven. This explains why you don't want to wrap food in metal foil before putting it in the microwave oven; the foil would scatter the radiation and prevent it from reaching the food inside and would probably overload the oven's circuits in the process. ●

Infrared Radiation

Infrared radiation includes wavelengths of electromagnetic radiation that extend from 1 millimeter down to about 1 micron (10^{-6} meter, or less than 1 ten-thousandth of an inch). Our skin, which absorbs infrared radiation, provides a crude kind of detector. You feel infrared radiation when you put your hands out to a warm fire or over the cooking element of an electric stove. Infrared waves are what we feel as radiant heat.

Warm objects emit infrared radiation, and this fact has been used extensively in both civilian and military technology. Infrared detectors are used to guide air-to-air missiles to the exhaust of jet engines in enemy aircraft, and infrared detectors are often used to "see" human beings and warm engines at night. Similarly, many insects (such as mosquitoes and moths) and other nocturnal animals (including opossums and some snakes) have developed sensitivity to infrared radiation; thus they can see in the dark.

Infrared detection is also used to find heat leaks in homes and buildings (Figure 19-5). If you take a picture of a house at night using film that is sensitive to infrared radiation, places where heat is leaking out show up as bright spots on the film. This information can be used to correct the loss and thus conserve energy. In a similar way, Earth scientists often monitor volcanoes with infrared detectors. The appearance of a new hot spot may signal an impending eruption.

FIGURE 19-5. A photograph using infrared film reveals heat energy escaping from houses. This false-color image is coded so that white is hottest, followed by red, pink, blue, and black.

Develop Your Intuition: Uses of Infrared Beams

Have you ever been to a public restroom in an airport or office building and found plumbing that works automatically? Water comes on in the sink as soon as you put your hands under the faucet and turns off as soon as you take your hands away. But there's no visible light beam anywhere, so how does the system know you're there?

What you're not seeing are beams of infrared radiation (Figure 19-6*a*). A fiber-optic cable inside the faucet emits a beam with a wavelength of 850 nanometers, which is not visible to the human eye. A second fiber-optic cable receives the beam reflected from the bottom of the sink. When you put your hand in the path of the beam, a sensor notes that a change in intensity of the reflected beam has occurred and it initiates electronic switches that turn on the water. When you take your hand away, the sensor returns to normal and the switches close.

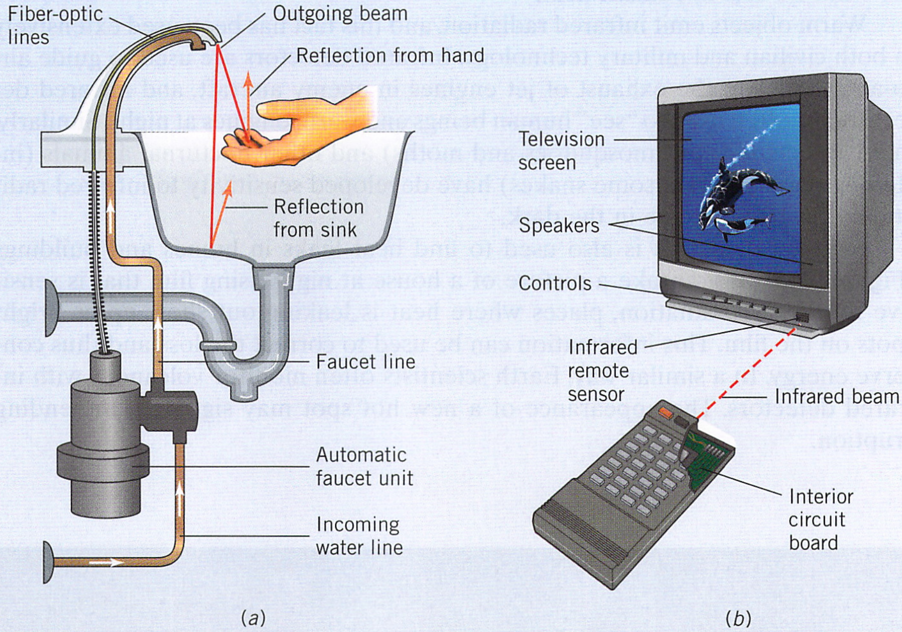


FIGURE 19-6. (*a*) Faucets in many public restrooms use infrared beams to detect a person's hands. Water comes on when you put your hands under the faucet and turns off when you take your hands away. (*b*) Your TV remote control sends a pattern of infrared signals to a sensor on the TV set.

Does this seem like a fairly exotic application of infrared beams? There's a far more common application closer to home: the TV remote control (Figure 19-6*b*). Every function on the remote is coded into a microchip. When you press a button, the chip activates a light-emitting diode that sends a pattern of infrared signals to a reader on the TV set. The pattern is usually repeated five times per second to make sure the message is received.

Visible Light

All of the colors of the rainbow are contained in **visible light,** whose wavelengths range from red light at about 700 nanometers down to violet light at about 400 nanometers (Figure 19-7). From the point of view of the larger universe, the visible world in which we live is a very small part of the total picture (see Figure 19-2).

Our eyes distinguish several different colors, but these portions of the electromagnetic spectrum have no special significance except in our perceptions. In fact, the distinct colors that we see—red, orange, yellow, green, blue, and violet—represent very different-size slices of the electromagnetic spectrum (Figure 19-8). The red and blue portions of the spectrum are rather broad, spanning more than 50 nanometers of wavelengths; we thus perceive many different wavelengths as red or blue. In contrast, the yellow part of the spectrum is quite narrow, encompassing wavelengths from only about 570 to 590 nanometers.

Why should our eyes be so sensitive to such a restricted range of the spectrum? The Sun's light is especially intense in this part of the spectrum, so some biologists suggest that our eyes evolved to be especially sensitive to these wavelengths in order to take maximum advantage of the Sun's light. Our eyes are ideally adapted for the light produced by our Sun during daylight hours. Animals that hunt at night, such as owls and cats, have eyes that are more sensitive to infrared wavelengths, radiation that makes warm living things stand out against the cooler background.

FIGURE 19-7. A glass prism separates white light into the visible spectrum.

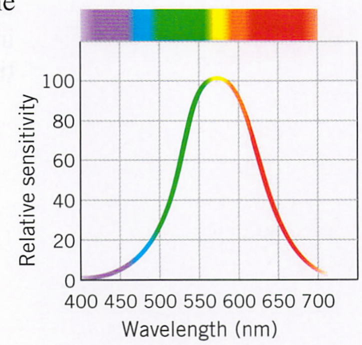
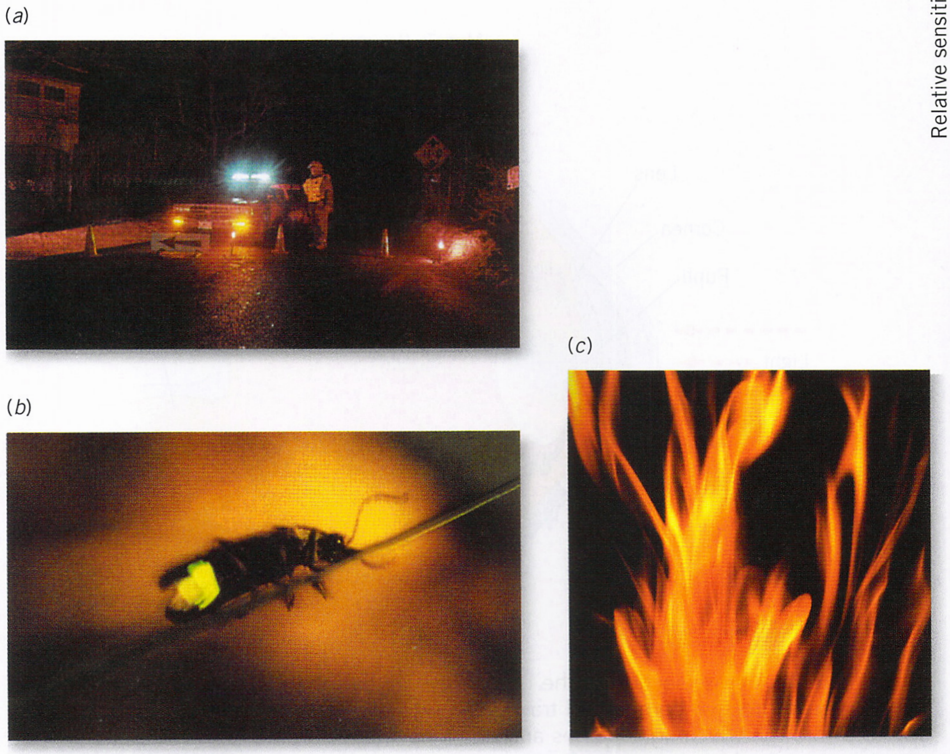


FIGURE 19-8. Humans perceive the visible light spectrum as a sequence of color bands. The relative sensitivity of the human eye differs for different wavelengths. Our perception peaks near wavelengths that we perceive as yellow, although the colors we see have no special physical significance.



A variety of chemical reactions produce light energy.

Develop Your Intuition: Stars of Different Colors

Not all stars in the sky have the same color. For example, the star Betelgeuse, located in the shoulder of the constellation Orion, is distinctly red, while the star Rigel, located in Orion's foot, emits blue light. Which of these stars is at a hotter temperature?

Blue light has a shorter wavelength (higher frequency) than red light, and higher frequencies mean higher energies. So Rigel emits light of higher energy than does Betelgeuse and is the hotter star. In fact, most young stars emit blue light, indicating their high temperatures. Near the end of their lives, their temperatures decrease and their light turns redder. Betelgeuse is classified as a red giant star, meaning it is nearing the last stages of its lifetime. Nevertheless, since stars last for billions of years, Betelgeuse still has a long time to go.

Connection
The Eye

The light detector with which we are most familiar is one we carry around with us all the time—the human eye. Eyes are marvelously complex organs, turning incoming electromagnetic radiation into images through the use of a combination of physical and chemical processes (Figure 19-9).

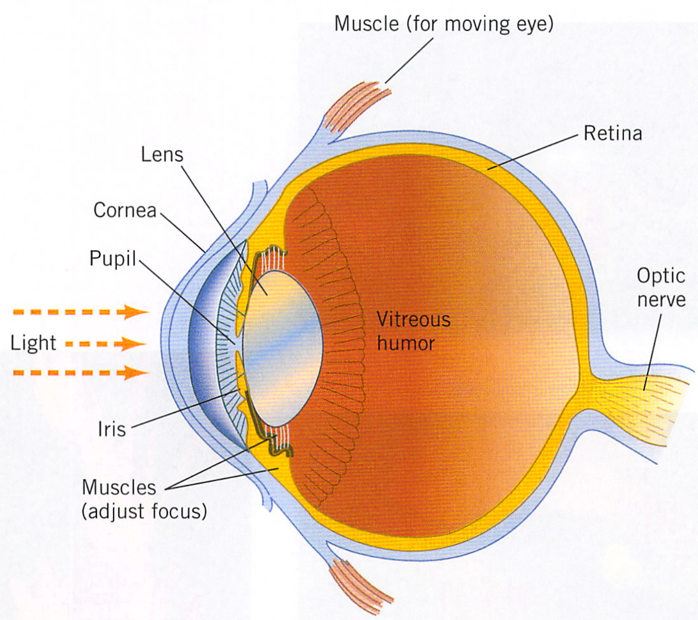


FIGURE 19-9. A cross section of the human eye reveals the path of light, which enters through the protective cornea and travels through the colored iris. The pupil is the aperture through which light passes and changes in size to control the amount of light entering the eye. Muscles move the eye and change the shape of the lens, which focuses light onto the retina, where the light's energy is converted into nerve impulses. These signals are carried to the brain along the optic nerve.

Light waves enter the eye through a clear lens whose thickness can be changed by a sheath of muscles around its edges. The direction of the waves is changed by refraction in the lens so that they are focused at receptor cells located in the retina at the back of the eye. There the light is absorbed by two different kinds of cells, called rods and cones (the names come from their shapes, not their functions). The rods are sensitive to light and dark, including low levels of light; they give us night vision. Three kinds of cones, sensitive to red, blue, or green light, allow us to see colors.

The energy of incoming light triggers complex changes in molecules in the rods and cones, initiating a series of reactions that eventually lead to a nerve signal that travels along the optic nerve to the brain. ●

Ultraviolet Radiation

At wavelengths shorter than visible light, we begin to find waves of high frequency and therefore high energy and potential danger. The wavelengths of **ultraviolet radiation** range from 400 nanometers down to about 100 nanometers (the size of 100 atoms placed end to end) in length. The energy contained in longer ultraviolet waves can cause a chemical change in skin pigments, a phenomenon known as tanning. This lower-energy portion of the ultraviolet is not particularly harmful by itself.

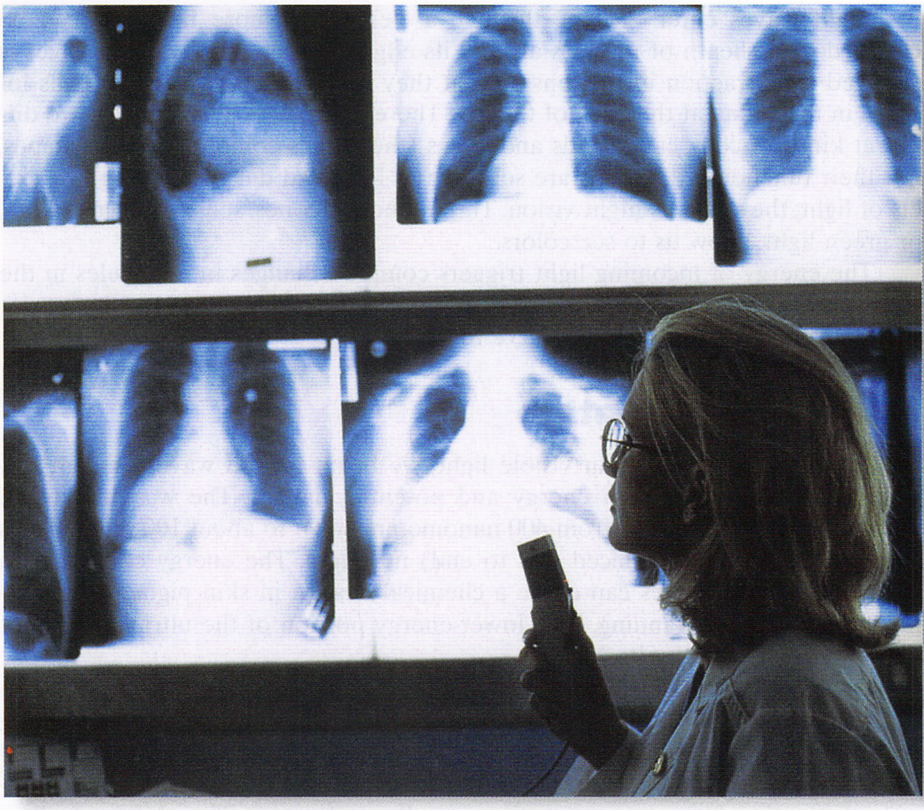
On the other hand, shorter-wavelength (higher-energy) ultraviolet radiation carries more energy—enough that this radiation can damage skin cells, causing sunburn and skin cancer in humans. The wave's energy is absorbed by cells and can cause extensive damage to DNA, the critical molecule that transfers biological information from one generation of cells to the next. The ability of ultraviolet radiation to kill living cells is used by hospitals to sterilize equipment and kill unwanted bacteria.

The Sun produces intense ultraviolet radiation in both longer and shorter wavelengths. Fortunately, our atmosphere (and particularly the ozone layer in the atmosphere) absorbs much of the harmful short wavelengths and thus shields living things. Nevertheless, if you spend much time outdoors under a bright Sun, you should protect exposed skin with a sunblocking chemical, which is transparent (colorless) to visible light but absorbs harmful ultraviolet rays.

The energy contained in both long and short ultraviolet wavelengths can be absorbed by atoms, which in special materials may subsequently emit a portion of that absorbed energy as visible light. (Remember, both visible light and ultraviolet light are forms of electromagnetic radiation, but visible light has longer wavelengths, and therefore less energy, than ultraviolet radiation.) This phenomenon, called fluorescence, provides the black-light effects so popular in stage shows and nightclubs. We examine the origins of fluorescence in more detail in Chapter 21.

X Rays

X rays are electromagnetic waves that range in wavelength from about 100 nanometers down to 0.1 nanometer, smaller than a single atom. These high-frequency (and thus high-energy) waves can penetrate several centimeters into most solid matter, but are absorbed to different degrees by all kinds of materials. This fact allows X rays to be used extensively in medicine to form visual images of bones and organs inside the body. Bones and teeth absorb X rays much



A physician examines medical X rays. Internal structures are revealed because bones and different tissues absorb X rays to different degrees.

more efficiently than skin or muscle, so a detailed picture of inner structures emerges. X rays are also used extensively in industry to inspect for defects in welds and manufactured parts.

The X-ray machine in your doctor's or dentist's office is something like a giant lightbulb with a glass vacuum tube. At one end of the tube is a tungsten filament that is heated to a very high temperature by an electric current, just like in an incandescent lightbulb. At the other end is a polished metal plate. X rays are produced by applying an extremely high voltage—negative on the filament and positive on the metal plate—so electrons stream off the filament and smash into the metal plate at high velocity. The sudden deceleration of the negatively charged electrons releases a flood of high-energy electromagnetic radiation—the X rays that travel from the machine to you at light speed.

Ongoing Process of Science

Intense X-Ray Sources

X rays have become supremely important in many facets of science and industry. X-ray crystallographers use beams of X rays to determine the spacing and positions of atoms in a crystal, physicians use X rays to reveal bone fractures and other internal injuries, and many industries use X rays to scan for defects in manufactured products. However, many potential applications, such as structural studies of very small crystals or scans of unusually large manufactured products, are unrealized because of the relatively low intensity of conventional X-ray sources.

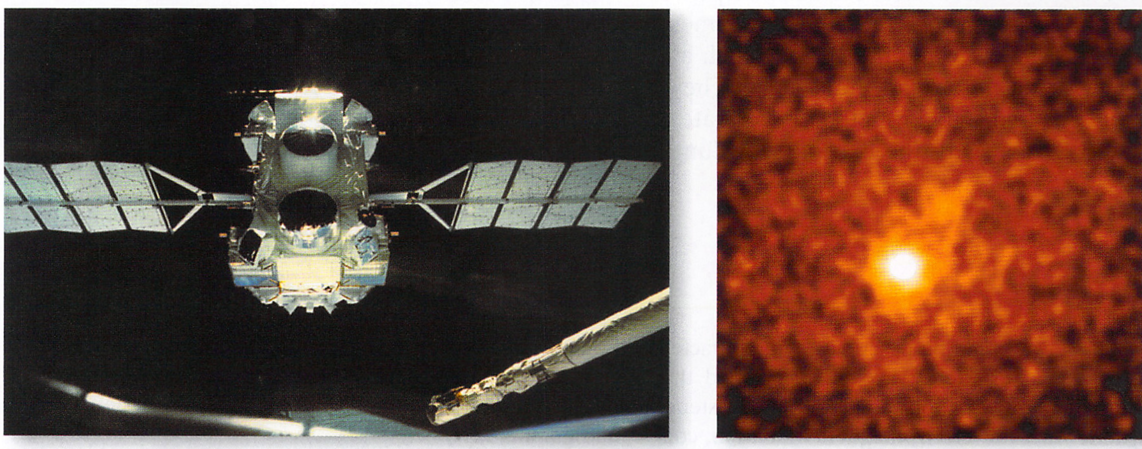
A major effort is now under way to develop new, more powerful X-ray sources. One such facility, the Advanced Photon Source (APS) near Chicago, Illinois, generates intense X-ray beams 1 billion times stronger than conventional sources by accelerating electrons in a circular path. (Remember, electromagnetic radiation is emitted when charged particles are accelerated.) Scientists converge on the APS from around the world to study the properties of matter. Eventually, an X-ray laser (see Chapter 21) might produce even more powerful X-ray beams, although such technology is now only a dream. ●

Gamma Rays

The wavelengths with the highest energies in the electromagnetic spectrum are called **gamma rays.** Their wavelengths range from slightly less than the size of an atom (about 0.1 nanometer, or 10^{-10} meter) to less than 1 trillionth of a meter, or 10^{-12} meter. Gamma rays are normally emitted only in very high-energy nuclear and particle reactions (see Chapters 26 and 27), and they are not as common on Earth as the other kinds of electromagnetic radiation that we have talked about.

Gamma rays have many uses in medicine. Some types of medical diagnosis involve giving a patient a radioactive chemical that emits gamma rays. If that chemical concentrates at places where bone is actively healing, for example, then doctors can monitor the healing by locating the places where gamma rays are emitted. The gamma-ray detectors used in this specialized form of nuclear medicine are both large (to capture the energetic waves) and expensive. Doctors also use gamma rays for the treatment of cancer in humans. In these treatments, high-energy gamma rays are directed at tumors or malignancies that cannot be removed surgically. When the gamma-ray energy is absorbed in those tissues, the tissues die and the patient has a better chance to live.

Gamma rays are also studied in astronomy because many of the interesting processes going on in our universe involve bursts of very high energy and, hence, the emission of gamma rays. The Compton Gamma Ray Observatory, a satellite



(*a*) (*b*)

(*a*) NASA's Compton Gamma Ray Observatory, which operated from 1991 to 1999, detected exploding stars and active galaxies. (*b*) Some of the most energetic events ever observed in the universe, such as this gamma-ray-emitting star in a distant galaxy, were recorded by this satellite.

launched in 1991, documented many such energetic events, including exploding stars and active distant galaxies. In 1999, the Compton's guidance system failed, so in June 2000 it was allowed to fall into the atmosphere and burn up.

THINKING MORE ABOUT

Electromagnetic Radiation: Is ELF Radiation Dangerous?

Maxwell's equations tell us that *any* accelerated charge emits waves of electromagnetic radiation, not just radiation with frequencies of millions or billions of hertz. In particular, the electrons that move back and forth in wires to produce the alternating current in household wiring generate electromagnetic radiation. Every object in which electric power flows, from power lines to toasters to computers, is a source of this weak, extremely low-frequency (ELF) radiation.

For more than a century, human beings in industrialized countries have lived in a sea of weak ELF radiation, but until recently no questions were raised about whether that radiation might have an effect on human health. In the late 1980s, however, a series of books and magazine articles created a minor sensation by claiming that exposure to ELF radiation might cause some forms of cancer, most notably childhood leukemia.

Scientists tended to downplay these claims because the electric fields most residents experience due to power lines are a thousand times weaker than those due to natural causes (such as electrical activity in nerve and brain cells). They also pointed out that age-corrected cancer rates in the United States (with the exception of lung cancer, which is caused primarily by smoking) have remained constant or dropped over the last 50 years, even though exposure to ELF radiation has increased enormously. They also questioned the statistical validity of some studies: more detailed analyses of results did not demonstrate the connection between ELF radiation and disease. In 1995, the prestigious American Institute of Physics reviewed the scientific literature on this subject and concluded that there is no reliable evidence that ELF radiation causes any form of cancer, and most funding for research in this area was cut off.

This situation is typical of encounters at the border between science and public health. Preliminary data indicate a possible health risk but do not prove that the risk is real. Settling the issue by further study takes years, while researchers carefully collect data and weigh the evidence. In the meantime, people have to make decisions about what to do. In addition, as in the case of ELF radiation, the cost of removing the risk is often very high.

Suppose you are a scientist who has shaky evidence that some common food—bread, for example, or a familiar kind of fruit—could be harmful. What responsibility do you have to make your results known to the general public? If you stress the uncertainty of your results and no one listens, should you make sensational (perhaps unsupported) claims to get people's attention?

Summary

The motion of every wave can be described by a characteristic wave equation. James Clerk Maxwell recognized that simple manipulation of his equations pointed to the existence of **electromagnetic waves** or **electromagnetic radiation,** consisting of alternating electric and magnetic fields that can travel through a vacuum at the **speed of light.** This discovery solved one of the oldest mysteries of science, the nature of **light.** Although visible light was the only kind of electromagnetic radiation known to Maxwell, he predicted the existence of other kinds with longer and shorter wavelengths. Soon thereafter a complete **electromagnetic spectrum** of waves was recognized, including **radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X rays,** and **gamma rays.**

We use the properties of electromagnetic waves in countless ways every day—in radio and TV, heating and lighting, microwave ovens, tanning salons, medical X rays, and more. Much of science and technology during the past 100 years has been an effort to find new and better ways to produce, manipulate, and detect electromagnetic radiation.

Key Terms

electromagnetic spectrum The entire collection of electromagnetic waves, from the shortest wavelength (gamma rays) to the longest wavelength (radio waves) and everything in between. (p. 403)

electromagnetic wave or **electromagnetic radiation** A wave that incorporates electric and magnetic fields that oscillate together. (p. 399)

gamma rays Electromagnetic waves with the shortest wavelength; they are usually emitted in nuclear reactions. (p. 413)

infrared radiation Electromagnetic waves with wavelengths in the range of about 1 micron to 1 millimeter; they are what we feel as radiant heat. (p. 407)

light Electromagnetic radiation detectable by the human eye, with wavelengths from about 400 to 700 nanometers in length. (p. 399)

microwaves Electromagnetic waves with wavelengths between about 1 millimeter and 1 meter. (p. 405)

radio waves Electromagnetic waves with the longest wavelength, used to broadcast radio signals. (p. 403)

speed of light, *c* The speed at which all electromagnetic waves travel when in a vacuum, 3.00×10^8 m/s. (p. 401)

ultraviolet radiation Electromagnetic waves with wavelengths from about 100 nanometers to 400 nanometers; they are known to cause sunburn. (p. 411)

visible light The specific frequencies of electromagnetic waves that can be detected by the human eye; they include all colors of the rainbow. (p. 409)

X rays Electromagnetic waves with wavelengths from about 0.1 nanometer to 100 nanometers. (p. 411)

Key Equations

1 hertz = 1 cycle/second

For light: Wavelength (m) $\times$ Frequency (Hz) = c

Constant: Speed of Light: $c = 300{,}000$ km/s $= 3 \times 10^8$ m/s

Review

1. Through which medium does an electromagnetic wave move? Explain.
2. Can an electromagnetic wave move through a complete vacuum? How?
3. How fast do electromagnetic waves travel? What was the significance of the discovery that light also moved at the same speed?
4. If a source of electromagnetic waves stops emitting waves, will the waves that have already been emitted be affected in any way?
5. What was meant by the "ether"? What prompted the assumption that it existed?
6. What did Michelson and Morley's experiment show about the medium that was thought to carry electromagnetic radiation?
7. What value is *c*, the speed of light? [*Hint:* Don't forget the units.]
8. What is the relationship among the frequency, the wavelength, and the speed of light?
9. What is the relationship between the frequency of an electromagnetic wave and its energy?
10. Which is hotter, the blue flame of a furnace or the orange flame of a campfire? Explain.
11. What is the range of wavelength of visible light in nanometers? How long is a nanometer? Write this using a decimal point.
12. What is meant by the term "electromagnetic spectrum"?
13. What is the significance of accelerating charges to the electromagnetic spectrum? What role did Hertz's discovery of radio waves play in the understanding of this spectrum?
14. How is a radio wave produced? What role does an antenna play in this?
15. What is the difference between AM and FM radio? How is each of these types of waves produced?
16. Identify some of the differences and similarities between radio waves and microwaves. Which has a longer wavelength? Which is more energetic?
17. Identify three common uses of microwaves.
18. How does a microwave oven work? What role does water play in facilitating its function? Why does a glass or paper container that holds the food inside such an oven not get hot even while the food does?

19. How do we perceive infrared radiation? Which of our five senses best detects it?

20. What is the difference between red light and yellow light? What is it that determines a difference in the color of light?

21. What quality of light do the rods within your eye detect? Do the cones detect?

22. Why is short-wave ultraviolet light more damaging to your skin than long-wave ultraviolet light?

23. What is an X ray and how is it generated in a simple machine in your doctor's office?

24. Why are X rays used for medical diagnosis? What other wavelengths of electromagnetic radiation are used in medicine?

25. How much energy does a gamma ray have relative to other parts of the electromagnetic spectrum? What is its wavelength and frequency relative to these other parts of the spectrum?

26. What are some uses of gamma rays?

27. What kinds of electromagnetic radiation can you detect with your body?

28. What is ELF radiation?

29. Summarize the arguments for and against ELF radiation with regard to human health.

Questions

1. Compare an electromagnetic wave to a wave on a pond. What are the similarities and differences?

2. In what ways do sound waves differ from radio waves? In what ways are they similar?

3. Suppose a sound wave and a light wave have the same frequency. Which one has the longer wavelength?

4. White light is a combination of all frequencies of electromagnetic waves in the visible spectrum. In a vacuum, all frequencies of light travel at the same speed. Suppose for a moment that lower frequencies traveled slower than higher frequencies. Would a distant star look any different? Explain. If that star suddenly disappeared, what would be the color of the last light that you would see from the star?

5. Why would walking down a flight of stairs be very hazardous if our eyes detected only infrared light? (*Hint:* What does the amount of infrared light emitted by an object indicate?)

6. An object that looks white when exposed to sunlight reflects all colors of light. What does a white object look like when it is exposed to red light? What does a red object look like when it is exposed to blue light?

7. Compare the frequency, speed, and wavelength of microwaves versus visible light.

8. Compare the frequency, speed, and wavelength of radio waves versus ultraviolet light.

9. Which has more energy, visible light or ultraviolet light? What determines the energy of electromagnetic waves?

10. A person is just as likely to get sunburned on a cloudy day as on a sunny day. Does this evidence support the hypothesis that ultraviolet light, not visible light, causes sunburn? Explain.

11. What is the primary difference between a radio wave and a sound wave? What is the difference between a radio wave and a light wave?

12. If someone asked you to prove that electromagnetic waves can travel in a vacuum, what would you say?

13. What is the difference between a gamma ray and an infrared ray?

14. Your friend proposes an experiment to measure the speed of light using items she has collected in her garage. Why should you be suspicious that this experiment may not work?

Problems

1. Radio and TV transmissions are being emitted into space, so *Star Trek* episodes are streaming out into the universe. The nearest star is 9.5×10^{17} meters away. If civilized life exists on a planet near this star, how long will they have to wait for the next episode?

2. What is the frequency of the wave used by your favorite radio station? What is the wavelength of that station's radio waves? If the station is 50 km away, how long does it take for the radio waves to reach you from the station?

3. The FM radio band in most places goes from frequencies of about 88 to 108 MHz. How long are the wavelengths of the radiation at the extreme ends of this range?

4. The AM radio band in most places goes from frequencies of about 535 to 1610 KHz. How long are the wavelengths of the radiation at the extreme ends of this range?

5. What are the frequency and wavelength of a microwave from a typical microwave oven? Does this have any implications for how these ovens are constructed? Why or why not?

6. **A.** What is the range of wavelengths in nanometers that make up the following?

   a. red light c. orange light
   b. green light d. blue light

   B. What is the range of each of these in meters?

7. If an X ray has a wavelength of 5 nanometers, what is its frequency?

8. Which has greater energy, an X ray with a wavelength of 90 nm or one with a wavelength of 2 nm? Explain.

9. If the frequency of an electromagnetic wave is 10^6 Hz what is the wavelength in nanometers? In meters? What type of electromagnetic wave is this?

10. Repeat Problem 9 for an electromagnetic wave with a frequency of 10^{21} Hz.

Investigations

1. Visit a local hospital and see how many types of electromagnetic radiation are used on a regular basis. From radio waves to gamma waves, how are the distinctive characteristics of each portion of the electromagnetic spectrum used at the facility?

2. What frequencies of electromagnetic radiation, if any, do police, fire, and medivac personnel in your community use for emergency communications? What are the corresponding wavelengths of these signals? What organizations allocate and monitor these frequencies?

3. In large metropolitan areas, a license to broadcast electromagnetic waves at an AM frequency may change hands for millions of dollars.

   a. Why is electromagnetic "real estate" so valuable? Investigate how frequencies are divided up and who regulates the process. Should individuals or corporations be allowed to own portions of the spectrum or to buy and sell pieces of it?

   b. Currently the only portions of the electromagnetic spectrum that are regulated by national and international law are the longer wavelengths, including radio waves and microwaves. Why are the shorter wavelengths, including infrared radiation, visible light, ultraviolet radiation, and X rays, not similarly regulated?

4. Different colors represent different wavelengths of electromagnetic radiation. Investigate the process by which the human eye detects color, as well as the means by which the brain interprets color. Do all mammals see in color? How do we know?

5. Investigate which portions of the electromagnetic spectrum from sunlight reach the surface of Earth. What happens to the other wavelengths?

WWW Resources

See the *Physics Matters* home page at **www.wiley.com/college/trefil** for valuable web links.

1. **http://imagine.gsfc.nasa.gov/docs/science/know_l1/emspectrum.html** A discussion and tutorial on the electromagnetic spectrum from NASA's education outreach resources.
2. **http://lectureonline.cl.msu.edu/~mmp/applist/Spectrum/s.htm** A Java applet illustrating the electromagnetic spectrum.
3. **http://hamjudo.com/notes/cdrom.html** Electromagnetic mayhem and experiments at home with your own microwave oven.
4. **http://www.mcw.edu/gcrc/cop/static-fields-cancer-FAQ/toc.html** Electromagnetic fields and human health issues from the Medical College of Wisconsin.
5. **http://webphysics.ph.msstate.edu/javamirror/ntnujava/emWave/emWave.html** An animation that describes the propagation of electromagnetic waves.