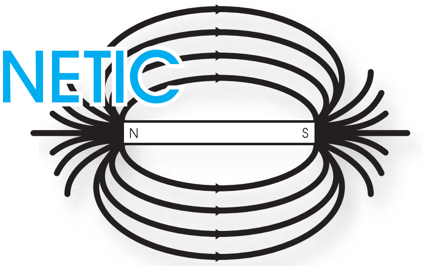
9.1 ELECTROMAGNETIC RADIATION



Objectives

- Explain the nature and source of electromagnetic radiation.
- Explain how a changing electric field can produce an electromagnetic wave.
- Explain how the wavelength, frequency, and speed of an electromagnetic wave are related.
- Calculate the energy and momentum of a photon from the wavelength or frequency.

Electromagnetic Waves

INTERNET *connection*

To find out more about electromagnetic radiation, follow the links at **www.learningincontext.com.**

In Section 5.3. you learned that an electric current in a wire produces a magnetic field that circles the wire. Figure 9-1 shows a wire with a constant potential difference and electric field through the wire. The potential difference causes electrons to move through the wire in the direction opposite the electric field. The current also produces a magnetic field that circles the wire in the clockwise direction as shown.

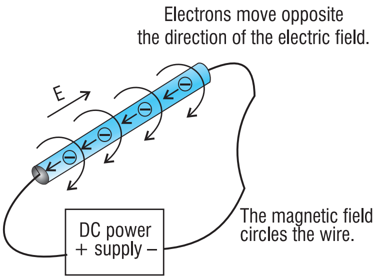


Figure 9.1
An electric field causes current to flow through a wire.
The current creates a magnetic field.

Figure 9-2 shows the same arrangement with the electric field reversed. Both the direction of motion of the electrons and the direction of the magnetic field reverse direction.

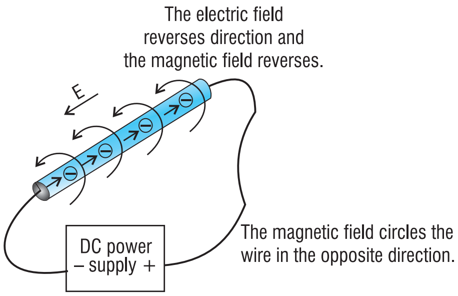


Figure 9.2
When the electric field is reversed, the current changes direction and so does the magnetic field.

Now consider what happens if the DC power supply is replaced by an AC power supply. The alternating potential difference has a sinusoidal waveform. Now the electric field continuously changes in amplitude and direction. The electrons in the wire oscillate back and forth following the changes in the electric field.

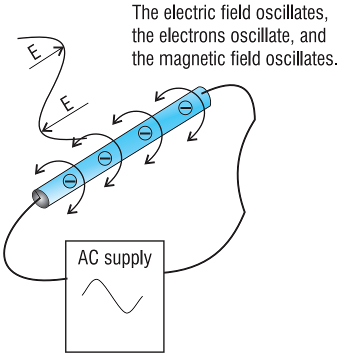


Figure 9.3
An AC power supply applies an alternating potential difference and electric field across the wire.
The current and magnetic field continuously change direction.

The oscillating current in the wire produces a magnetic field that circles the wire, as before. But the magnitude of the field and its direction continuously change in step with the electric field. Therefore, a changing electric field produces a changing magnetic field.

In Section 5.3 you learned that an electromotive force (EMF) is produced in a wire when the wire is in a magnetic field that changes magnitude or direction. This process is called electromagnetic induction. The EMF is actually a potential difference, and therefore the induced EMF creates an electric field. The induced EMF and the magnitude and direction of the electric field change in step with the changing magnetic field.

These processes can be summarized as follows. When something like an AC power supply or a moving magnet causes an electric field or a magnetic field to change, the other field is produced and changes in step.

> *A changing electric field produces a changing magnetic field.*
>
> *A changing magnetic field produces a changing electric field.*

In the 1860s, the English physicist James Clark Maxwell predicted that changing electric and magnetic fields can transmit energy across empty space, without wires. The combination of the changing fields is called an **electromagnetic wave**. In 1887, the German physicist Heinrich Hertz demonstrated experimentally that Maxwell's theory was correct.

The wire connected to the AC power supply in Figure 9.3 is an **antenna**. The current in the wire changes at the same frequency as the power supply. The changing current produces changing electric and magnetic fields that move away from the antenna as an electromagnetic wave. The wave travels away from the antenna at the speed of light. The wave carries energy away from the current in the antenna. The energy is contained in the electric and magnetic fields of the wave. This energy is sometimes called **electromagnetic radiation**.

Speed, Wavelength, and Frequency of EM Radiation

Electromagnetic waves travel through a vacuum at the speed of light, 2.99792×10^8 m/s. In equations, we use c to represent this speed. For most calculations c can be rounded to three significant figures, 3.00×10^8 m/s. The speed in air is approximately the same as in vacuum, but in other media the speed is lower.

All electromagnetic waves travel at the same speed, but they can have vastly different wavelengths and frequencies. For example, you can change the wavelength and frequency of the wave radiated by the antenna in Figure 9.3

by changing the frequency of the AC power supply. Recall from Chapter 8 that the wavelength λ, frequency *f*, and speed of a wave are related. This relationship is expressed in the following equation for electromagnetic waves.

$$\boxed{\begin{array}{l}\text{speed} = \text{wavelength} \cdot \text{frequency} \\ \quad c = \lambda f\end{array}}$$

The wavelength of an electromagnetic wave is the distance between peaks of the electric field or magnetic field in the wave. The frequency is the rate at which peaks pass a stationary point. Since the product λf is constant, as the wavelength increases, the frequency decreases (and vice versa).

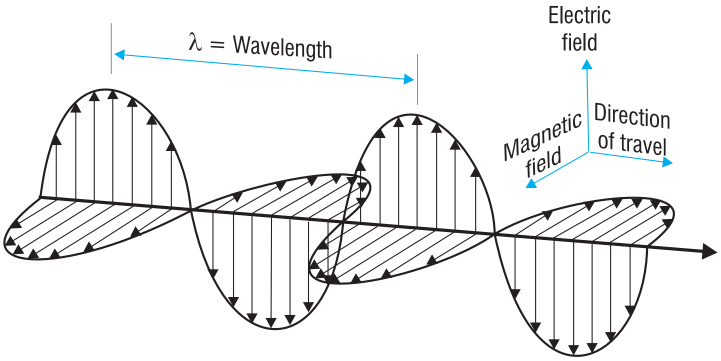


Figure 9.4
In an electromagnetic wave, the electric field is perpendicular to the magnetic field. Both fields are perpendicular to the direction of travel.

Note: Many important physical constants such as the speed of light, π, and the charge of an electron are known to a large number of significant figures. You should always use at least as many significant figures for these constants as are given in other numerical values in a problem. Notice the use of significant figures in the following examples.

Example 9.1 Wavelength of a Radio Wave

Find the wavelength of a 1200-kilohertz radio wave.

Solution: $c = \lambda f$

$$\lambda = \frac{c}{f} \qquad [\text{kHz} = 10^3\ \text{Hz}]$$

$$\lambda = \frac{3.0 \times 10^8\ \text{m/s}}{1200 \times 10^3\ \text{Hz}} = 250\ \text{m} \qquad [\text{Hz} = 1/\text{s}]$$

A 1200-kHz radio wave has a wavelength of 250 meters.

Example 9.2 Speed of Light in Glass

The light from a helium-neon laser has a wavelength of 632.8 nm in air. The same light has a wavelength of 472.2 nm in glass. The frequency of the light is the same in air and glass. Find the speed of the laser light in glass.

Solution: The speed is always the product of wavelength and frequency. The speed in air is approximately c, so $c = \lambda_{\text{air}} f$.

Find the frequency:

$$\begin{aligned} f &= \frac{c}{\lambda_{\text{air}}} \\ &= \frac{2.998 \times 10^{8}\ \text{m/s}}{632.8 \times 10^{-9}\ \text{m}} && [\text{nm} = 10^{-9}\ \text{m}] \\ &= 4.738 \times 10^{14}\ \text{Hz} \end{aligned}$$

Find the speed in glass:

$$\begin{aligned} c_{\text{glass}} &= \lambda_{\text{glass}} f \\ &= (472.2 \times 10^{-9}\ \text{m})(4.738 \times 10^{14}\ \text{Hz}) \\ &= 2.237 \times 10^{8}\ \text{m/s} && [\text{Hz} = 1/\text{s}] \end{aligned}$$

The glass is called a medium. The speed of light or any electromagnetic wave is less in a medium than in a vacuum.

The Electromagnetic Spectrum

The wavelengths of electromagnetic waves range from millions of meters to as short as 10^{-14} m. The **electromagnetic spectrum** is an arrangement of the continous wavelengths and frequencies of all electromagnetic waves. Figure 9.5 is a chart showing the electromagnetic spectrum. For convenience, the spectrum is divided into sections, called **bands**, based on wavelength. These bands have names. For example, *radio waves* are the longest, and can have wavelengths of many kilometers. *Visible light* is electromagnetic radiation whose wavelengths can be sensed by the human eye. The visible band is a very small part of the electromagnetic spectrum. *Infrared radiation* has longer wavelengths than visible, and *ultraviolet* has shorter wavelengths. We will discuss each of the major bands and some of their applications.

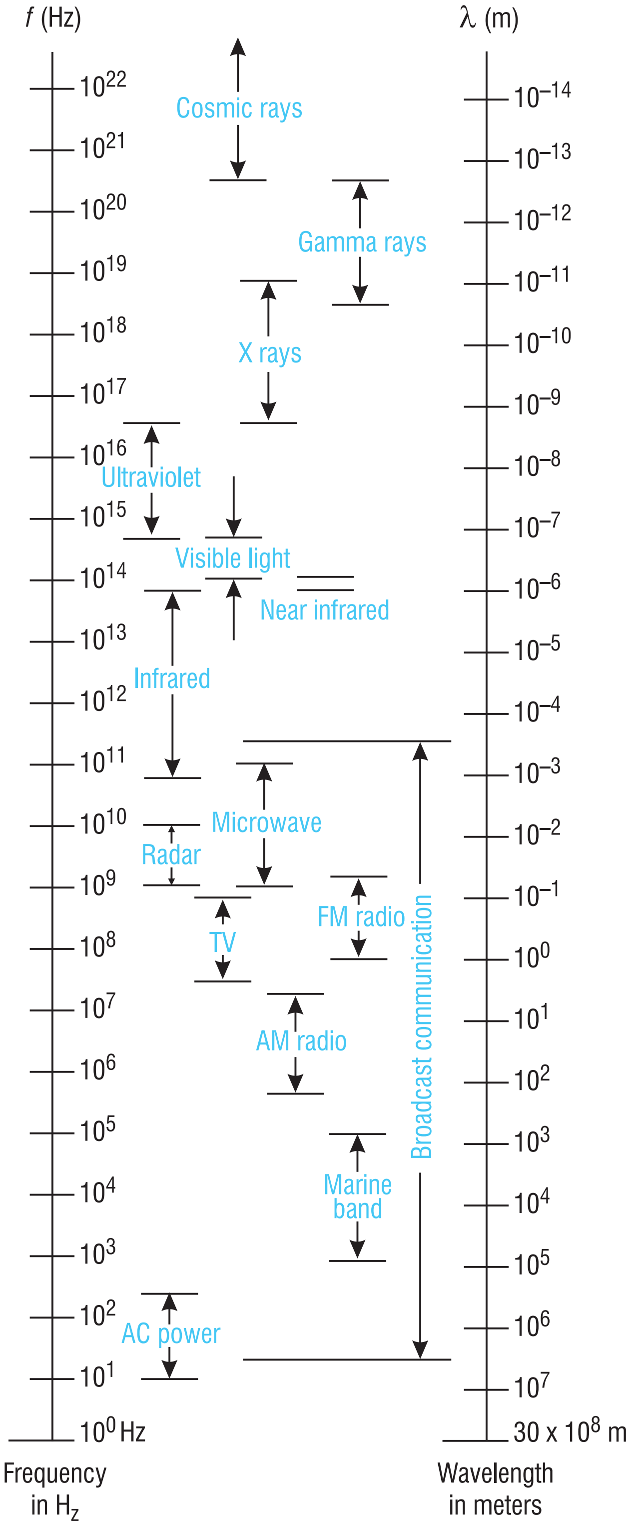
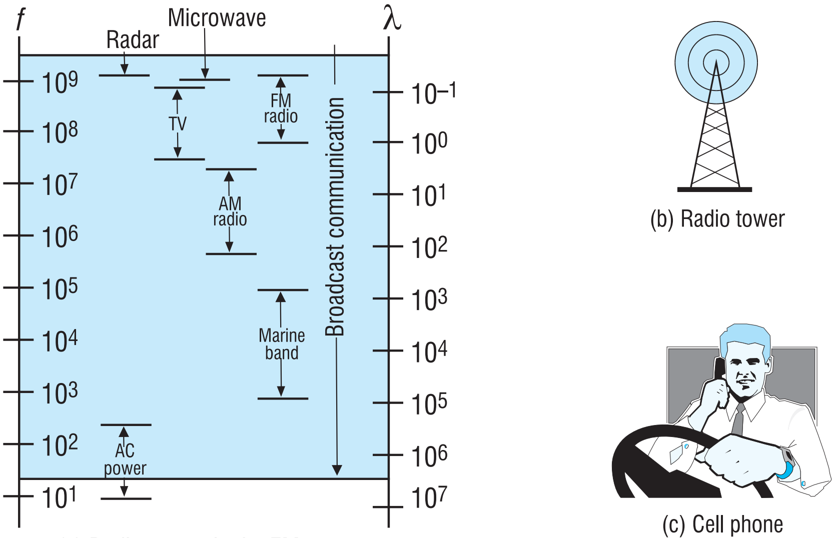


Figure 9.5
The electromagnetic spectrum

Radio Waves

Radio waves are used to transmit radio and television signals. The process of transmission and reception for a sound signal works as follows. At the radio or TV station, electronic devices called *transducers* convert sound into electrical signals (a time-varying current). These signals cause electrons in the transmitting antenna to oscillate back and forth along the length of the antenna. The oscillating electrons generate electromagnetic radiation whose frequency is the same as the electrons' frequency of oscillation. These electromagnetic waves are radio waves, and they are broadcast in all directions from the antenna. The waves travel to a receiving antenna at the speed c. The changing electric and magnetic fields in the electromagnetic wave cause electrons in the receiving antenna to oscillate back and forth, duplicating the electrical signal that originated at the radio or TV station. After signal amplification, another transducer changes the electrical signal into sound made by a loudspeaker. Since the electrical signal received duplicates the signal transmitted, the sound from the loudspeaker duplicates the sound at the radio or TV station.



(a) Radio waves in the EM spectrum

(b) Radio tower

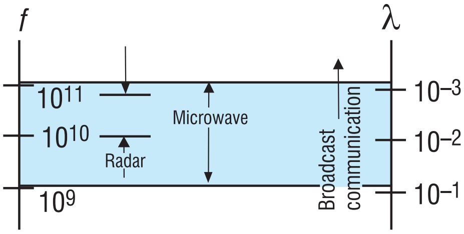
(c) Cell phone

Figure 9.6
Radio waves

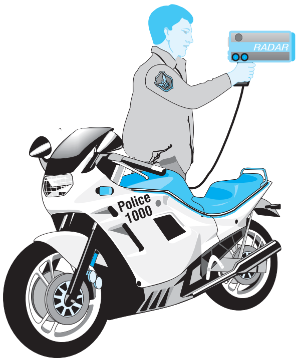
Radio waves have wavelengths that range from less than a centimeter to tens or even hundreds of kilometers. FM (frequency modulated) radio waves are shorter than AM (amplitude modulated) radio waves. For example, an FM radio station at 100 on the radio dial (100 megahertz) would have a wavelength of about three meters. An AM station at 750 on the dial (750 kilohertz) uses a wavelength of about 400 meters. Cell phones use radio waves with frequencies between approximately 800 megahertz (800 MHz) and 2 gigahertz (2 GHz).

Microwaves

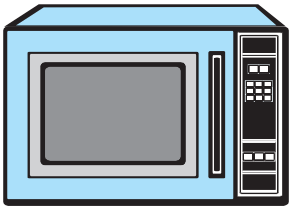
Microwave radiation has shorter wavelengths and higher frequencies than radio waves. Microwave wavelengths range from approximately one millimeter (the thickness of a pencil lead) to thirty centimeters (about one foot).



(a) Microwave radiation in the EM spectrum



(b) Radar



(c) Microwave oven

(d) Satellite TV

Figure 9.7
Microwave radiation

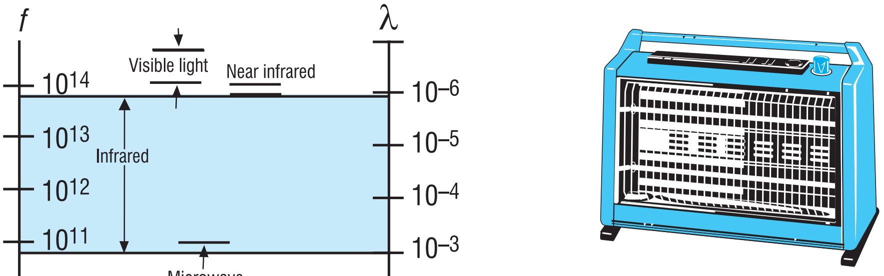
Microwaves are used in telecommunication. They carry information from point to point on the Earth, or from Earth to satellites and back down again using the satellite TV frequencies.

Microwaves can also be used in radar systems to detect and track moving objects. Radar waves are transmitted from an antenna, reflected by an object, and received by the transmitter. The direction of the reflected wave can be measured to locate the object. The reflected wave frequency is altered if the object is moving. The amount of change is determined by the object's speed.

In a microwave oven, the electromagnetic waves generated are tuned to frequencies that can be absorbed by water molecules. As water molecules absorb energy, they vibrate faster and faster and the temperature of the water increases. So, when you place food that contains water molecules in a microwave oven, the food gets hot. The dish holding the food doesn't absorb a significant amount of microwave energy. The dish stays cool until the heated food conducts thermal energy into the dish.

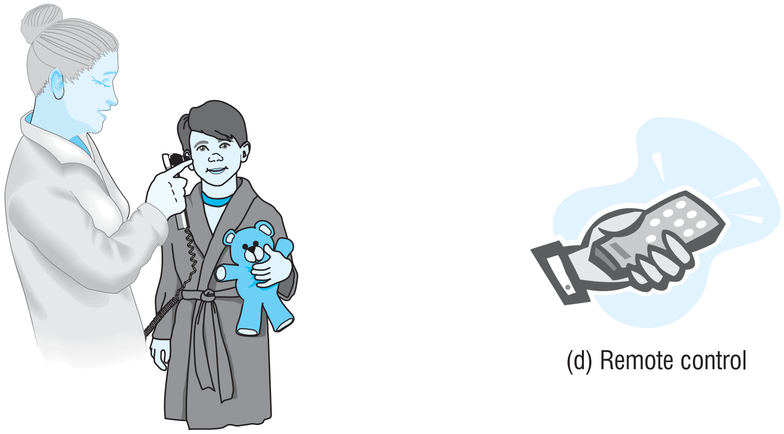
Infrared Radiation

Infrared radiation has longer wavelengths (and lower frequencies) than visible light, and shorter wavelengths than about one millimeter. Infrared waves include thermal radiation. For example, heat is transferred from an electric heater, burning wood or charcoal, and the sun with infrared waves.



(b) Electric heater

(a) Infrared radiation in the EM spectrum



(d) Remote control

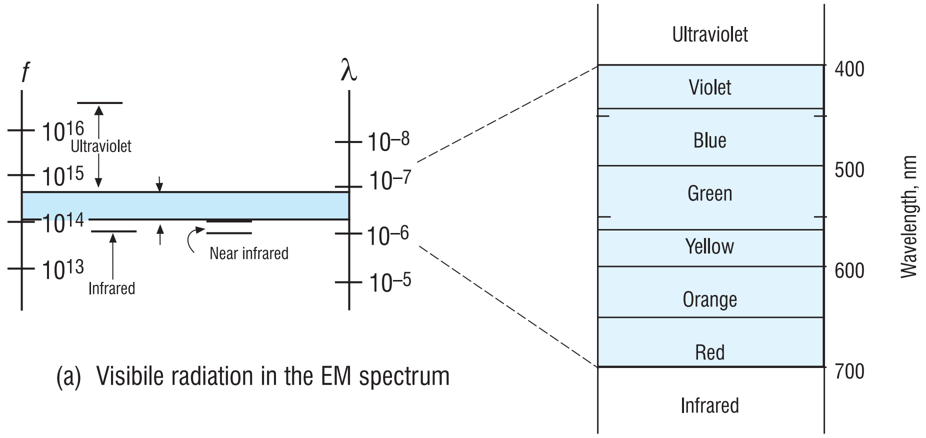
(c) Infrared thermometer

Figure 9.8
Infrared radiation

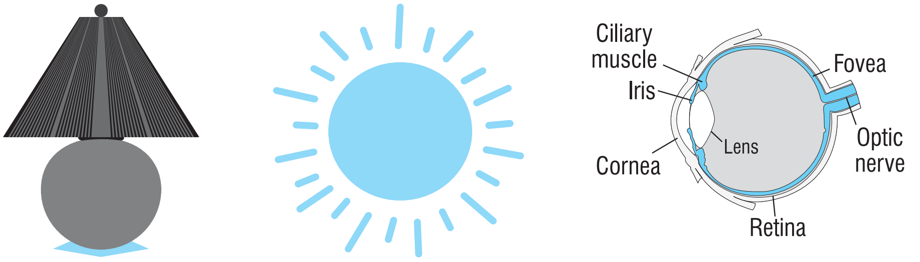
Infrared radiation is not visible—you cannot see it. But it can be measured using electronic detectors. For example, in medicine, a person's temperature can be measured with an electronic thermometer that detects infrared radiation. Infrared photographs are used to find heat leaking from houses. Infrared images obtained by sensors in satellites and airplanes can yield important information on the weather, the health of crops, and the location of forest fires obscured by smoke. Remote-control devices also use infrared radiation.

Visible Light

Visible light is a very small part of the electromagnetic spectrum, but it is probably the most important part. Sight is a result of our eyes detecting visible electromagnetic waves. The wavelengths of visible light are between 400 nanometers and 700 nanometers (400×10^{-9} m and 700×10^{-9} m).



(a) Visibile radiation in the EM spectrum



(b) Incandescent light

(c) Sunlight

(d) The human eye detects visible light.

Figure 9.9
Visible light

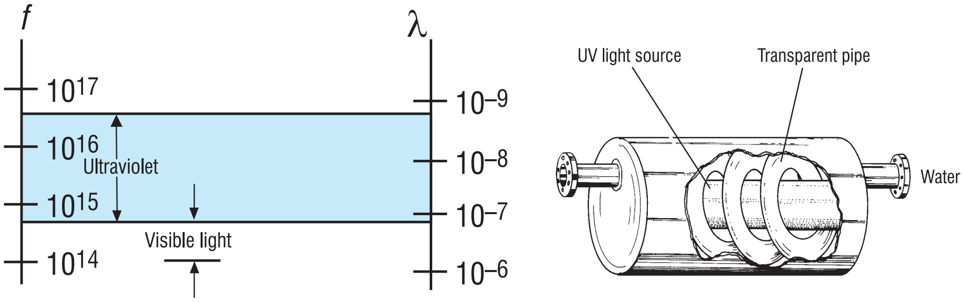
The human eye can detect the difference in colors in this wavelength range—from violet to blue to green to yellow to orange to red. Violet has the shortest wavelength (and highest frequency); red has the longest wavelength (and lowest frequency).

The sun radiates *white light*. This is light that mixes nearly equal amounts of light of all colors. When white light falls on an object, molecules on the object's surface absorb part of the light and reflect the rest. When a molecule absorbs electromagnetic energy, its energy level increases. The molecules *reradiate* some of the absorbed light. (If some of the absorbed energy is retained, the thermal energy of the molecule increases.)

This reradiation of light explains an object's color. A white sheet of notebook paper reradiates nearly equal amounts of light of all colors. But a ripe apple reradiates light primarily in the red part of the spectrum, between 650- and 700-nm wavelength. What part of the spectrum is reradiated by molecules in the surface of an apple that is not ripe?

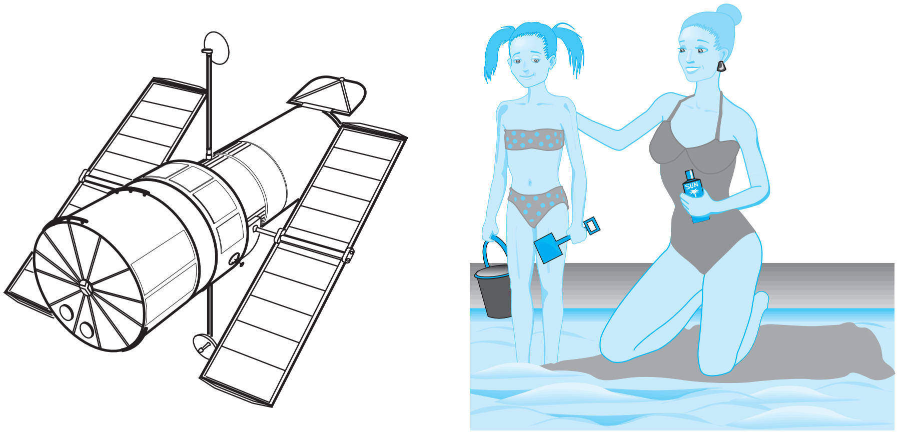
Ultraviolet Radiation

Ultraviolet radiation has shorter wavelengths (and higher frequencies) than visible light. Like infrared, the human eye cannot see ultraviolet radiation. Sunlight contains ultraviolet waves, which can tan or burn your skin. Ozone molecules in the Earth's upper atmosphere absorb most of the ultraviolet waves from the sun. A small dose of ultraviolet radiation is beneficial to humans, but larger doses cause skin cancer and eye cataracts.



(a) Ultraviolet radiation in the EM spectrum

(b) Water purifier



(c) Space-based telescope

(d) Sun-blocking lotion contains molecules that absorb ultraviolet waves.

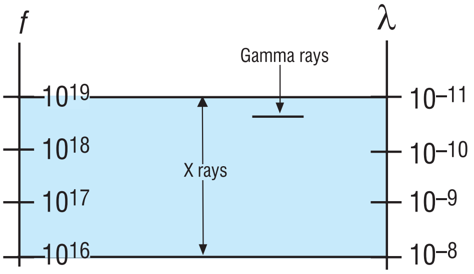
Figure 9.10
Ultraviolet radiation

Ultraviolet wavelengths are used in water purifiers. In astronomy, telescopes and electronic detectors measure ultraviolet radiation from the atmospheres of other planets, stars, quasars, supernovae, and interstellar gas clouds. These measurements are best made from space, above the Earth's atmosphere.

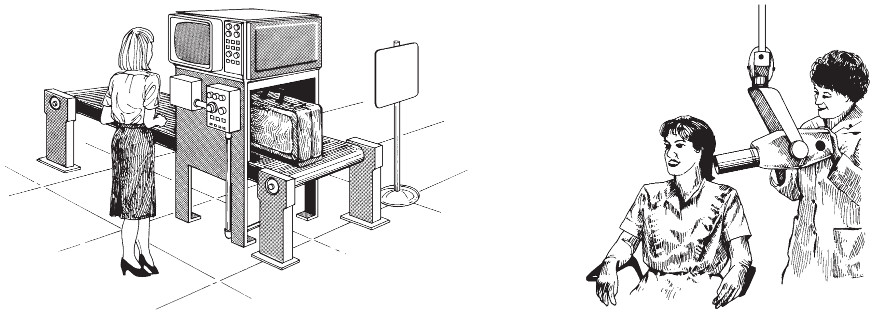
Refer to Appendix F for a career link to this concept.

X Rays

X rays have short wavelengths and high frequencies. These are high-energy waves that have great penetrating power. They are used in medicine, in airport security systems, to detect fake gems and works of art, and in checking for flaws in welds—a process called nondestructive testing.



(a) X-ray radiation in the EM spectrum



(b) Airport security

(c) Dental X ray

Figure 9.11
X rays

X rays have enough energy to pass through human cell tissue, but not through bones or teeth. In an x-ray photograph of a broken arm, a doctor can see a shadow of the bone. This is like sunlight shining on a tree—the light can't penetrate the tree, so it leaves a shadow of the tree on the ground. Thin beams of lower-energy X rays are used in computerized axial tomography (CAT) scanners to create very clear pictures of any part of a patient's anatomy.

X rays are produced by an X-ray "gun." In this device, electrons are accelerated to high speeds with large voltages. The high-speed electrons are directed into a "target" that contains an element such as copper or molybdenum. The electrons stop abruptly when they hit a target atom. The rapidly decelerating electrons lose energy, which is emitted as electromagnetic radiation in the X-ray region of the spectrum.

X rays can be dangerous if not used with caution. Overexposure to X rays damages healthy cells, and can cause cancer. This is why X-ray technicians wear protective lead aprons or move to a shielded room when X-ray pictures are made.

Gamma Rays

Gamma rays have wavelengths of less than about ten trillionths of a meter. They have higher frequency and energy than X rays, and they are more penetrating than X rays. Gamma rays are produced by nuclear reactions and by radioactive nuclei (the plural of nucleus). They are used in many medical applications and to destroy bacteria on food. Detectors on satellites above the Earth's atmosphere have recorded images of the universe in the gamma-ray part of the electromagnetic spectrum. These images have yielded important information on the life and death of stars. You will learn more about gamma rays in the next section.

The Photoelectric Effect

All electromagnetic radiation has wavelength and frequency—two properties of waves. In the next chapter, you will learn how electromagnetic radiation reflects off a surface and refracts, or changes direction, when it travels from one medium into another. These are also wavelike properties. But sometimes electromagnetic radiation acts like a particle, not a wave. We say that electromagnetic radiation has both wavelike and particle-like properties.

The **photoelectric effect** is shown in a famous experiment that demonstrates the particle-like behavior of electromagenetic radiation. Figure 9.12 shows the equipment used in the experiment. A metal target, *T*, and a metal electrode cup are placed inside a glass container with a quartz window at the end. The air is pumped from the container. A light beam can pass through the window and through a hole in the cup to hit the target.

A potential difference, adjustable through a range of positive and negative voltage, is applied between the target and the cup. A sensitive ammeter can measure small currents through the circuit, and a voltmeter measures the potential difference between target and cup.

Experimenters first observed that, when the cup was positive with respect to the target, a current would flow any time sunlight hit the target. The current would stop when the sunlight was removed. Apparently the sunlight caused electrons to be released from the target. The electric field between the cup and the target caused the electrons to flow in the circuit. With no light, no electrons were emitted to conduct current across the gap.

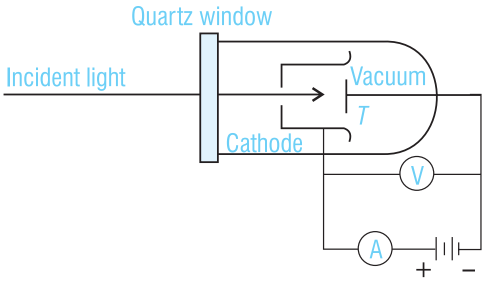


Figure 9.12
A photoelectric-effect experiment

More experimentation produced unexplainable results. When the sunlight was filtered so that only red light (long wavelength—low frequency) hit the target, *no current would flow*. Even very bright red light produced no current. However, very small amounts of blue (short wavelength—high frequency) light *would cause current to flow*. Careful measurements revealed that, for any given target metal, there was a lower limit to the frequency of light that would produce current. If the frequency was too low (wavelength too long), no intensity of light would produce current.

Albert Einstein provided an explanation, and he was awarded the Nobel prize in physics in 1921 for his insight. Einstein proposed that the incident light consisted of very small particle-like bundles of energy. These bundles of energy were later named **photons**. The energy of a photon is proportional to the frequency of the electromagnetic radiation. The constant of proportionality is called **Planck's constant**. We use the symbol h to represent Planck's constant. The numerical value is given below.

$$E_{\text{photon}} = hf = h\frac{c}{\lambda}$$

$$h = 6.626176 \times 10^{-34}\ \text{J}\cdot\text{s}$$

Example 9.3 Energy in an X-Ray Photon

Find the energy of an X-ray photon with a wavelength of 1.34×10^{-11} m.

Solution: $E_{\text{photon}} = h\frac{c}{\lambda}$

$$E_{\text{photon}} = (6.63 \times 10^{-34}\ \text{J}\cdot\text{s})\left[\frac{3.00 \times 10^{8}\ \text{m/s}}{1.34 \times 10^{-11}\ \text{m}}\right]$$

$$E_{\text{photon}} = 1.48 \times 10^{-14}\ \text{J}$$

Einstein explained that the electrons on the surface of the target were bound to the metal by the overall electrical force between the electrons and the nuclei of the metal atoms. A specific minimum amount of energy must be provided to "break" an electron out of the metallic surface. The minimum energy required is called the **work function**, ϕ, of the metal. A single photon had to have enough energy to break the electron loose and make it a free electron.

A photon with less energy than the work function would do nothing. Even many low-energy photons (as in a bright beam of red light) would do nothing, because only a single photon could be absorbed by an electron. A high-energy photon could transfer enough energy to break the electron loose, and any excess energy would provide kinetic energy to the free electron. In other words, energy is conserved.

Conservation of energy in the photoelectric effect requires the following relation to be true for a photon with frequency, *f*, interacting with an electron in a metal whose work function is ϕ.

$$\textit{photon energy} = \textit{work function} + \textit{kinetic energy}$$

$$hf = \phi + KE_{\mathrm{e}}$$

Example 9.4 Kinetic Energy of a Photoelectron

A photon with a wavelength of 535 nm is absorbed by an electron on the surface of aluminum. The electron breaks free of the metal. The work function ϕ for aluminum is 1.88×10^{-19} J. What is the kinetic energy of the free electron?

Solution:

$$hf = \phi + KE_{\mathrm{e}}$$

$$h\frac{c}{\lambda} = \phi + KE_{\mathrm{e}} \qquad \left[f = \frac{c}{\lambda}\right]$$

$$\left(\frac{(6.63\times 10^{-34}\ \mathrm{J\cdot s})(3.00\times 10^{8}\ \mathrm{m/s})}{535\times 0^{-9}\ \mathrm{m}}\right) = (1.88\times 10^{-19}\ \mathrm{J}) + KE_{\mathrm{e}}$$

$$KE_{\mathrm{e}} = 1.84\times 10^{-19}\ \mathrm{J}$$

Einstein also concluded that photons must carry momentum. The momentum of a photon p_{photon} depends on the wavelength of the photon as shown below.

$$p_{\mathrm{photon}} = \frac{h}{\lambda}$$

Example 9.5 Momentum of a Microwave Photon

Find the momentum of a microwave photon with a wavelength of 2.54 cm.

Solution:

$$p_{\mathrm{photon}} = \frac{h}{\lambda}$$

$$p_{\mathrm{photon}} = \frac{6.63\times 10^{-34}\ \mathrm{J\cdot s}}{0.0254\ \mathrm{m}}$$

$$p_{\mathrm{photon}} = 2.61\times 10^{-32}\ \frac{\mathrm{kg\cdot m}}{\mathrm{s}} \qquad \left[\mathrm{J} = \mathrm{kg\cdot m/s^2}\right]$$

Summary

- Electromagnetic radiation is a form of energy transfer produced by accelerating charge. The energy is transferred in the electromagnetic wave's electric and magnetic fields.
- The speed of an electromagnetic wave is the product of the wavelength and frequency.

  $$c = \lambda f$$

  In vacuum and air, $c = 2.99792 \times 10^8 \frac{\text{m}}{\text{s}}$.
- Visible light is a small part of the electromagnetic spectrum. Radio waves, microwaves, and infared radiation have wavelengths longer than visible light. Ultraviolet radiation, X rays, and gamma rays have wavelengths shorter than visible light.
- Albert Einstein explained the photoelectric effect using a particle-like, or photon, model of electromagnetic radiation. A photon is a discrete "bundle" of energy that has no mass, travels at the speed of light, and has wavelength and frequency.
- The energy of a photon is the product of the frequency and Planck's constant.

  $$E_{\text{photon}} = hf = h\frac{c}{\lambda}$$

  $$h = 6.626172 \times 10^{-34}\ \text{J} \cdot \text{s}$$
- Photons have momentum. The momentum of a photon is the ratio of Planck's constant to the wavelength of the photon.

  $$p_{\text{photon}} = \frac{h}{\lambda}$$

Exercises

1. An AC power supply transfers energy to electrons that make up the current in a wire. Name two ways the electrons lose energy.
2. Explain why a radio station would not use a DC power supply to generate radio waves. When would a DC power suppply create electromagnetic waves?
3. Do radio waves, visible light, or X rays have the greatest
   (a) frequency? (b) wavelength? (c) speed?
4. Find the frequency of an electromagnetic wave if the wavelength is 320.0 nm.

5. Find the wavelength of a cell-phone signal if the frequency is 985 MHz.

6. One of the wavelengths of light emitted by a mercury arc lamp is 496.0 nm.
   (a) Find the frequency of the light.
   (b) Find the energy of a photon of this light.

7. When a spark plug fires, the potential difference between the cathode and the anode is 15 kV (1.5×10^4 V).
   (a) An electron in the gap between the anode and the cathode is accelerated by this potential difference. What is the energy of the electron? (Remember from Section 1.3, the work done on the electron is $q\Delta V$.)
   (b) When the electron is stopped, it converts 25% of this energy to electromagnetic radiation. What is the wavelength of the radiation?

8. Extremely low-frequency (ELF) radio waves have been used to communicate with submarines while they are submerged. These long waves penetrate into water. Frequencies between 30 and 300 Hz have been used.
   (a) Find the wavelength of a 150-Hz radio wave in air.
   (b) The speed of an EM wave in water is about 2.24×10^8 m/s. Find the wavelength of a 150-Hz wave in water.

9. A tungsten electrode is exposed to a light source with a wavelength of 261.5 nm. The work function of tungsten is 7.28×10^{-19} J.
   (a) Find the kinetic energy of an electron on the surface of the tungsten that absorbs one of the photons and is ejected from the surface.
   (b) Find the speed of the electron. (The mass of an electron is 9.110×10^{-31} kg.)

10. A radar transmitter is operated at a wavelength of 1.8 cm. The transmitter emits pulses that last 120 ns. The maximum power output during the pulse is 75 MW.
    (a) Find the energy of a photon in the radar beam.
    (b) Find the momentum of one of the radar photons.
    (c) Find the maximum rate of photon emission (photons/second) of the transmitter.
    (d) Find the maximum force the beam would apply to a target that completely absorbed the radar beam.
    (e) Find the maximum force that would act on a target that completely reflected the beam back at the transmitter.
    (f) Find the impulse applied to the reflecting target by one pulse from the radar beam. Assume that the beam power is constant for the length of the pulse.

11. A helium-neon laser produces light with a wavelength of 632.8 nm.

    (a) What is the energy of a photon in the laser beam?

    (b) How many photons per second are emitted by the laser if the output beam power is 150 mW?

12. Find the momentum of one of the photons in exercise 11.

13. The laser beam in exercise 11 hits a target. Half of the photons are absorbed by the target. Half of the photons are reflected back toward the laser.

    (a) Find the power absorbed by the target.

    (b) Find the rate of change in momentum of the absorbed photons.

    (c) Find the rate of change in momentum of the reflected photons. (A reflected photon's momentum has the same magnitude as its initial momentum, but opposite direction.)

    (d) Find the force exerted on the target by the laser beam.

14. The laser in exercises 12 and 13 is part of an environmental monitoring system. The laser light is used to count particles of dust in the air. The beam is focused to a very small spot and hits a dust particle with a diameter of 12.64 mm and a mass of 1.28×10^{-12} kg. Half of the light is absorbed and half reflected as in exercises 12 and 13. Find the acceleration of the dust particle.