# Chapter 3: Electromagnetic Waves – Radiant Energy II

**Goals of Period 3**

Section 3.1: To discuss some properties of radiant energy
Section 3.2: To describe the transfer of energy and information
Section 3.3: To discuss radio and television signal transmission

## 3.1 Radiant Energy from the Sun

The sun emits 3.3 x $10^{31}$ joules of radiant energy each day. Because the earth is so far away from the sun, only about 2 x $10^{-9}$ of the sun's radiation reaches the earth's upper atmosphere. Some of this energy is absorbed or reflected by clouds and gases in the atmosphere, so that only about one half of this amount reaches the earth's surface. Nevertheless, the radiant energy reaching the surface of the earth each day is about 15,000 times the total energy used by the earth's population each day. The maximum, or peak, power falling on the roof of a house of average size in an average location on a clear sunny day is almost 100 kW. If radiant energy could be converted into electrical energy and stored with 100% efficiency, an average family could run their household electrical appliances (excluding heating) on two sunny days a month.

The interior of the sun emits radiant energy at all wavelengths. The matter in the outer layers of the sun (or any other star) absorbs radiation of particular wavelengths. Most of the radiation reaching the Earth’s surface is in the visible region. If we view the light from a star through a device that spreads out the wavelengths, such as a prism, we see that some wavelengths are missing, producing black lines in the pattern seen with the prism. Electromagnetic radiation spread out over a range of wavelengths is called a spectrum. The gaps in the spectrum due to the missing, or absorbed, wavelengths are called absorption bands. The absorption bands in the spectra of stars help us to identify the elements in the stars. You will see examples of absorption bands in class.

### Solar Cells and the Photoelectric Effect

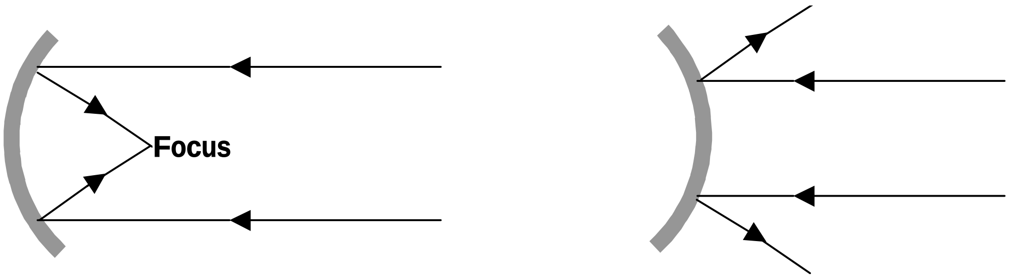
Radiant energy from the sun can be converted into electrical energy by solar cells, which are sometimes called photoelectric cells or photovoltaic (PV) cells, which make use of the photoelectric effect. The photoelectric effect can be explained using the quantum model of radiant energy, but not the wave model. What happens is that the absorption of a photon by an atom may cause an electron to escape from the atom, provided that the energy of the photon is large enough. Any energy of the photon that is in excess of the energy required to free the electron appears as energy of motion of the electron. If the photon does not have sufficient energy to release an electron, the photoelectric effect does not take place. It was Albert Einstein’s explanation of the photoelectric effect in 1905 that later earned him a Nobel Prize.

Solar cells are used to provide power for earth satellites, where it is important to have energy without having to carry fuel. For sometime, the principal difficulties with solar cells have been their high cost and relative inefficiency. However, solar cells are becoming both cheaper and more efficient and can be used to supplement other sources of electricity. They are particularly useful in remote areas without other sources of electricity. For example, solar cells are used to provide power for highway signs. In this period, we will use solar cells to convert radiant energy into electrical energy in the classroom. We will also discuss solar cells when we look for efficient energy sources that do not require the use of oil, gas, or coal to produce electricity.

### Focusing Radiant Energy

For a variety of applications it is desirable to focus, or concentrate, radiant energy. This can be accomplished using curved mirrors or lenses. We will refer to two types of curvature. If a mirror or lens is curved inward, it is said to be ***concave****.* A mirror or lens that bulges outward is ***convex***. When light strikes the surface of a mirror, it is reflected at an angle equal to the angle at which it struck the mirror. From Figure 3.1, you can see that this means a concave mirror can concentrate light. Curved mirrors are used in common devices such as flashlights and headlights to provide a beam of light.

**Figure 3.1 Radiant Energy Reflecting from Mirrors**

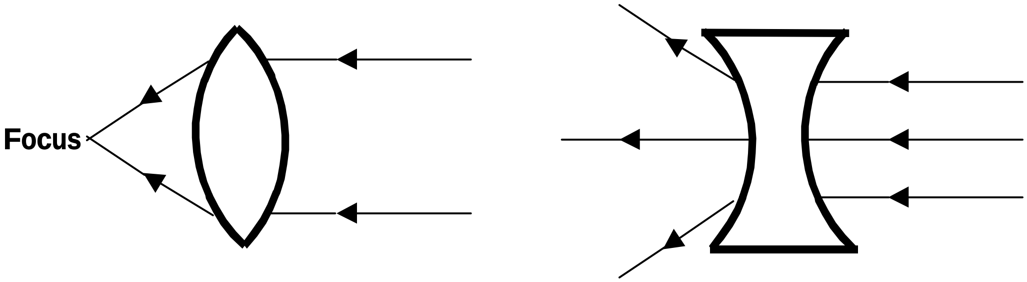


**A Concave Mirror Focuses Radiant Energy**

**A Convex Mirror Spreads Radiant Energy**

As light travels from one medium to another, such as traveling from air into a glass lens, it changes speed. If the light does not enter the new medium perpendicular to the boundary, it will also change direction, or refract, just as a row of marchers in a band will change direction if the marchers at one end of the row slow down before the others do. As shown in Figure 3.2, this means that curved lenses can concentrate light.

**Figure 3.2 Radiant Energy Passing through Lenses**



**A Convex Lens Focuses Radiant Energy**

**A Concave Lens Spreads Radiant Energy**

### Polarized Radiant Energy

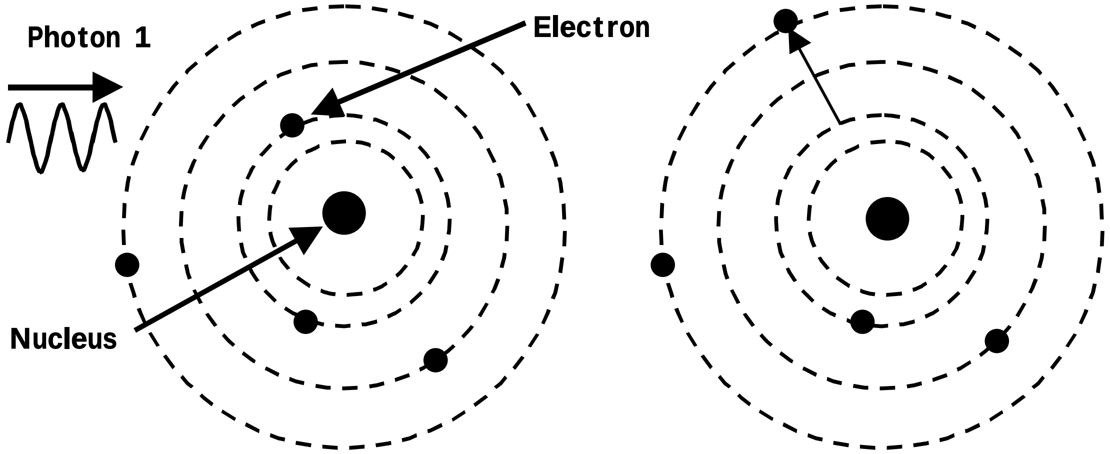
So many electrons are involved in producing visible light that the result is electromagnetic waves that vibrate in all directions perpendicular to the direction of the wave. The electromagnetic waves may move through an object that causes some of the electromagnetic waves to be absorbed, while the rest continue on. A polarizer absorbs all of the electromagnetic waves except those that vibrate in one direction. Waves that vibrate in a single direction are called ***polarized***. When non-polarized light reflects off of a horizontal surface, it becomes polarized in the horizontal plane. For example, sunlight reflecting off of a wet or snow-covered road produces horizontally polarized waves. Polarizing sunglasses block the glare from the horizontally polarized light by allowing only the vertically polarized light to reach your eyes.

### Ultraviolet Light and Fluorescence

Photons in the ultraviolet region have enough energy to induce fluorescence. ***Fluorescence*** is the absorption of radiant energy and the re-emission of radiant energy at longer wavelengths. Fluorescence can be explained using the quantum model of electromagnetic radiation. A relatively high energy photon is absorbed by an atom in the fluorescent material. The atom then gives off this extra energy, but as several lower energy photons, rather than one photon of the original energy as shown in Figure 3.3.

The lower energy photons emitted by the atom have longer wavelengths and smaller frequencies than the absorbed photon. Some toothpaste and detergents contain fluorescent materials, so that human teeth and clothes washed in detergent that contains “whitener" fluoresce when exposed to ultraviolet light. In class you will see examples of materials that fluoresce and ***phosphoresce***. Phosphorescent materials absorb photons of ultraviolet and, after some time delay, emit photons of visible light. This time delay in emitting photons produces an afterglow that can last from a few seconds to many hours.

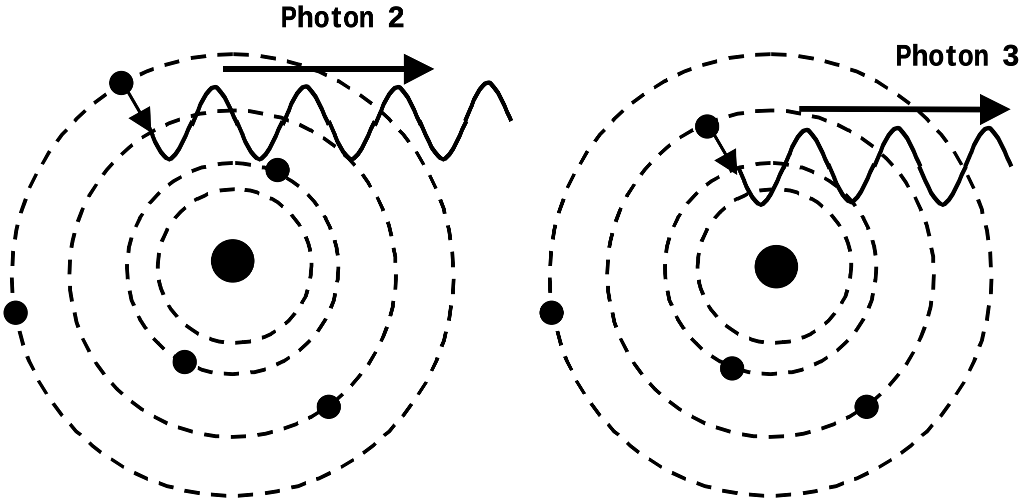
**Figure 3.3 A Sketch of an Atom Fluorescing**



**Time 1: An ultraviolet light photon is absorbed by an electron.**

**Time 2: The electron moves up two energy levels.**

**Figure 3.3, Continued   A Sketch of an Atom Fluorescing**



**Time 3: The electron drops down one one energy level and emits one photon of visible light.**

**Time 4: The electron drops down one more energy level and emits a second photon.**

The law of conservation of energy tells us that the energy of the absorbed ultraviolet photon must equal the sum of the energies of the two emitted visible light photons.

Photons in the ultraviolet region also have enough energy to induce tanning in human skin and can damage the retina of the eye. Sunscreens help to protect skin against harmful effects of ultraviolet radiation. Sunglasses, glasses and even contact lenses can be purchased with ultraviolet filters to absorb the ultraviolet light and help protect your eyes. In fact, sunglasses without UV block can increase the risk of eye damage, because when your pupils open to allow more visible light to enter, more ultraviolet light enters the eye as well.

## 3.2 Information Transfer with Radiant Energy

When radiant energy is transferred, it can carry information. Information transfer is a special case of energy transfer. In this case, the amount of energy transferred is less important than the information that the energy transfers. One of the goals in information transfer is to minimize the amount of energy being transferred without compromising the quality and accuracy of the information transferred. To transfer information, energy must be modulated, or changed, in ways that are meaningful to the sender and to the receiver. This transfer of information is called communication. The information sent is called the signal. Sometimes the radiant energy is referred to as the signal, as in using the phrase “we are receiving a signal from the radio station.” This means that we are receiving radiant energy from the radio station. More often, however, the term ***signal*** means the information contained in the radiant energy.

Since the amount of energy necessary to communicate from one place to another is not fixed, the usual goal in communication is to maximize the transfer of information, while minimizing the energy used for the transfer. Anything unwanted that is sent, or is mixed into the signal during the process of transmission and reception, is called noise. The amount of signal divided by the amount of noise is called the signal-to-noise ratio (SNR). The higher the signal-to-noise ratio in a given information transfer, the less likelihood there is for error (a detectable difference between the signal being sent and the signal being received) in that information transfer. The SNR is defined by the ratio

$$\text{SNR} = \frac{\text{average energy in the signal}}{\text{average energy in the noise}} \qquad \textbf{(Equation 3.1)}$$

**(Example 3.1)**

If the average energy in the noise of a signal is reduced by ½, how does the signal-to-noise ratio (SNR) change?

$$\frac{\text{average energy in the signal}}{\text{average energy in the noise}} = \text{SNR}$$

Using ratio reasoning, we see that if the denominator of a ratio is reduced by a factor of ½, the value of the ratio is increased by the inverse of the factor, or 2.

$$\frac{\text{average energy in the signal}}{\tfrac{1}{2}\ \text{average energy in the noise}} = 2\ \text{SNR}$$

Thus, the signal-to-noise ratio is doubled.

### Communication Involves the Modulation of Energy

When we talk, we produce bursts of energy in the form of sound waves. Modulation, or changing, of the sound is necessary to produce speech. No information is conveyed by a person producing a constant sound, other than the information that the sound is present. If the sender and receiver are sufficiently far apart that they cannot hear one another, they cannot communicate using the energy associated with sound waves. In this situation, some form of electromagnetic energy is often used for communication. Electromagnetic radiation in the form of visible light was used in two of the earliest forms of communication, for example, smoke signals used by Native Americans and signals sent by reflecting light off of shiny surfaces. In 1835 Samuel Morse invented the telegraph, in which an electric current was modulated to send information in the form of dots and dashes. In 1876 Alexander Graham Bell patented the microphone, which converts a sound signal into an electrical signal. An electromagnet can convert the electrical signal back into a sound signal, which is the basis of the telephone.

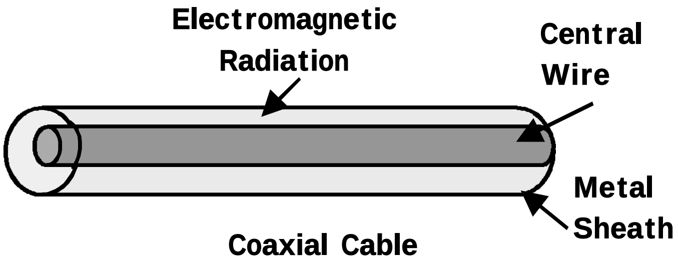
Modern communication utilizes modulated electromagnetic radiation in the form of radio waves for radio and TV broadcasts, microwaves for cellular phones, infrared waves for remote controls, and visible light for fiber optic cables. There are many ways in which the flow of energy can be modulated to transfer information. Two of the most common methods are analog signals and digital signals. An analog signal results when the energy is modulated in a manner such that a change in the energy being transferred is proportional to the amount of the signal being sent – that is, the signal is analogous to the information to be transferred. A good example of an analog signal is an amplitude modulated (AM) radio signal, to be discussed later, or the amount of electric current on the wire connected to your telephone. In class you will see an example of phonograph records that store analog information. Phonograph records were the method of storing sound for about 80 years, until the advent of CD's. They were recorded by having a needle cut a spiral groove from the outside edge of the record to the center. The sound was then recorded as a vibration perpendicular to that groove, the shape and size of the vibration being a direct analog to the sound to be reproduced.

A digital signal is produced by sequentially stopping and starting the energy being transferred. The simplest digital signal is one in which the energy transfer is sequentially turned off or on for a fixed amount of time and is known as a binary digital signal. Computer keyboards work by each key sending a unique combination of binary digital signals. Compact discs and DVD's record information in a binary digital format. Digital signals were used by Morse on his telegraph lines, but because there are so many letters in the alphabet, Morse devised a digital signal consisting of two kinds of "on" signal – a long "on" signal (a dash) and a short "on" signal (a dot). He then made up each of the letters of the alphabet and other necessary symbols as combinations of long and short digital signals. Morse code is still in use and will be demonstrated in class.

Pictures can be transmitted digitally by breaking the image into very small dots, or ***pixels***. The pixels must be sufficiently close together so that when the picture is viewed, the eye blends the pixels to form the picture from which they were created. The signal, from which the picture can be reconstructed, is then transmitted as digital information about how dark or light each pixel should be, as well as the color of the pixel. Cameras for digital photography are based on this principle.

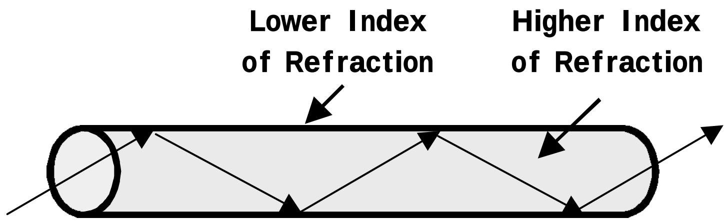
One of the most effective methods of sending signals is by ***coaxial cable***. Coaxial cables are used in television and internet connections. A coaxial cable consists of an insulated central conducting wire surrounded by a conducting tube. Electromagnetic radiation from the broadcasting station or internet provider can move through the cable, even though the cable may have many turns and twists to the television receiver. Since the cable can handle frequencies to 1,000 MHz, it can carry many channels. Coaxial cables require only a very small amount of current to transmit signals because the electromagnetic signal is confined to the space between the central wire and the outer tube, and that space is quite small.

**Figure 3.4 Electromagnetic Radiation Traveling in a Coaxial Cable**



Another recently developed method of transmitting signals uses visible light in ***fiber optic cables***. Such cables send optical signals (light) along a transparent, flexible fiber. The core of each optical fiber has a large index of refraction. The core is wrapped in material that has a lower index of refraction. When the light tries to leave the optical fiber, it is reflected. This process is called ***total internal reflection*** . Fiber optic cables transmit information very efficiently because the walls of the cable reflect light with little energy loss. Fiber optic signals are used in telephone transmission and as optical outputs from digital equipment, such as CD and DVD players.

**Figure 3.5 Total Internal Reflection of Light in an Optical Fiber**



**Many of these optical fibers are combined into a cable.**

## 3.3 Radio and Television Transmission

When sending a signal by electromagnetic radiation, whether using broadcasting, coaxial cable, fiber optic cable, or a beam of light, the signal must be encoded. Encoding converts a message into a code understood by the sender and the receiver. Information transferred from one system to another by electromagnetic radiation is usually encoded on a carrier wave. A ***carrier wave*** is a continuous sine wave of a single amplitude, wavelength and frequency that is sent from the sender to the receiver. The carrier wave is modulated or changed so that the information sent corresponds to the signal being sent. The carrier wave frequency for radio and television broadcasting is the frequency at which the station operates. For example, WOSU AM operates at a frequency of 820 kHz (kilohertz), corresponding to a wavelength of 366 meters. WOSU FM operates at a frequency of 89.7 MHz (megahertz), with a wavelength of 3.34 meters.

**(Example 3.2)**

Verify that the wavelength of WOSU AM's broadcast is 366 meters.

$$S = fL \quad \text{or} \quad L = \frac{S}{f} = \frac{3 \times 10^8 \text{ m/s}}{820 \times 10^3 \text{ 1/s}} = 366 \text{ meters}$$

**Concept Check 3.1**

Verify that WOSU FM, which broadcasts at a frequency of 89.7 MHz, has a wavelength of 3.34 meters.

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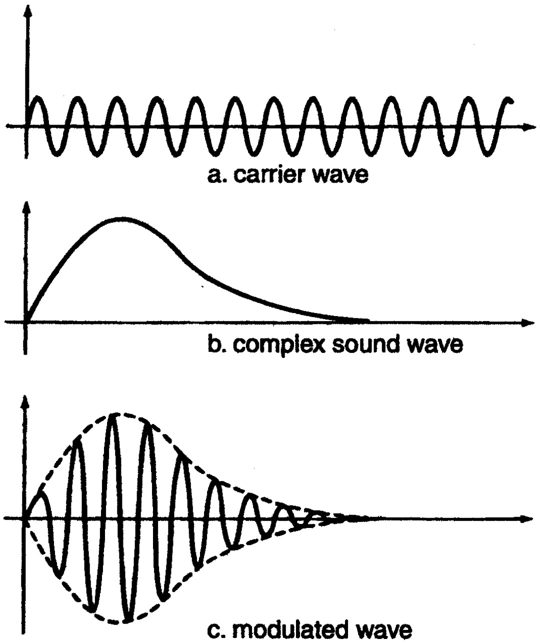
If you do not have cable or satellite television service, when you choose channel 4 you will get channel 4. If you do not have cable or satellite service, channel 4 may be on channel 62. You may wonder why this happens. It is because the carrier wave frequency is often changed by the cable or satellite company. The carrier wave frequency for optical transmission, for example fiber optics, is the frequency of the light used.

### Amplitude Modulation – AM Radio

AM radio operates on the principle of encoding by modulating the amplitude of the carrier wave. Figure 3.6 illustrates a carrier wave whose amplitude has been modulated to encode the signal of a complex sound wave.

**Figure 3.6 Amplitude Modulation**

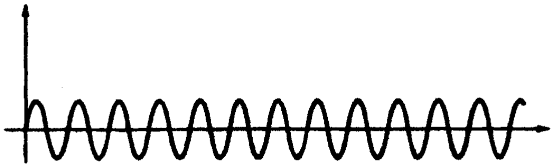


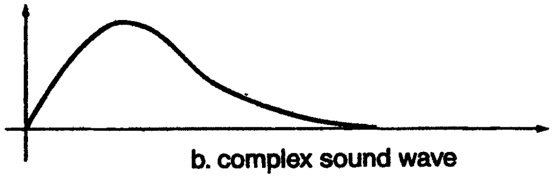
AM broadcasts have several limitations. The amplitude of a carrier wave is subject to disturbance by lightning, which introduces noise into an AM signal. Also, the human ear is capable of hearing a much wider range of frequencies than the range of frequencies that can be used to modulate the amplitude of a radio wave. Therefore, AM radio does not reproduce music and voice with complete fidelity. FM radio was invented to overcome both of these problems. FM broadcasts at a higher frequency to better match the hearing range of the human ear.

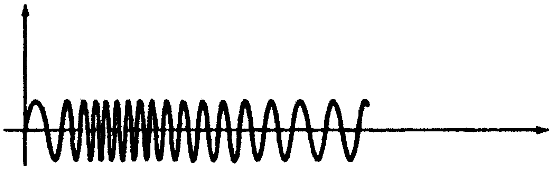
### Frequency Modulation – FM Radio

FM radio operates on the principle of modulating the frequency of the carrier wave rather than modulating the amplitude of the wave. Figure 3.7 illustrates a carrier wave whose frequency has been modulated to encode the signal of a complex sound wave.

**Figure 3.7 Frequency Modulation**


a. carrier wave


b. complex sound wave


c. modulated carrier wave

Because FM radio works on the principle of frequency modulation, the actual frequency of the transmission will vary. Therefore, instead of broadcasting at a single frequency, FM radio broadcasts over a range of frequencies. The range of frequencies over this bandwidth is small compared to the frequency of the FM carrier wave. This means that the FM station can still be assigned a single frequency.

## Period 3 Summary

**3.1:** The sun emits radiant energy at all wavelengths, with most of the radiation emitted in the visible region.

Radiant energy from the sun can be used to produce an electric current in a solar cell. Solar cells (photoelectric cells) make use of the photoelectric effect as photons of radiant energy are absorbed by electrons. A photon of sufficient energy can cause an electron to escape from its atom and generate an electric current.

Radiant energy can be focused by reflecting beams from a mirror or passing beams through a lens. As light travels from one medium to another, it changes speed. If the light does not enter the new medium perpendicular to the boundary, it will change direction as well.

## Period 3 Summary, Continued

Waves of polarized light travel in a single plane. Polarizing filters can block polarized light such as the glare of light reflected from a horizontal surface.

Photons of ultraviolet radiation can cause materials to fluoresce and skin to tan or burn.

**3.2:** Changing, or modulating, energy in a meaningful way transfers information as well as energy. Radio waves are modulated to transfer radio and television signals.

**3.3:** Modulating the amplitude of a carrier wave to encode information produces AM signals. Modulating the frequency of a carrier wave produces FM signals.

## Period 3 Exercises

E.1 If a solar cell produces electricity when illuminated with green light, identify all of the following types of radiation that will definitely produce electricity using the same cell. How can you tell?

a) red light
b) blue light
c) ultraviolet light
d) radio waves
e) infrared radiation

E.2 The part of the electromagnetic spectrum that causes tanning is

a) the infrared.
b) the ultraviolet.
c) the yellow end of the visible spectrum.
d) radio waves.
e) All of the above cause tanning.

E.3 Which of the following statements about infrared radiation and ultraviolet radiation is **TRUE**?

a) Energy can be transferred by infrared radiation but not by ultraviolet radiation.
b) The sun emits infrared radiation but not ultraviolet radiation.
c) An ultraviolet photon carries more radiant energy than an infrared photon.
d) Ultraviolet radiation has a longer wavelength than infrared radiation.
e) In vacuum, ultraviolet radiation travels at a greater speed than infrared radiation.

E.4 A signal with an average energy of 4,000 joules has a signal-to-noise ratio of 200. The average energy of the noise is then reduced so that it is 4 times smaller. What is the new signal-to-noise ratio?

a) 20
b) 50
c) 200
d) 800
e) 1,000

E.5 In broadcasting, the term “carrier wave” refers to the sine wave being sent out from a radio station at its operating frequency. Which of the following techniques could be used to encode a signal on a carrier wave?

a) modulation of the amplitude of the carrier wave
b) modulation of the frequency of the carrier wave
c) modulation of the speed of the carrier wave
d) Either a) and b) could be used to encode a signal.
e) All of the above techniques could be used to encode a signal.

E.6 A radio station broadcasts at a frequency of 105.7 megahertz (MHz). What is the wavelength of the station’s carrier wave?

a) 0.35 meters
b) 2.8 meters
c) 5.6 meters
d) 28 meters
e) 105.7 meters

E.7 You are attending a concert and have a seat at the back of the auditorium. Your friend is listing to the same concert on her radio at home, 50 miles from the concert hall. If there is no delay in the broadcast of the concert, who do you think hears the sound first?

## Period 3 Review Questions

R.1 You have a strong source of microwave radiation and a very weak source of ultraviolet radiation. When you shine the microwaves on a solar cell no current is produced but when the ultraviolet light is used a current is produced. How can you explain this phenomenon?

R.2 Why do you think it is unsafe to leave glass soft drink bottles in a forest?

R.3 Microwave manuals tell owners that they can test dishes to see if they will work in the microwave by filling them with water and putting them in the microwave for a certain length of time. If the water gets hot, and the dish does not, then the dish is safe to use. Explain this.

R.4 Describe one difference between information transfer using electrical energy and using radiant energy. Give examples of each type of information transfer.

R.5 How does an AM radio signal differ from an FM signal? Does an AM or FM signal contain photons with greater energy per photon? Which signal uses radio waves of a longer wavelength? Which signal uses radio waves with a higher frequency?