Chapter 2: Electromagnetic Radiation – Radiant Energy I

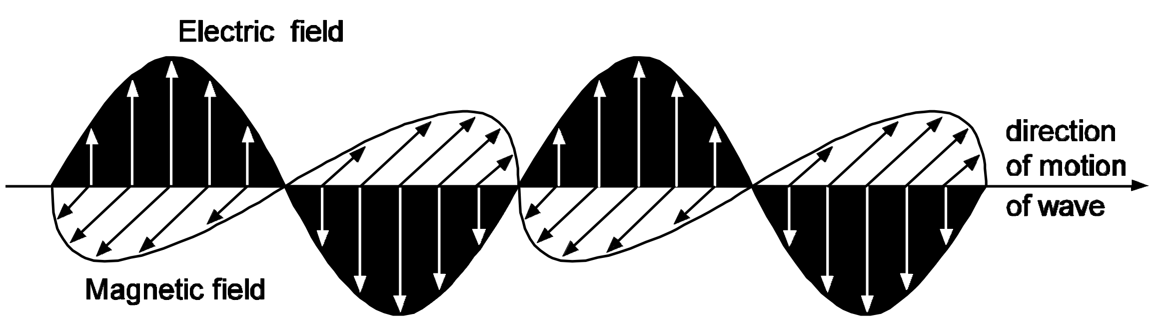
Goals of Period 2

Section 2.1: To introduce electromagnetic radiation
Section 2.2: To discuss the wave model of radiant energy
Section 2.3: To describe the electromagnetic spectrum
Section 2.4: To discuss the quantum model of radiant energy

2.1 Introduction to Radiant Energy

Electromagnetic radiation, which is the basis of this period, is one form of radiant energy. Visible light is an example of electromagnetic radiation. In Physics 103 you learned that a moving charge (an electric current) is surrounded by a magnetic field. A change in this magnetic field generates an electric field. We called this electromagnetic induction. Changing electric fields are always accompanied by a changing magnetic field and vice versa. These changing fields allow a changing current in a wire or a moving charge to produce electromagnetic radiation, which is a source of energy. The electromagnetic radiation moves outward from the source as long as the energy that causes the charge to move is present. Figure 2.1 illustrates waves of electromagnetic radiation.

Figure 2.1 Electromagnetic Radiation Wave



You have already seen that the electric field associated with electromagnetic radiation exerts a force on a charge. This fact is used in many devices. Almost every day we experience an example in antennas used for radio, telephone, or television. As we will discuss in Period 3, electrons in a broadcasting antenna are made to move with some frequency. ***Frequency*** describes how often something repeats a ***cycle***. In this case, the frequency of the electromagnetic radiation being broadcast is the same as the frequency that describes how often the electrons in the broadcasting antenna vibrate per second. The electric field of the broadcast electromagnetic radiation exerts a force on the charges in the receiving antenna, causing those electrons to move with the same frequency. In other words, the current in one antenna induces a current in the other antenna, even though the antennas may be miles apart.

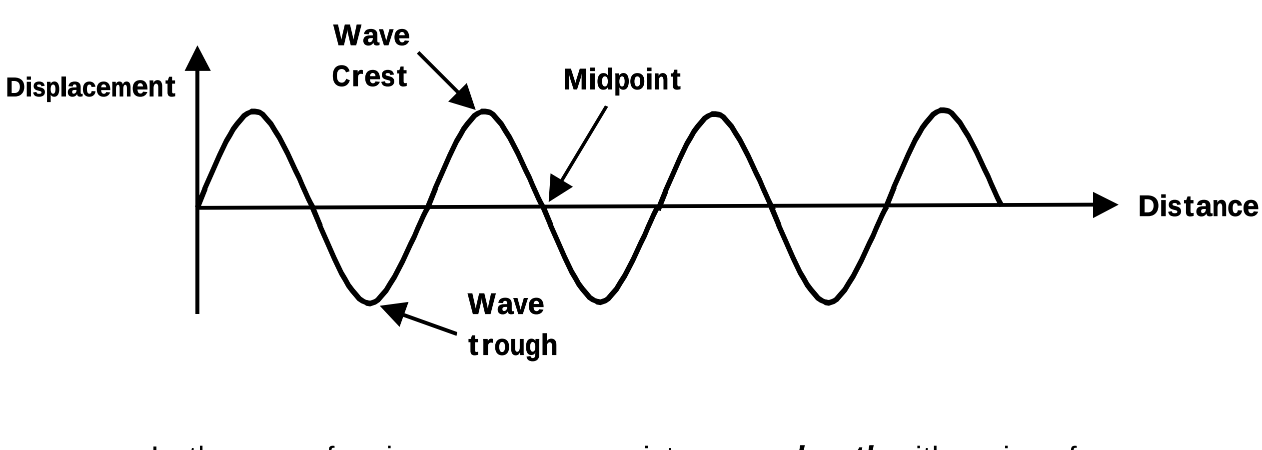
As discussed above, the electrons in the receiving antenna move, so they must experience a force that produces the motion. Thus we know that energy is transferred from the broadcasting antenna to the receiving antenna. In order to be transferred, this energy must be associated with the electromagnetic radiation. We will use the term ***radiant energy*** to refer only to energy associated with and transferred by electromagnetic radiation.

The radiant energy from the broadcasting antenna does not reach the receiving antenna instantaneously. Rather, it travels at a finite, although very fast, speed. The distances in the classroom are too small to be able to measure this effect, but you may have noticed it if you have listened to communications between people on the earth and on the space shuttle or to a live news broadcast from overseas. The speed at which radiant energy travels depends on the medium that it is passing through, but in a vacuum it is about 3×10^8 meters per second, or 186,000 miles per second. This speed is true for all frequencies of radiant energy. This constant speed, usually referred to as the speed of light, is given the symbol c, that appears in Einstein's famous equation $E = m c^2$, which we will study later this quarter.

2.2 The Wave Model of Radiant Energy

One of the ways to transfer energy without the transfer of mass is to produce a wave. A wave can be a pulse, as in the pulse of sound made by clapping your hands together. Another example of a pulse is a tsunami, a tidal wave of energy that travels many miles over an ocean. But many waves are generated by a cyclic vibration of some given frequency. This type of wave is referred to as a ***sine wave***. Sine waves are used to describe many features of radiant energy. We will use the term ***electromagnetic wave*** to refer to a model that describes radiant energy in terms of sine waves. In Section 2.4 we will discuss the quantum model of radiant energy. Figure 2.2 illustrates sine waves.

Figure 2.2 Sine Waves



In the case of a sine wave, we associate a ***wavelength*** with a given frequency. The wavelength is the distance between two adjacent crests of a wave or two adjacent troughs of a wave. All sine waves, regardless of the frequency of the wave, obey the relationship

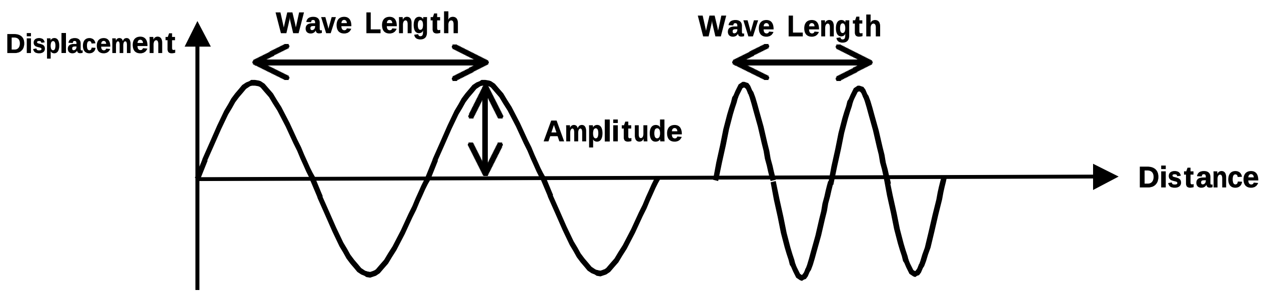
$$s = f L \qquad \text{(Equation 2.1)}$$

where

s = speed at which radiant energy travels (meters/sec or feet/sec)
f = frequency (cycles/sec, or Hertz)
L = wavelength (in meters or feet)

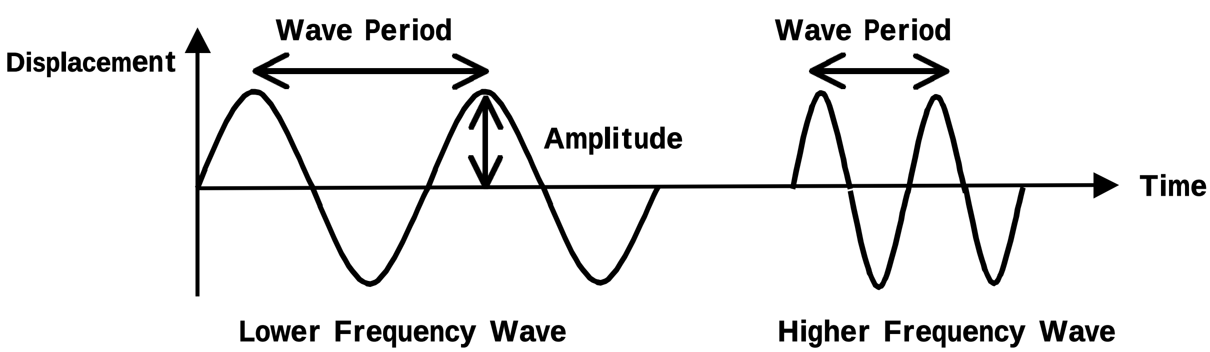
A wave also has an ***amplitude***, which is the maximum height or displacement of the crest of the wave shown in Figure 2.3 above or below its midpoint.

Figure 2.3 Wavelength and Amplitude



The crest of the longer wavelength of the two waves shown in Figure 2.2 travels past a given point less frequently during a specified period of time than the crest of the shorter wavelength wave. Therefore, the longer wavelength wave has the lower frequency and the shorter wavelength wave has the higher frequency, as shown in Figure 2.3. The horizontal axis of Figure 2.4 is the time measured at any given point on the horizontal axis of Figure 2.3.

Figure 2.4 Wave Frequency and Period



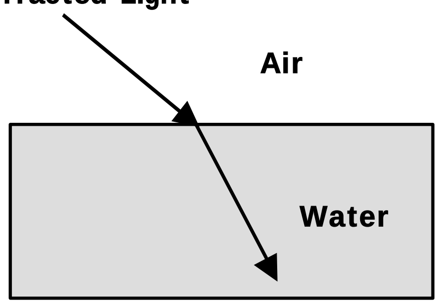
The time that it takes for a wave to go through one complete cycle is called the ***period*** of the wave. The shorter the period, the more cycles the wave completes in a given amount of time, and thus the higher its frequency. This can be expressed by the relation given by Equation 2.2.

$$\textit{frequency} = 1 / \textit{period} \qquad \textbf{(Equation 2.2)}$$

Since the period of a wave is expressed in seconds, the frequency of the wave is expressed in 1/seconds, to which we assign the name Hertz (Hz).

All electromagnetic radiation, regardless of its source, is characterized by a frequency associated with the source and with the radiation. The wave model can describe electromagnetic radiation as sine waves of a given wavelength and frequency. Regardless of their wavelength and frequency, all waves of electromagnetic radiation travel at the same speed in a vacuum, 3×10^8 meters per second, the speed of light. However, light travels at different speeds in different materials. When light enters a transparent material, the speed of the wave changes and the light beam is ***refracted***, or bent, as shown in Figure 2.5

Figure 2.5 Refracted Light



The ratio of the speed of light in a vacuum to the speed of light in a material is called the ***index of refraction***. The index of refraction is a measure of the amount that a light beam is bent as it passes from one medium to another medium. Equation 2.3 expresses the index of refraction as a ratio. Because an index of refraction is the ratio of two quantities of the same kind, there are no units associated with an index of refraction.

$$n = \frac{\text{speed of light in a vacuum}}{\text{speed of light in material}} \qquad \textbf{(Equation 2.3)}$$

The speed of light in a vacuum is always 3×10^8 m/s. A beam of white light is made up of light with many frequencies. The speed of each frequency of light is different when it travels through a medium. Thus, red light bends (refracts) less than blue light. When calculating the index of refraction using Equation 2.3, it is the average speed of the light in the material that is used. Table 2.1 gives the average indices of refraction for some common materials.

Table 2.1 Average Indices of Refraction

Medium	Index of Refraction		Medium	Index of Refraction
Vacuum	1.0000		Glass	1.52
Air	1.0003		Plexiglas	1.51
Diamond	2.42		Water	1.33

(Example 2.1)

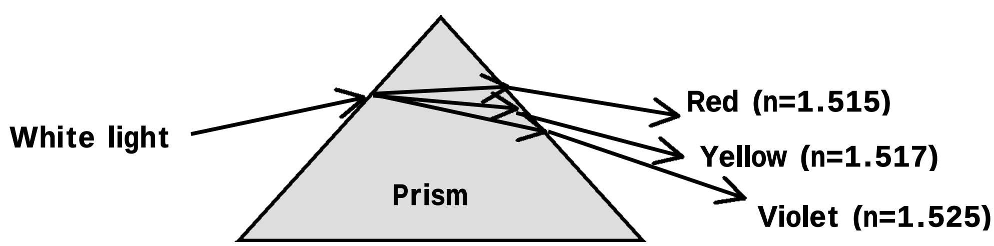
Light travels in a diamond at a speed of 1.24 x 10^8 meters/second. What is the index of refraction of light in a diamond?

$$\mathbf{n = \frac{speed\ of\ light\ in\ vacuum}{speed\ of\ light\ in\ diamond} = \frac{3 \times 10^8\ m/s}{1.24 \times 10^8\ m/s} = 2.42}$$

As discussed earlier, electromagnetic waves are unique in that they can travel through a vacuum, and all do so with the same speed (3 x 10^8 m/s). Other types of waves, such as sound waves, must travel through a medium such as air or water. Sound waves travel at varying speeds, for example at 343 m/s in dry air at room temperature and at 1,440 m/s in water.

The amount that light is refracted depends on the frequency of the light wave. When light passes through a prism, the waves with the highest frequency are refracted more than waves of lower frequency. This difference in refraction separates the light into a rainbow of colors.

Figure 2.6 A Prism Refracts Light



The difference between the speed of red light and violet light is greatest for materials with the largest index of refraction. For this reason, a well-cut diamond is very effective in breaking light up into colors. The best cut for this purpose is known as a brilliant cut.

2.3 The Electromagnetic Spectrum

All electromagnetic waves are the same, though they may differ in wavelength and frequency. The electromagnetic spectrum can be divided into regions according to wavelength or frequency. These regions are named radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays.

The classifications of some regions of the spectrum are identified by the way that the waves interact with matter. For example, because the typical human eye can see over a certain range of wavelengths, we call that region visible light. Names of other regions of the spectrum are historical. When X-rays were discovered, they were called X-rays because it was not yet known that they were electromagnetic radiation. Next we discuss properties of the various regions of the electromagnetic spectrum, starting with the longest wavelengths and lowest frequencies.

Radio Waves

The longest wavelength region of the spectrum is ***radio waves.*** They have wavelengths longer than a meter and frequencies lower than about 1×10^8 Hertz. (Radio wave frequencies are often given in megahertz or kilohertz. A megahertz is abbreviated MHz, and is equal to 1×10^6 Hz. A kilohertz is abbreviated kHz, and is equal to 1×10^3 Hz.)

Microwaves

The next region is the ***microwave*** region of the spectrum. Microwaves have wavelengths of a meter to a few millimeters, and frequencies from about 1×10^8 to 1×10^{11} Hz. You have probably used microwave ovens. Some garage door openers use microwaves. You may also have seen microwave relay stations used by the telephone company for transmission of information over long distances. A small scale microwave generator and receiver will be demonstrated in the classroom.

Infrared Radiation

The region of the spectrum with wavelengths from several millimeters down to about 7×10^{-7} meters (and frequencies from 1×10^{11} to 4.3×10^{14} Hz) is called the ***infrared*** region. The fact that radiant energy is present in this region of the spectrum can be illustrated by using a radiometer. We find that the radiometer vanes rotate when exposed to infrared radiation. Another type of device for detecting radiation in the infrared is the photoelectric infrared imaging device. The sniper scope, a particular example of this type of device, will be demonstrated in class. Television remote controls use radiation in this frequency range. The nerves of our skin are sensitive to some of the infrared portion of the spectrum.

Visible Light

Visible light ranges in wavelength from 4×10^{-7} meters (violet light) to 7×10^{-7} meters (red light). Our eyes do not respond to wavelengths outside this small portion of the electromagnetic spectrum. Within this region, our eyes respond to different wavelengths as different colors. In class, we will use prisms and diffraction gratings to separate white light into the colors of the visible spectrum.

Ultraviolet Radiation

Wavelengths of ***ultraviolet radiation*** extend from the short wavelength end of the visible spectrum (4×10^{-7} meters) to wavelengths as small as 1×10^{-9} meters. The frequencies range from 7 x 10^{14} Hz to about 3 x 10^{17} Hz. Ultraviolet radiation can induce fluorescence and can cause tanning in human skin.

X–rays

Even shorter wavelengths (down to about 1 x 10^{-11} meters) are the ***X-ray*** region. Frequencies in this region extend from 3 x 10^{17} Hz to about 3 x 10^{19} Hz. X-rays have a number of industrial and medical uses, which are associated with the ability of X-rays to penetrate matter. X-rays pass through flesh but are absorbed by bone; thus, X-ray photographs can show bone structure and assist the medical profession in diagnosis.

Gamma Rays

Electromagnetic waves with wavelengths shorter than about 1 x 10^{-11} meters and frequencies above 3 x 10^{19} Hz are called ***gamma rays***. They may be produced by nuclear reactions and will be discussed further in the period on nuclear energy.

2.4 The Quantum Model of Radiant Energy

While many properties of radiant energy are explained by the electromagnetic wave model, some are not. These properties can be explained by a different model, called the ***quantum model***. This model treats radiant energy as being composed of small packets of energy called ***photons***, or ***quanta***. As radiant energy interacts with matter, it absorbs or deposits energy in amounts that are integer multiples of this photon energy. The photon energy can be related to frequency or wavelength by the relation shown in Equation 2.4.

$$E = h f = (h c)/L \qquad \textbf{(Equation 2.4)}$$

where

E = energy of a photon (joules)

h = is a proportionality constant = 6.63 x 10^{-34} joule sec

f = frequency (Hertz)

c = speed of the radiant energy = 3 x 10^{8} meters/sec in a vacuum

L = wavelength (meters).

From these equations, the higher the frequency or the shorter the wavelength, the higher the energy of the photon. The fact that two different models are needed to describe electromagnetic radiation has bothered people for a long time. It is an indication that we still do not have a full understanding of this phenomenon.

(Example 2.2)

What is the wavelength of a photon with an energy of 5 x 10^{-20} J?

$$E = \frac{h c}{L} \qquad L = \frac{h c}{E}$$

$$= \frac{(6.63 \text{ x } 10^{-34} \text{ J s}) \text{ x } (3 \text{ x } 10^{8} \text{ m / s})}{5 \text{ x } 10^{-20} \text{ J}} = 4.0 \text{ x } 10^{-6} \text{ m}$$

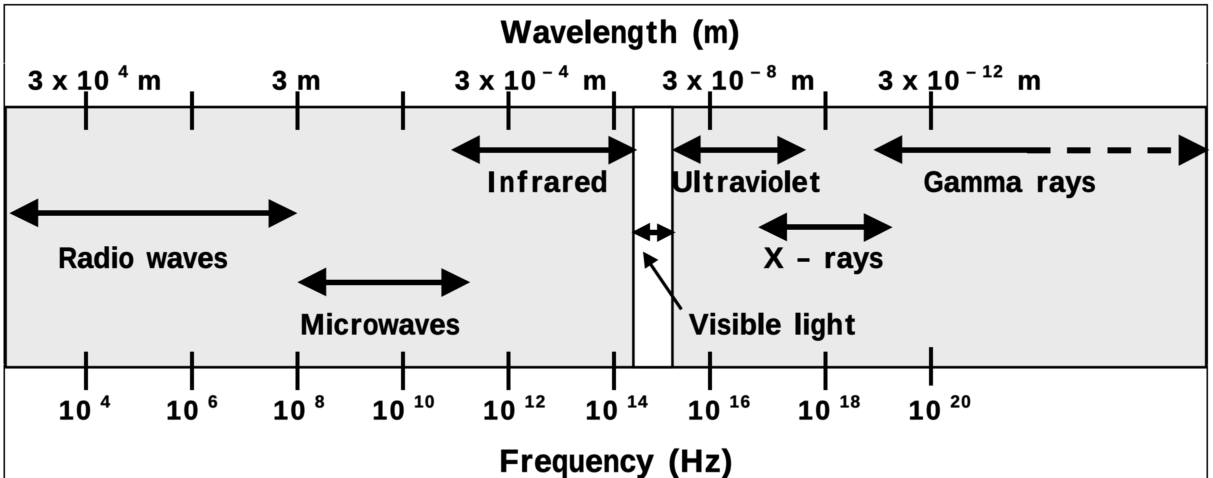
Concept Check 2.1

a) What is the wavelength of radiant energy with a frequency of 2×10^{9} Hz? __________

b) How much energy does each photon of this radiant energy have? __________

Table 2.2 shows the relationship between the wavelength, frequency, and photon energy for radiant energy.

Table 2.2: The Electromagnetic Spectrum



Type of Radiant Energy	Wavelength Range (meters)	Frequency Range (Hertz)	Photon Energy Range (joules)
Radio waves	longer than a meter	below about 1×10^{8} Hz	below about 6.6×10^{-26} J
Microwaves	a meter down to a few millimeters	about 1×10^{8} Hz to 1×10^{11} Hz	about 6.6×10^{-26} J to 6.6×10^{-23} J
Infrared	a few millimeters to 7×10^{-7} meters	about 1×10^{11} Hz to 4.3×10^{14} Hz	about 6.6×10^{-23} J to 2.8×10^{-19} J
Visible light	7×10^{-7} meters to 4×10^{-7} meters	about 4.3×10^{14} Hz to 7.5×10^{14} Hz	about 2.8×10^{-19} J to 5×10^{-19} J
Ultraviolet	4×10^{-7} meters to about 1×10^{-9} meters	about 7×10^{14} Hz to 3×10^{17} Hz	about 4.6×10^{-19} J to 2×10^{-16} J
X-rays	1×10^{-9} meters to about 1×10^{-11} meters	about 3×10^{17} Hz to 3×10^{19} Hz	about 2×10^{-16} J to 2×10^{-14} J
Gamma rays	shorter than about 1×10^{-11} meters	above about 3×10^{19} Hz	above about to 2×10^{-14} J

Period 2 Summary

2.1: Electrons moving with some frequency produce electromagnetic radiation, or radiant energy. This energy is associated with an electromagnetic field.

Radiant energy of any frequency travels in a vacuum at 3×10^8 meters per second, or 186,000 miles per second. This constant is known as the speed of light and is given the symbol ***c***.

2.2: Radiant energy can be thought of as a wave with a wavelength and frequency. The speed of a wave = frequency x wavelength: $s = f\ L$

As light passes from one medium to another it is refracted, or bent.

Light travels at 3.0×10^8 m/s in a vacuum, but travels at different speeds in materials such as in water or glass. The ratio of these speeds is the index of refraction, n, of the material.

$$n = \frac{\text{speed of light in a vacuum}}{\text{speed of light in a material}}$$

2.3: The electromagnetic spectrum can be divided into types of radiant energy based on the wavelength or frequency of the radiation: radio waves, microwaves, infrared radiation, visible light, ultraviolet light, X–rays, and gamma rays.

2.4: An explanation of electromagnetic radiation also requires the quantum model, which treats radiant energy as consisting of small packets of energy called photons.

Photon energy is related to frequency or wavelength by the relation:

$$E = h\,f = (h\,c)/L$$

Period 2 Exercises

E.1 Each of the following travels, in a vacuum, at the speed of light except

a) radio waves
b) sound waves
c) X-rays
d) infrared rays
e) All of the above travel at the speed of light.

E.2 Which of the following does NOT make use of wave motion?

a) A bowling ball strikes a bowling pin.
b) A radio plays music transmitted from a radio station.
c) A microwave oven heats a slice of pizza.
d) Jane is reading by the light of an incandescent lamp.
e) A tennis ball floating on the river bobs up and down as a boat passes by.

E.3 Estimate the wavelength of a 1500 Hz sound wave. What would be the wavelength of an electromagnetic wave of the same frequency?

a) 0.23 m; 5×10^{-6} m
b) 0.23 m; 2×10^{5} m
c) 4.4 m; 5×10^{-6} m
d) 4.4 m; 2×10^{5} m
e) 8.8 m; 6.2×10^{5} m

E.4 The index of refraction of a piece of glass is 1.5. What is the speed of the photons of light in this glass?

a) 2×10^{8} m/s
b) 3×10^{8} m/s
c) 4.5×10^{8} m/s
d) The speed depends on the period of the electromagnetic wave.
e) The speed depends on the frequency of the wave.

E.5 Which of the following sequences has the various regions of the electromagnetic spectrum arranged in order in increasing wavelength?

a) infrared, visual, ultraviolet, gamma ray
b) radio, infrared, ultraviolet
c) ultraviolet, visual, microwave, radio
d) X-ray, visual, microwave, infrared
e) gamma ray, X-ray, microwave, visual

E.6 In a vacuum, microwaves travel ________ waves of visible light.

a) faster than
b) slower than
c) at the same speed as

E.7 Which of the following statements about the microwaves used in microwave ovens is **not** correct?

a) Microwaves are electromagnetic radiation.
b) Microwaves are the same wavelength as waves used in radio broadcasting.
c) Microwaves have wavelengths longer than those of visible light.
d) Microwaves heat food by the conversion of radiant energy into thermal energy.
e) All of the statements are correct.

E.8 How many photons of wavelength 6×10^{-5} meters are required to produce electromagnetic radiation with 3.32×10^{-15} joules of energy?

a) 1×10^{-6} photons
b) 1×10^{3} photons
c) 1×10^{6} photons
d) 5×10^{6} photons
e) 1×10^{14} photons

Period 2 Review Questions

R.1 What is the source of radiant energy?

R.2 How are the forms of radiant energy associated with the electromagnetic spectrum similar? How do they differ?

R.3 Give an example of each of the forms of radiant energy.

R.4 How can you find the energy of a photon of radiant energy?

R.5 Compare the speed of sound to the speed of light in air. What is the ratio of the speed of sound to the speed of light?