Chapter 1: The World of Energy, Introduction to Physics 104

Goals of Period 1

Section 1.1: To describe course requirements for Physics 104
Section 1.2: To review the use of ratios
Section 1.3: To review scientific notation
Section 1.4: To review linear and exponential growth
Section 1.5: To review electromagnetic energy
Section 1.6: To define radiant energy
Section 1.7: To describe the electromagnetic spectrum

1.1 Physics 104: The World of Energy, Part II

The World of Energy courses, Physics 103 and 104, are a 10-credit hour, two-quarter sequence. The courses explore the basic principles of physics in the context of energy use. The courses include practical examples from everyday life to help you use energy safely and wisely. They help prepare you to make rational, informed decisions regarding energy policy, the environment, and your own place in the changing World of Energy.

Class Activities

During two, 2-hour classes per week, your instructor will explain physics concepts and introduce hands-on activities and demonstrations to illustrate these concepts. To help organize, understand, and remember the information from the demonstrations and class activities, students complete and turn in activity sheets during each class. Activity sheets are found in Part I of the *Physics 104 Activity Book*. Students must be present for the full class period to receive credit for an activity sheet, unless excused by the instructor.

Lectures

In addition to attending two 2-hour classes per week, students attend a 1-hour lecture. At most lectures, you will see a video or hear a speaker discussing energy use. These videos and lectures are an important part of the course. They explain physics principles and help relate these principles to the role of energy in everyday life. A list of questions for each video is included in Part II of the *Physics 104 Activity Book.* These questions help students identify important concepts in the videos. Answers to these video questions are not handed in. Instead, students write and turn in a summary of each lecture video of at least two paragraphs. The dates and location of the lectures are given in the course syllabus. Midterm and final exams will include questions based on the material in the lectures.

Examinations

Course examinations consist of two midterms of 30 questions each and a comprehensive final examination of 45 questions. All exam questions are multiple choice. Midterm exams are given during the lecture hour. The dates of the examinations are listed in the course syllabus. **No** make-up examinations will be given. If you have a conflict with any of the exam times, notify your instructor immediately.

Students may use calculators during exams, but may not program them or use their graphing capabilities. Cell phones, pagers, and other such devices must be turned off during exams. Exams include a sheet with useful equations and constants. Equation sheets are provided because the World of Energy emphasizes understanding concepts, rather than memorizing equations and constants. However, it is essential that students understand the meaning of the equations, their symbols, and their units. Appendix A of the *Physics 104 Textbook* lists the equations used in Physics 103. Part III of the *Physics 104 Activity Book* contains six practice exams with equation sheets. The textbook provides help in understanding equations and solving problems in the Skills and Strategies and Concept Check solutions.

How to Succeed in The World of Energy

In the World of Energy, students learn physics concepts primarily by doing activities in class, observing instructor demonstrations, and participating in class discussions. While your textbook contains important information and should be read before each class, it does not provide all the information you will need – some physics concepts have been left for you to discover in your classroom activities. *Therefore, class attendance and active participation are very important*.

In the World of Energy we will explore different forms of energy and the many ways in which energy is used to do work. We begin by discussing some of the mathematical tools used in the course.

1.2 Review of Ratios

To simplify comparisons among quantities, information is often presented as a ratio. A ratio is a fraction – or one quantity divided by another quantity. The word ***per*** means *for each* and designates a ratio.

Ratios and Efficiency

One common use of ratios is to represent the efficiency of an energy conversion process. The efficiency of an energy conversion process is the ratio of the amount of energy of the desired type produced divided by the total amount of energy put into the conversion process. This ratio may be expressed as a fraction, as a decimal, or as a percent. Equation 1.1 below and Figure 1.1 on the next page describe this relationship.

$$\text{Efficiency} = \frac{\text{Useful Energy Out}}{\text{Total Energy In}} \qquad \textbf{(Equation 1.1)}$$

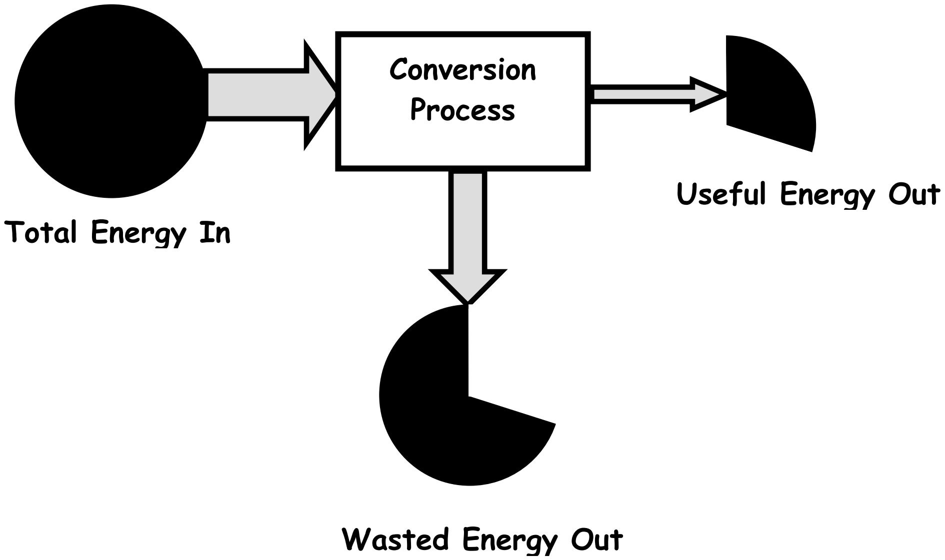
When a series of energy conversions is required to produce the desired form of energy, energy is wasted in each step of the process. The overall efficiency of a series of energy conversion processes can be quite low. The overall efficiency is the product of the efficiencies of each step in the process.

$$\text{Overall Efficiency} = (\text{Efficiency of step 1}) \times (\text{Efficiency of step 2}) \times (\text{Efficiency of step 3}) \times \ldots$$

or $$\text{Overall Efficiency} = = \text{Efficiency}_1 \times \text{Efficiency}_2 \times \text{Efficiency}_3 \times \ldots..$$

Efficiencies given as a percent must be converted to a decimal before performing the multiplication indicated above.

Fig. 1.1 Efficiency of an Energy Conversion



Total Energy In = Useful Energy Out + Wasted Energy Out

Ratios and Unit Conversions

Another important use of ratios is for converting a quantity from one unit into another. Ratios formed from any two equivalent quantities, such as 60 min = 1 hour or 365 days = 1 year are just another way of writing unity, or one, and can be used to convert units. Multiplying a quantity by such a ratio does not change the value of the quantity, but merely changes the units in which that value is expressed. For example, to convert from hours to minutes, use a ratio to cancel the unit you wish to eliminate.

$$3\ \cancel{\text{hours}}\ \text{x}\ \frac{60\ \text{min}}{1\ \cancel{\text{hour}}} = 180\ \text{min}$$

(Example 1.1)

There are 1,609 meters per 1 mile. Use ratios to convert 60 miles per hour into meters per second.

$$\frac{60\ \cancel{\text{miles}}}{1\ \cancel{\text{hour}}}\ \text{x}\ \frac{1{,}609\ \text{meters}}{\cancel{1\ \text{mile}}}\ \text{x}\ \frac{1\ \cancel{\text{hour}}}{60\ \cancel{\text{min}}}\ \text{x}\ \frac{1\ \cancel{\text{min}}}{60\ \text{sec}} = \frac{27\ \text{meters}}{1\ \text{sec}} = 27\ \text{meters/sec}$$

Ratios Reasoning

Ratio reasoning is a powerful mathematical tool that allows you to write equations using ratios to solve everyday problems by making the equation yourself. To use ratios in this way, units must be included with each quantity.

To calculate the cost of electricity from an electric bill, use ratios to cancel all units except the one you wish to use to express the result of your calculation. Remember that power is the energy or work transferred divided by the time required, as shown in Equation 1.2.

$$P = \frac{E}{t} = \frac{W}{t}$$ **(Equation 1.2)**

(Example 1.2)

Given kilowatt-hours (kWh) and cost per kilowatt-hour, find the total cost.

$$0.44\ \cancel{\text{kWh}} \times \frac{\$0.075}{\cancel{\text{kWh}}} = \$0.033$$

Given the total cost and the kilowatt-hours of use, find the cost per kWh.

$$\$0.033 \times \frac{1}{0.44\text{ kWh}} = \frac{\$0.075}{\text{kWh}}$$

Given the total cost and the cost per kilowatt-hour, find the kilowatt-hours used.

$$\cancel{\$}\,0.033 \times \frac{\text{kWh}}{\cancel{\$}\,0.075} = 0.44\text{ kWh}$$

Ratio reasoning can also be used to determine whether the additional cost of purchasing an energy-efficient compact fluorescent light bulb is paid back through savings in operating costs.

(Example 1.3)

A 25 watt CF bulb costs $5 to purchase and lasts for 10,000 hours. A 75 watt incandescent bulb, which produces about the same amount of light, costs $0.50 to purchase and lasts for about 750 hours. If electricity costs 8.5 cents per kilowatt-hour, what is the cost of purchasing and operating each type of bulb for 10,000 hours?

$$\text{Total Cost} = \left(\frac{\text{cost}}{\text{kWh}} \times \text{kWh used}\right) + \text{purchase price}$$

Compact Fluorescent Bulb

Operating cost of CF bulb:

$$25\ \cancel{\text{watts}} \times \frac{1\ \text{k}\cancel{\text{ilowatt}}}{1{,}000\ \cancel{\text{watts}}} \times 10{,}000\ \cancel{\text{hours}} \times \frac{\$0.085}{\cancel{\text{kilowatt hour}}} = \$21.25$$

Purchase price of CF bulb = $5.00

Total cost for 10,000 hours use of CF bulb = $21.25 + $5.00 = $26.25

Incandescent Bulb

Operating cost of incandescent bulb:

$$75\ \cancel{\text{watts}} \times \frac{\cancel{1\ \text{kilowatt}}}{1{,}000\ \cancel{\text{watts}}} \times 10{,}000\ \cancel{\text{hours}} \times \frac{\$0.085}{\cancel{\text{kilowatt hour}}} = \$63.75$$

Number of bulbs needed: $$10{,}000\ \cancel{\text{hours}} \times \frac{1\text{ bulb}}{750\ \cancel{\text{hours}}} = 14\text{ bulbs}$$

Purchase price of incandescent bulbs: $14\ \cancel{\text{bulb}}\text{s} \times \frac{\$0.50}{\cancel{\text{bulb}}} = \$7.00$

Total cost for 10,000 hours use of incandescent bulbs = \$63.75 + \$7.00 = \$70.75

Therefore, the compact fluorescent bulb saves \$70.75 - \$21.25 = \$49.50

1.3 Review of Scientific Notation (Powers of Ten)

A number in ***scientific notation*** is written as a number with one digit to the left of the decimal point times 10 raised to an exponential power. When any number is raised to an exponential power, that number is called the base. Scientific notation uses the base 10 and is sometimes called ***powers of 10*** notation. Scientific notation is useful when considering very large or very small numbers.

Mass of the Earth = 5.98×10^{24} kg

Universal gravitational constant, G = $6.67 \times 10^{-11}\ \text{N m}^2/\text{kg}^2$

Radius of a proton = 1×10^{-15} m

When converting any number to scientific notation, the exponent of base 10 is found by counting the number of places the decimal point is shifted to the left for positive exponents or shifted to the right for negative exponents. A positive exponent of 10 indicates how many times the base 10 is multiplied by itself. A negative exponent indicates how many times 1 is divided by 10. Any number to the power zero equals one.

$$10^2 = 10 \times 10 = 100$$

$$10^1 = 10$$

$$10^0 = 1$$

$$10^{-1} = 1/10 = 0.1$$

$$10^{-2} = 1/(10 \times 10) = 0.01$$

Table 1.1: Rules for Using Scientific Notation

1. When multiplying powers of 10, add their exponents.

   $$\mathbf{10^A \times 10^B = 10^{(A + B)}}$$

2. When dividing powers of 10, subtract their exponents.

   $$\mathbf{10^A / 10^B = 10^{(A - B)}}$$

3. When raising a power of 10 to a power, multiply the exponents.

   $$\mathbf{(10^A)^B = 10^{(A \times B)}}$$

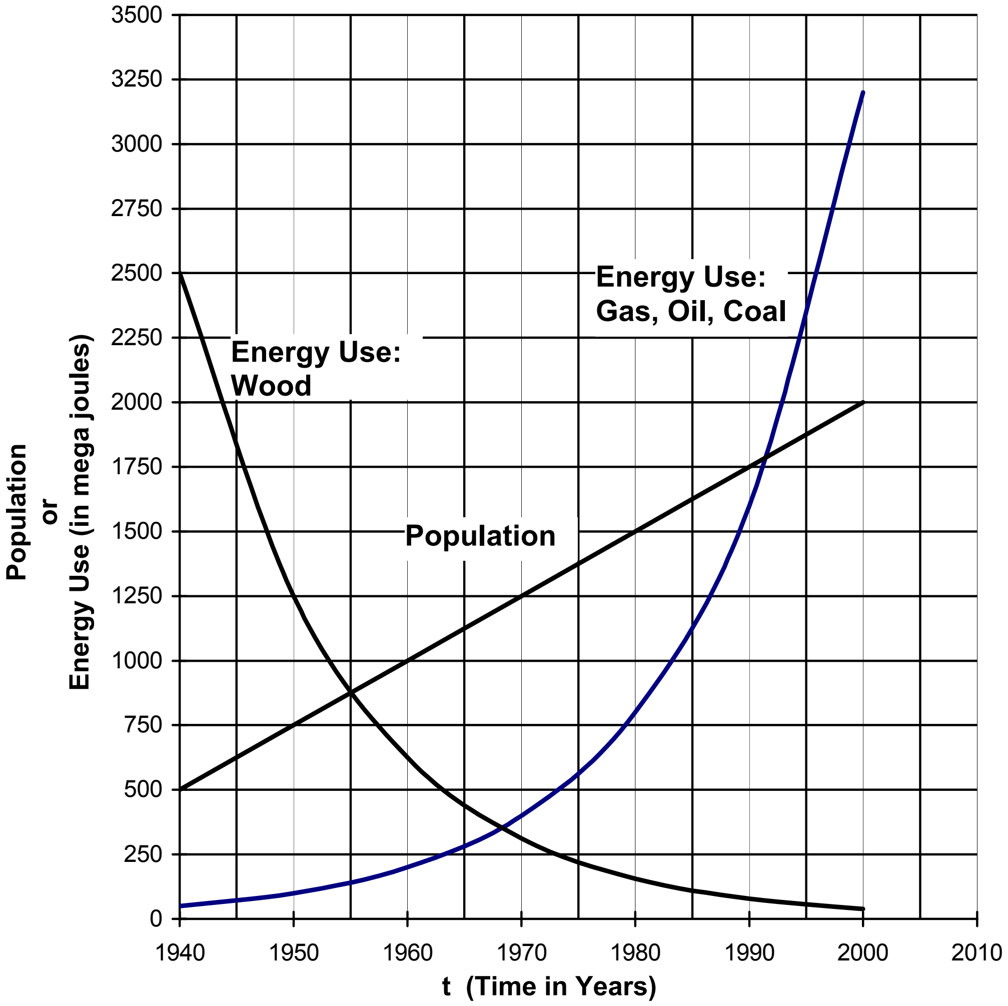
4. Any number raised to the power zero equals 1.

   $$\mathbf{A^0 = 1} \qquad 10^0 = 1; \quad 27^0 = 1$$

1.4 Review of Linear and Exponential Growth

A growth rate is the ratio of the amount of increase to the time elapsed. Figure 1.2 illustrates two common models for growth rates – linear growth and exponential growth. It also illustrates what happens when a quantity decreases exponentially with time – exponential decay.

Fig. 1.2 Sample Data on Population and Energy Use



In Figure 1.2, the graph of population is a straight line, which has a constant slope. Graphs with a constant positive slope represent ***linear growth***. Linear growth is characterized by the addition of a constant amount during a fixed time period. The equation describing linear growth is

(Equation 1.3)

$$N = A \times a + B$$

where

N = the amount of the quantity at a given time
A = the amount of increase per time period
a = the number of time periods elapsed
B = the initial amount of the quantity

Concept Check 1.1

A population of 12,500 people increases by 25 people per year. What will the population be 12 years from now?

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The graph of energy use in Figure 1.2 illustrates ***exponential growth.*** An exponential growth graph is not a straight line because the amount of the increase per time period is not constant. Exponential growth is characterized by a doubling of the amount of the quantity during a fixed time period. The time between doublings is called the ***doubling time***. Since the amount increases by a factor of two, exponential growth is described by base 2 raised to an exponential power equal to the number a of time periods elapsed. The equation describing exponential growth is

$$N = B \times 2^{a} \qquad \textbf{(Equation 1.4)}$$

where

N = the amount of the quantity at a given time

a = the number of time periods elapsed

B = the initial amount of the quantity

Concept Check 1.2

a) A town uses 7,500 MJ of energy per year. If the energy use doubles every 5 years, how much energy would the town require 20 years from now?

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b) Another town used 40,000 MJ of energy from wood in 1950. If the amount of wood used decreases by a factor of two every 10 years, how much energy from wood did this town use in 2000?

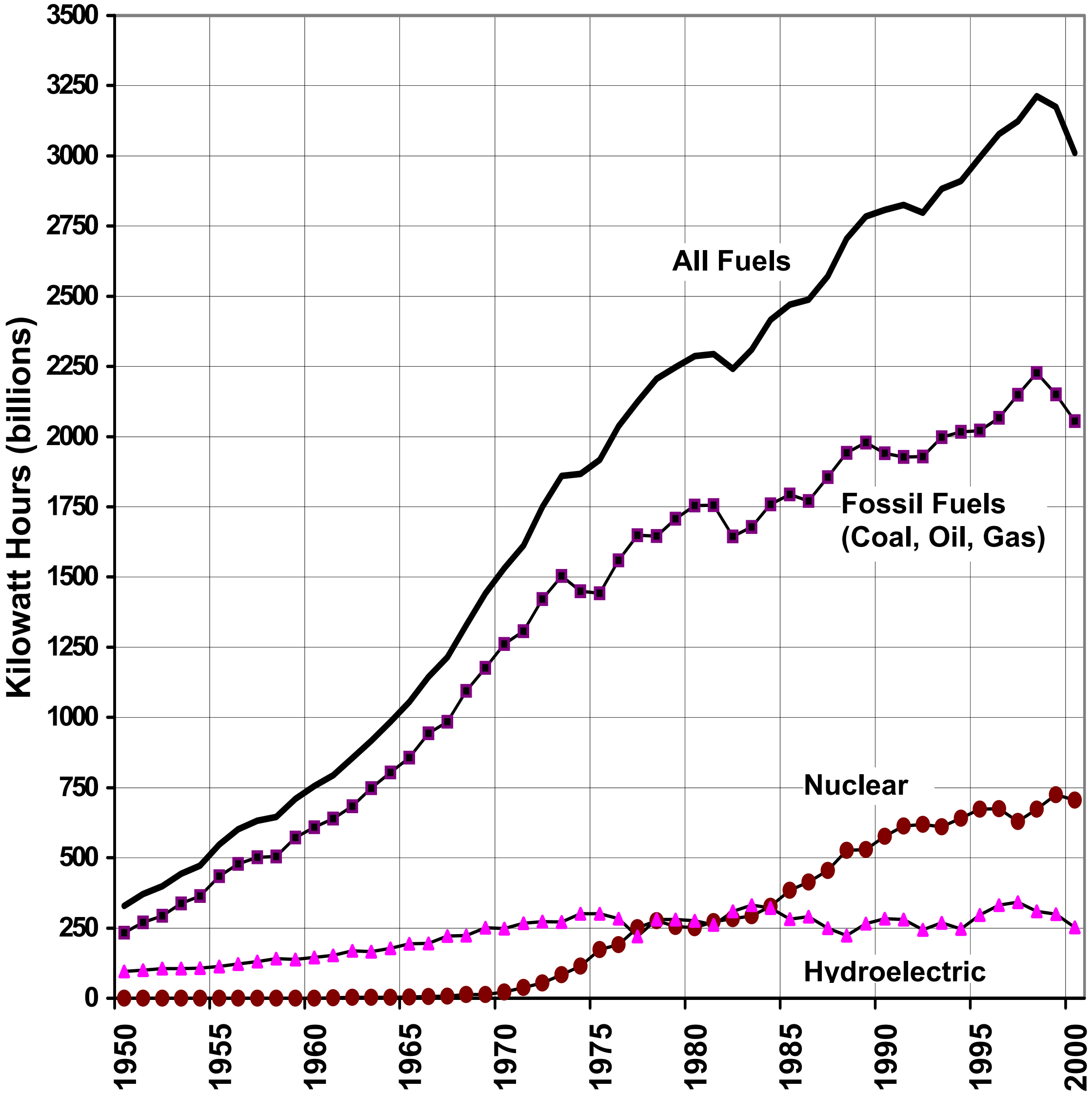
____

When carrying out the calculation in part b of Concept Check 1.2, it is necessary to count backwards in time from 1990 to 1950. When a quantity decreases exponentially with time, the variable a is the number of halving times instead of the number of doubling times. When a quantity decreases exponentially, Equation 1.4 is written with a negative exponent of a, as shown in Equation 1.5.

$$N = B \times 2^{-a} \qquad \textbf{(Equation 1.5)}$$

Dependence on particular energy sources in the U.S. has changed over the past century. Figure 1.3 on the next page illustrates the growth of electrical energy production in the U.S. from 1950 to 2000 and the energy sources for this electricity.

Figure 1.3 Annual Electricity Production in the U.S. by Type of Fuel



Concept Check 1.3

a) Between 1950 and 1970, what type of growth best represents the graph of electricity production from all fuels in Figure 1.3? ____________________________

b) If this growth rate had continued, what would the energy production have been in 1980? ________________ in 1990? ____________________

c) Between 1975 and 1995, what type of growth best represents the graph of electricity production from all fuels? ____

d) If this growth rate continues, what would the electricity production from all fuels be in 2005? ________________ in 2015? ________________

Exponential growth and decay rates have many applications in business and finance and in physical and biological systems. The length of time for a quantity to double, the doubling time, is particularly important. Table 1.2 gives the doubling time in years for various growth rates when compounded annually.

Table 1.2: Growth Rates and Doubling Times

Annual Growth Rate (in percent)	Doubling Time (in years)		Annual Growth Rate (in percent)	Doubling Time (in years)
0	Infinite		20	3.8
1	69.7		30	2.6
2	35.0		40	2.1
3	23.4		50	1.7
4	17.7		60	1.5
5	14.2		70	1.3
6	11.9		80	1.2
7	10.2		90	1.1
8	9.0		100	1.0
9	8.0		200	0.6
10	7.3		300	0.5
12	6.1		400	0.4
14	5.3		900	0.3
16	4.7		9900	0.15
18	4.2			

Concept Check 1.4

a) If you invest $5,000 at 8% interest compounded annually, how long will it take for your money to double to $10,000? ____________________

b) If a stock doubles in value every 4.2 years, what is its rate of growth? ________

1.5 Review of Electromagnetic Energy

Electric Charge

The world around us is full of electric charge. Evidence for the existence of electric charge comes from the electric forces between charged objects. Because electric charges on two adjacent objects can cause the objects to move, we conclude that a force must exist between the electric charges. An electric force can move charged objects closer together (an attractive force) or move them apart (a repulsive force). Since electric forces can move charged objects together or apart, we conclude that two opposite types of electric charge must exist. We rarely notice electric charge because most objects contain equal amounts of these two opposite types of electric charge, which cancel one another.

A charged object results when a quantity of one type of charge is separated from an equal quantity of the opposite type of charge. The sum of equal quantities of opposite charge is zero. For this reason, the two types of electric charge are called positive charge (+) and negative charge (–). Objects with equal numbers of positive and negative charge have a total ***net charge*** of zero and are electrically neutral. Objects with more positive than negative charge have a net positive charge, and objects with more negative than positive charge have a net negative charge. Charge is measured in units of ***coulombs*** (coul).

When the attractive electric force between positive and negative charges pulls charge together, we must do work against this attractive force to separate the charges. When we allow separated charges to come back together, we can get work back out. On the other hand, since two positive charges or two negative charges repel one another, we must do work against this repulsive electric force to bring the charges together. We can get work out as the two charges move apart. The energy per charge is called the ***voltage***.

Separated positive and negative charge may be stored on the metal surfaces of a ***capacitor***. Insulating materials, such as plastic or air, keep the charges in the capacitor separated. The ease with which a capacitor or other object can hold charge is called its capacitance (C). Capacitance is measured in units of ***farads*** (f). The capacitance of an object is defined by the ratio of the charge it can store to the energy per unit charge (the voltage) of the stored charge, as shown in Equation 1.6.

$$C = Q/V \qquad \textbf{(Equation 1.6)}$$

where Q = charge (in coulombs)
C = capacitance (in farads)
V = voltage (in volts)

(Example 1.4)

A 0.5 farad capacitor is used to store 5.0 coulombs of charge. At what voltage is the capacitor?

Solve Equation 1.6 for V:

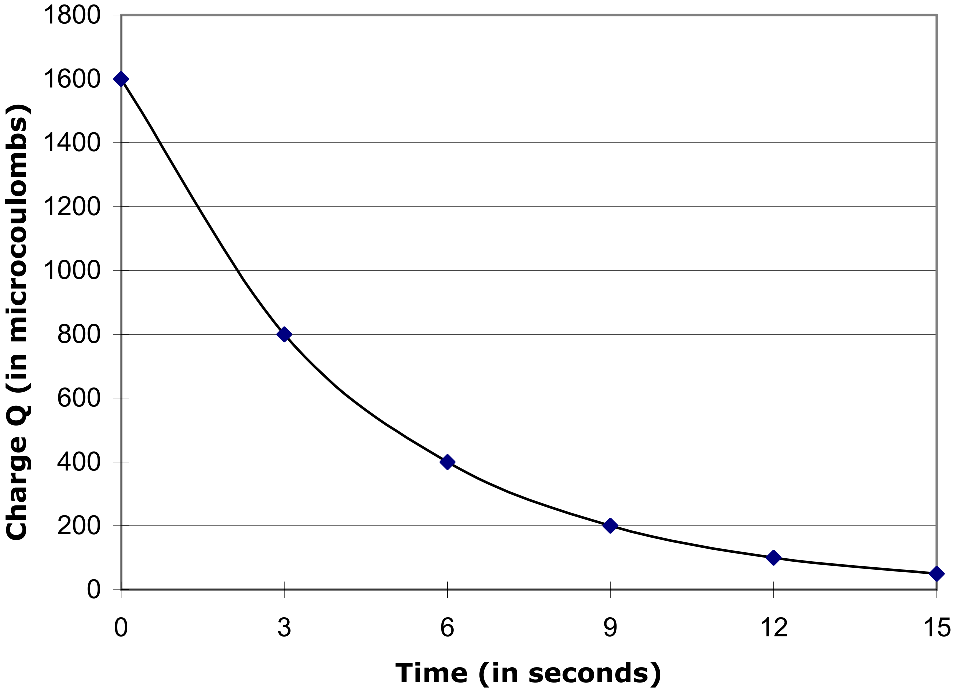
$$V = \frac{Q}{C} = \frac{5.0\ \text{coul}}{0.5\ \text{farad}} = 10\ \text{volts}$$

When a capacitor discharges its stored charge over a period of time, the amount of charge on the capacitor decreases exponentially. Table 1.3 shows sample data for the discharge of a 1.0 farad capacitor. The left column indicates the time that has elapsed since the capacitor began to discharge. The right column indicates the amount of charge in microcoulombs left on the capacitor. Figure 1.4 graphs these data.

Table 1.3: Discharge of a Capacitor

Time (seconds)	Charge on capacitor (microcoul)
0	1600
3	800
6	400
9	200
12	100
15	50

Fig. 1.4 Discharge of a Capacitor versus Time



Concept Check 1.5

a) What is the halving time of the charge in the capacitor described in Figure 1.4?

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b) How much charge remains when the capacitor has discharged for 21 seconds?

____

Moving Electric Charge Produces Electric Current

When separated electric charge flows through conducting material, the moving charge constitutes an ***electric current*** in the conductor. Electric current usually consists of flowing electrons, which can move freely in a conducting material. The amount of electric current is the rate at which charge Q flows past a given point in the conductor. Since charge is measured in coulombs, current I is measured in units of coulombs per second. One coulomb per second is called one ampere (amp). The greater the amount of charge that flows, the larger the electric current. We can express this definition of current with the equation:

$$\text{Current} = \frac{\text{Amount of Charge moved}}{\text{Elapsed Time}}$$

or

$$I = \frac{Q}{t} \qquad \textbf{(Equation 1.7)}$$

with I = current (in amperes)

Q = charge (in coulombs)

t = time elapsed (in seconds)

(Example 1.5)

How much charge must flow to provide a current of 10 amps for 20 seconds?

Solve equation 1.7 for Q by multiplying both sides by t and canceling:

$$Q\,\frac{\cancel{t}}{\cancel{t}} = I\ t = 10 \text{ amps x } 20 \text{ sec} = 200 \text{ coul}$$

Concept Check 1.6

a) How much current is present if 10 coulombs of charge flow through a conductor every 5 seconds? ____________________

b) How long must a 5 amp current flow to provide 200 coul of charge?

____

Sources of Electric Current

If we wish to light a bulb or operate an electric appliance for longer than a few seconds, we need a continuous supply of separated charge, rather than a quick burst of energy. Solar cells produce a flow of charge when energy from the sun or other source of radiant energy strikes the surface of the solar cell, causing electrons to be ejected. The electrons flow along conducting wires, producing an electric current. A capacitor provides only a brief source of separated charge and is quickly exhausted. When a continuous source of electric charge is needed, both capacitors and solar cells have limitations.

To provide a longer lasting source of separated charge at a constant voltage, we may use a battery. The chemicals in batteries react to produce a continuous supply of separated charge, a process which lasts until most of the stored chemical potential energy has been converted into electrical potential energy. We can think of a battery as a charge pump, which boosts charge to a higher electrical potential energy, just as a water pump lifts water to higher gravitational potential energy. A 3 volt battery provides each coulomb of charge with 3 joules of potential energy, twice as much potential energy per coulomb of charge as a 1.5 volt battery provides.

The current produced by a capacitor, solar cell, or battery is known as direct current (DC). In direct current circuits, electric charge flows through the circuit in one direction only. However, flowing separated charge can also be produced as an alternating current (AC), such as the electric current from wall outlets. In alternating current circuits, electric charge is separated in such a way that the current flows first in one direction, and then in the opposite direction. The alternating current from our wall outlets changes direction 120 times per second. This change of direction occurs so rapidly that alternating current moving through a resistor produces the same effect as if the current were moving continuously in one direction. Therefore, the concepts and equations we have introduced for direct current circuits involving resistors apply to alternating current circuits, as well.

Moving Electric Charges and Magnetic Fields

When an electric charge, such as an electron, moves, the charge is surrounded by a magnetic field. The magnetic field produced by an electric current can exert a force and do work on nearby permanent magnets or on other moving electric charges. Likewise, a nearby magnetic field can do work on a current-carrying wire.

But an additional effect also occurs – a changing magnetic field can produce a current in a nearby conductor such as a piece of metal or a wire that is part of a closed circuit. The changing magnetic field can be produced by moving the permanent magnet or electromagnet responsible for the field or by moving the conductor. This process of generating a current in a conductor is known as ***inducing*** a current.

Generating Electricity

In class, we will induce a current by moving a magnet into and out of a coil of wire. Moving the magnet into the coil induces a current in one direction in the wire. When the magnet stops moving, the current stops flowing. Pulling the magnet out of the coil produces a current flowing in the opposite direction. If the magnet is put into and pulled out of the coil in a rhythmic fashion, the current reverses direction with each motion in or out, and an alternating current (AC) flows in the coil. To produce this current, only the relative motion of the coil and wire is important – the same current is induced whether the coil moves or the magnet moves.

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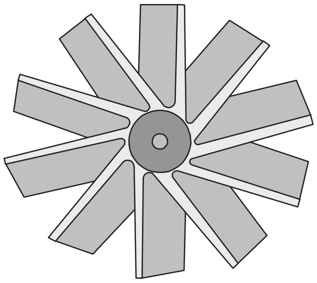
The principle that a magnet moving with respect to a wire induces a current in the wire is used in power plants to generate electricity. Generators use magnets and coils of wire to convert kinetic energy into electrical energy. Electric generating plants convert the kinetic energy of rotating magnets into electrical energy by spinning large magnets near coils of conducting wire. To rotate the magnets, generating plants use kinetic energy from sources described below to turn the blades of turbines. Turbines are wheels with blades attached, similar in principle to waterwheels. A shaft attached to the rotating turbine causes the magnets to spin.

Fig. 1.5 Turbine

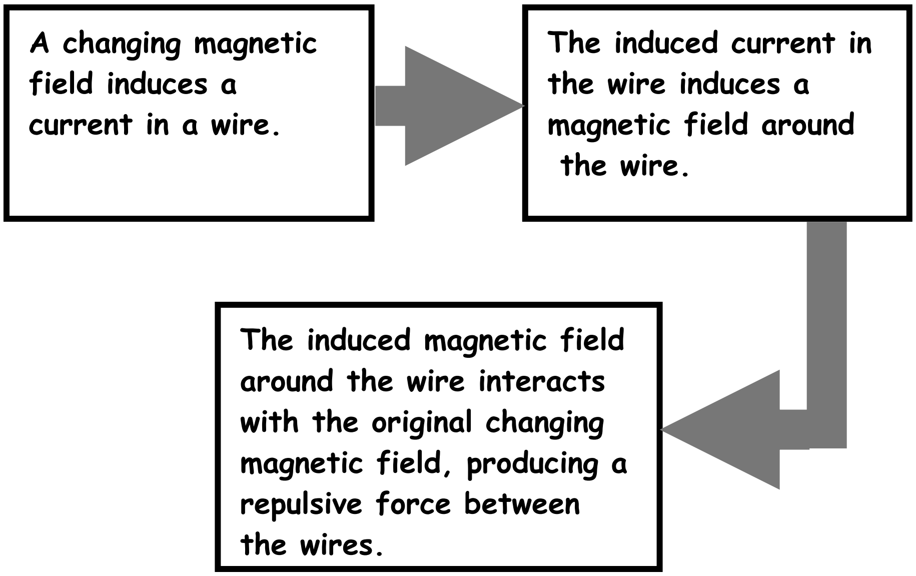


The most common mechanism for turning turbines is steam pressure. In steam generating plants, water is heated in a closed container. As the water changes to steam, the volume and pressure increase. The steam exerts pressure on the turbine blades, turning them. In many generating plants, water is heated by burning coal, oil, natural gas, or other fuels. In nuclear power plants, water is heated by the thermal energy that results from reactions in radioactive fuels. In hydroelectric plants, falling water rotates the turbines. The gravitational potential energy of the water is converted into kinetic energy of motion as the water falls and turns the turbines. In addition to the many hydroelectric power plants built along rivers, a tidal powered generating plant along the ocean shore can use tides to turn turbines. In tidal plants, water flows in during high tide and is trapped behind gates. As the tide recedes, the trapped water is left at a higher level than the surrounding ocean. The trapped water returning to the ocean spills over the turbines, turning them.

Induced Current Induces a Magnetic Field

We have seen that a current flowing through a wire induces a magnetic field around the wire and that a changing magnetic field induces a current in a nearby wire. The changing magnetic field can result from the motion of a permanent magnet or an electromagnet or from a change in the current flowing through an electromagnet, such as the changing direction of AC current. But no matter how the current induced in the second wire has been produced, it has the very useful property that this current will result in another magnetic field surrounding the second wire. The force between the magnetic field of a current-carrying wire and the magnetic field induced in a second wire by the changing current of the first wire can also be used to do work. This relationship is illustrated in Figure 1.6.

Fig. 1.6 Induced Current and Magnetism



1.6 Radiant Energy

We have seen that static (motionless) electric charge produces an electric force. Electric charge flowing through a conductor produces an electric current. Radiant energy is produced when electric charge vibrates. We can think of radiant energy as waves of energy. These waves can travel through a medium, such as air or water, or through the vacuum of empty space, such as the radiant energy waves the Earth receives from the Sun.

Radiant energy is the energy associated with an electromagnetic field; thus, it is also known as ***electromagnetic radiation***. We are constantly surrounded by radiant energy. Light bulbs transfer radiant energy to our eyes in the form of visible light. A warm oven transfers radiant energy in the form of infrared energy, which we experience as heat. The Sun transfers radiant energy to the Earth in the form of infrared energy, visible light, and ultraviolet rays. Microwave ovens use radiant energy to cook food. And radio waves transfer information to our radios and televisions via radiant energy.

We have 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 1.7 illustrates waves of electromagnetic radiation.

Figure 1.7 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.

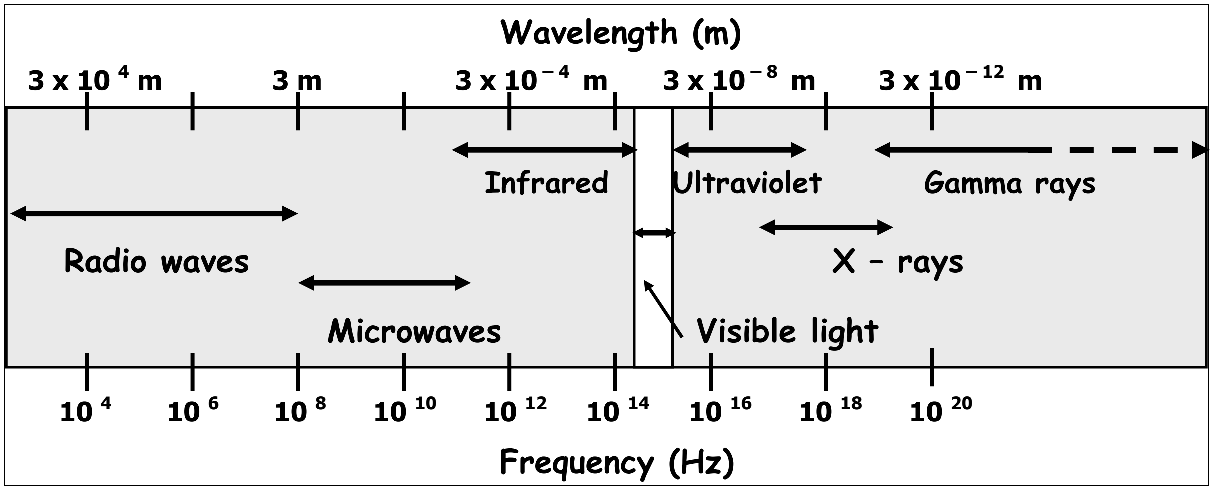
As discussed above, the electrons in the receiving antenna move, so they must experience a force that produces the motion. Thus we know that energy is transferred from the broadcasting antenna to the receiving antenna. In order to be transferred, this energy must be associated with the electromagnetic 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, which appears in Einstein's famous equation $E = m c^2$ to be studied later this quarter.

1.8 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, as illustrated in Figure 1.8.

Figure 1.8 The Electromagnetic Spectrum



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, and we see the combination of these colors as white light. 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 7×10^{14} Hz to about 3×10^{17} Hz. Ultraviolet radiation can induce fluorescence and can cause tanning in human skin.

X-rays

Even shorter wavelengths (down to about 1×10^{-11} meters) are the ***X-ray*** region. Frequencies in this region extend from 3×10^{17} Hz to about 3×10^{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 1×10^{-11} meters and frequencies above 3×10^{19} Hz are called ***gamma rays***. They may be produced by nuclear reactions and will be discussed further in the period on nuclear energy.

In Chapters 2 and 3 we will discuss some of the properties of radiant energy in more detail and illustrate some of the applications of radiant energy to modern technology.

Period 1 Summary

1.1: The World of Energy presents physics concepts in the context of energy use. The hands-on format of the course makes student class participation especially important.

1.2: The concept of *per* is represented by a ratio – one quantity divided by another quantity. When converting units, use ratios that allow cancellation of the unwanted units.

The efficiency of an energy conversion process equals the amount of energy of the desired type produced per total amount of energy put into the process.

Efficiency = Useful Energy Out/Total Energy In

Ratio reasoning is a mathematical tool that allows you to solve practical problems using ratios.

1.3: Powers of 10 simplify calculations with very large or small numbers.

When multiplying powers of 10, add exponents.

When dividing powers of 10, subtract exponents.

1.4: Linear growth adds a constant amount of a quantity during each time period

Linear growth is expressed by $N = A \times a + B$

Exponential growth doubles the amount of the quantity during each time period.

Exponential growth is expressed by $N = B \times 2^{a}$

Exponential decay is expressed by $N = B \times 2^{-a}$

where N = the amount of the quantity
A = the amount of increase per time period
B = the initial amount
a = the number of time periods elapsed

The doubling time for exponential growth is the length of time required for the amount of a quantity to double. Growth rate tables (Table 1.2) provide an easy way to determine growth rates and doubling times.

1.5: Charges come in two types: positive (+) and negative (–). Charges of the same sign (+), (+) or (–), (–) repel each other and charges of the opposite sign (+), (–) attract. Electrical forces result from the repulsion between same sign charges and the attraction between opposite sign charges.

Electric charge Q is measured in units of coulombs (coul.)

The amount of electrical energy per charge is the voltage V of the charge.

Period 1 Summary, Continued

Capacitors store electric charge. Their charge-holding capability is called capacitance, C, which is measured in farads. $C = Q / V$

Electric current I is the rate of flow of charge. $I = Q/t$ where I is measured in units of amperes.

Two types of electric current exist: direct current (DC) and alternating current (AC). In direct current circuits, electric charge flows through the circuit in one direction. In alternating current circuits, electric charge is separated in such a way that the current flows first in one direction, and then in the opposite direction, changing direction 120 times per second.

Sources for electric current include electric generating plants for alternating current, and batteries, solar cells, or capacitors for direct current.

Electricity is generated when magnets spin near coils of wire wrapped around an iron core. In generating plants, turbines are used to spin the magnets. To turn the turbine blades, gravitational potential energy from falling water or thermal energy from steam is used.

All moving charges are surrounded by magnetic fields. A changing magnetic field induces a current in a nearby wire. When a changing magnetic field induces a current in a wire, the current induces a second magnetic field around the wire. The force between these two magnetic fields is repulsive and can do work.

1.6: Vibrating electric charge 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.

1.7: 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.

Period 1 Exercises

E.1 How many gallons of gasoline would each vehicle require to go 245 miles?

(a) goes 50 miles
on 2.25 gallons

(b) goes 50 miles
on 3.5 gallons

(c) goes 50 miles
on 6.5 gallons

E.2 The British thermal unit (BTU) is a common unit of measurement for thermal energy. If one gallon of gasoline contains 126,000 BTU's, what is the energy content of 15.5 gallons of gasoline?

a) 8.13×10^3 BTU's
b) 8.13×10^4 BTU's
c) 1.95×10^5 BTU's
d) 1.95×10^6 BTU's
e) 1.95×10^7 BTU's

E.3 What is the efficiency of an energy conversion process that requires 1,600 joules of energy and produces 400 joules of wasted energy?

a) 25%
b) 30%
c) 50%
d) 75%
e) 400%

E.4 Use the data in Table 1.2 to find when a population of 50,000 people, with an annual growth rate of 20%, will reach 1,600,000.

a) 7.6 years
b) 15.2 years
c) 19.0 years
d) 22.8 years
e) 35.0 years

E.5 The return on an investment is 9% per year. If you invested $5,000 in 2002, how much will you have in 2026 if the annual growth rate remains constant?

a) $15,000
b) $20,000
c) $25,000
d) $30,000
e) $40,000

E.6 The population of a rural area decreases by a factor of two every 20 years. If the population was 60,000 in 2000, what will the population be in 2040, assuming that the halving time remains the same?

a) 45,000
b) 30,000
c) 25,000
d) 15,000
e) 7,500

E.7 An electrical circuit has a current of 15 amps. How many electrons flow through this circuit each second? (Hint: An electron has a charge of 1.6×10^{-19} coulombs.)

a) 2.4×10^{-20}
b) 9.4×10^{-19}
c) 15
d) 9.4×10^{19}
e) 2.4×10^{20}

E.8 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, X-ray
c) ultraviolet, visual, microwave, radio
d) X-ray, visual, microwave, infrared
e) gamma ray, X-ray, microwave, visual

E.9 Which of the following statements about the microwaves used in microwave ovens is **FALSE**?

a) Microwaves are electromagnetic radiation.
b) Microwaves have 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) Microwaves travel at the speed of light.

Period 1 Review Questions

R.1 When using ratio reasoning to solve a problem, how do you decide which value to put in the numerator and which in the denominator of each ratio? Explain your answer by finding the cost of operating a 1,000 watt microwave oven for 15 minutes per day every day for a year, if electricity costs $0.10/kWh.

R.2 Explain how to tell whether a graph exhibits linear growth, exponential growth, or exponential decay. Does every growth rate fit into one of these two types?

R.3 What is the halving time of a quantity? How long will it take a stock that decreases in value at a rate of 12% per year to reach one-half of its original value?

R.4 Electric charge is involved in the production of electrical energy (electricity) and electromagnetic radiation (radiant energy). How does charge produce electrical energy? How does charge produce electromagnetic radiation?

R.5 Give examples of each of the forms of radiant energy are used: radio waves, microwaves, infrared radiation, visible light, ultraviolet light, X-rays, and gamma rays.

Chapter 2: Electromagnetic Radiation – Radiant Energy I

Goals of Period 2

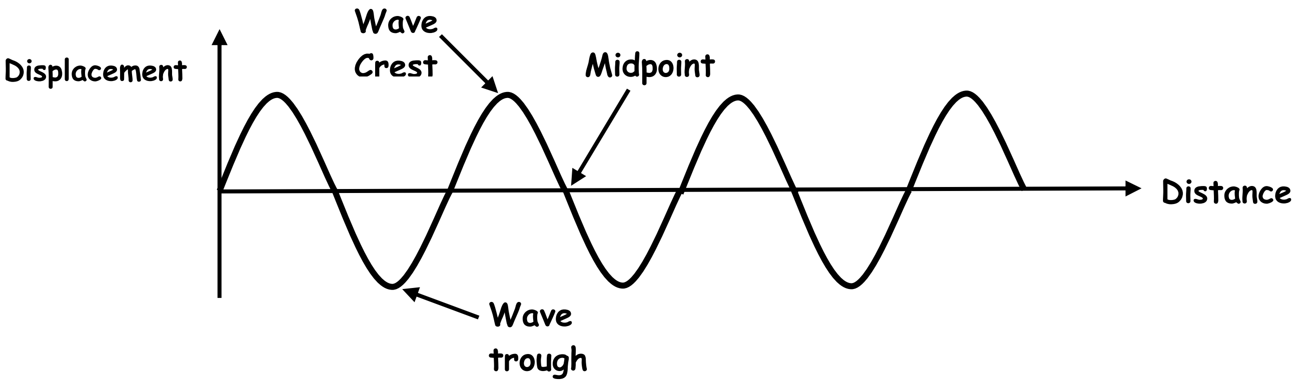
Section 2.1: To describe the wave model of radiant energy
Section 2.2: To discuss the wave model of radiant energy
Section 2.3: To describe the electromagnetic spectrum
Section 2.4: To discuss the quantum model of radiant energy

As discussed in Chapter 1, moving electric charge produces an electric current, while vibrating electric charge produces electromagnetic radiation, or radiant energy. Waves of electromagnetic radiation energy transfer radiant energy by traveling outward from the source of radiation. Chapter 2 continues the study of electromagnetic radiation by examining the properties of waves.

2.1 The Wave Model of Radiant Energy

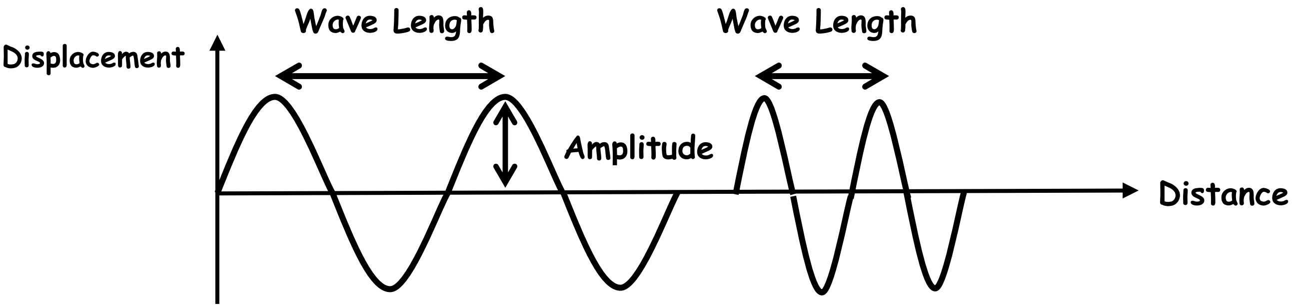
One of the ways to transfer energy without the transfer of mass is to produce a wave. A wave can be a pulse, as in the pulse of sound made by clapping your hands together. Another example of a pulse is a tsunami, a tidal wave of energy that travels many miles over an ocean. But many waves are generated 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. Figure 2.1 illustrates sine waves.

Figure 2.1 Sine Waves



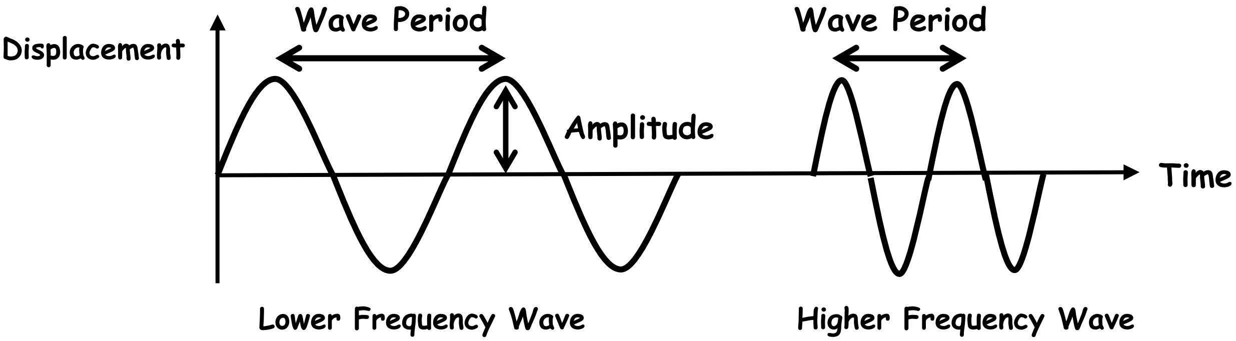
A wave can be characterized by its ***wavelength***, which is the distance between two adjacent wave crests or two adjacent wave troughs, as shown in Figure 2.2. A wave also has an ***amplitude***, which is the maximum height or displacement of the crest of the wave above or below its midpoint.

Figure 2.2 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. ***Frequency*** describes how often something repeats a cycle. 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 2.3 is the time measured at any given point on the horizontal axis of Figure 2.2.

Figure 2.3 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 the higher its frequency. This can be expressed by the relation given by Equation 2.1.

$$\textit{frequency} = 1/\ \textit{period} \qquad \text{(Equation 2.1)}$$

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).

Wave Speed

All electromagnetic radiation, regardless of its source, is characterized by a frequency associated with the source and with the radiation. The wave model of radiant energy can describe electromagnetic radiation as sine waves of a given wavelength and frequency. In the case of a sine wave, we associate a wavelength with a given frequency. All sine waves, regardless of the frequency of the wave, obey the relationship

$$s = f\,L \qquad \textbf{(Equation 2.2)}$$

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)

The speed s 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 cr.

(Example 2.1)

a) A wave of electromagnetic radiation has a period of 2.5×10^{-15} seconds. Calculate the frequency of the wave in cycles/second (Hertz).

frequency = 1/period = $1/2.5 \times 10^{-15}$ sec = 4.0×10^{14} cycles/sec

= 4.0×10^{14} Hz

b) Find the wavelength of this wave of electromagnetic radiation.

$$S = f L, \text{ or } L = \frac{S}{f} = \frac{3 \times 10^8 \text{ m/s}}{4 \times 10^{14}\ \text{1/s}} = 0.75 \times 10^{-6}\text{ m} = 7.5 \times 10^{-7}\text{ m}$$

Concept Check 2.1

a) What is the frequency of electromagnetic radiation with a wavelength of 0.15 meters?

____

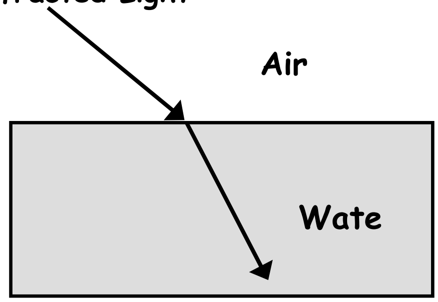
b) What is the speed of a wave with a frequency of 0.5 Hz and a wavelength of 0.6 meters? Is this a wave of electromagnetic radiation?

____

2.2 Refraction of Radiant Energy

Regardless of their wavelength and frequency, all waves of electromagnetic radiation travel at the same speed in a vacuum, 3 x 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 2.4

Figure 2.4 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.

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

The speed of light in a vacuum is always 3 x 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 2.2)

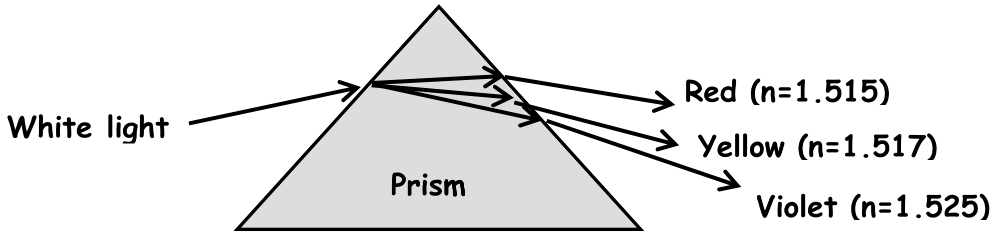
Light travels in a diamond at a speed of 1.24×10^8 meters/second. What is the index of refraction of light in a diamond?

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

As discussed earlier, electromagnetic waves are unique in that they can travel through a vacuum, and all do so with the same speed (3×10^8 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 2.5 A Prism Refracts Light

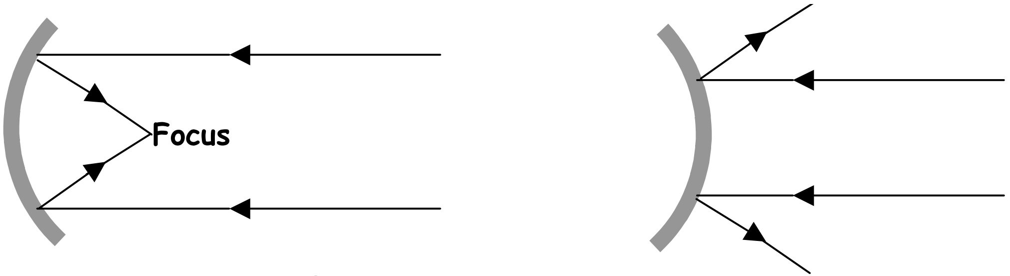


The difference between the speed of red light and violet light is greatest for materials with the largest index of refraction. For this reason, a well-cut diamond is very effective in breaking light up into colors. The best cut for this purpose is known as a brilliant cut.

2.3 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 2.6, 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 2.6 Radiant Energy Reflecting from Mirrors

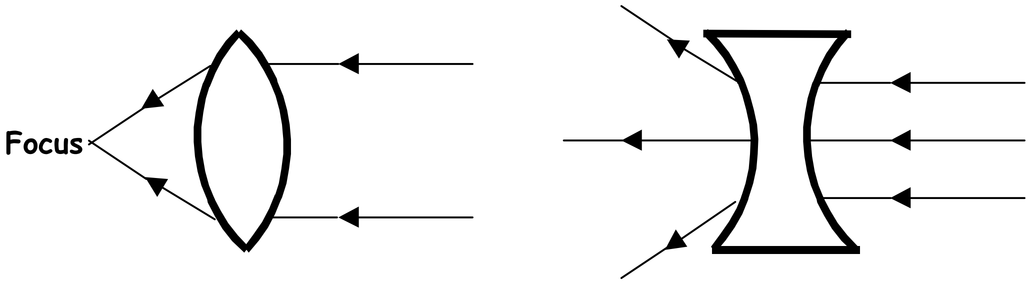


A Concave Mirror Focuses Radiant Energy

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 2.7, this means that curved lenses can concentrate light.

Figure 2.7 Radiant Energy Passing through Lenses



A Convex Lens Focuses Radiant Energy

A Concave Lens Spreads Radiant 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 = 6.63×10^{-34} joule sec

f = frequency (Hertz)

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

L = wavelength (meters).

These equations show that 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 5×10^{-20} J?

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

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

Concept Check 2.2

a) What is the wavelength of radiant energy with a frequency of 6×10^{11} Hz?

____

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

____

2.5 Radiant Energy and Solar Cells

Radiant Energy from the Sun

The interior of the Sun emits radiant energy at all wavelengths and frequencies. 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.

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.

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 because they make use of the photoelectric effect. The photoelectric effect can be explained using the quantum model of radiant energy, but not the wave model. In the photoelectric effect, 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 some time, 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.

Period 2 Summary

2.1: A wave is characterized by its wavelength (the distance between two adjacent wave crests or two adjacent wave troughs), its frequency (how many times per second a wave crest or trough passes a fixed point), and its amplitude (the maximum height of the wave above or below its midpoint).

The period of a wave is the time it takes to complete one cycle. The frequency of a wave is the inverse of its period**: frequency = 1 / period**

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

2.2 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: 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.

A concave mirror focuses beams of radiant energy, but a convex mirror spreads the beams. The opposite is true of lenses: a convex lens focuses radiant energy and a concave lens spreads the energy.

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:

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

2.5: 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.

Period 2 Exercises

E.1 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.2 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.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 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

E.6 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.7 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

Period 2 Review Questions

R.1 What is the difference between wave length, wave amplitude, and wave frequency? Which of these variables are used to find the speed of a wave?

R.2 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?

R.3 What is refraction of light? Why is white light that travels through a prism split into its constituent colors?

R.4 Why is it unsafe to leave glass soft drink bottles in a forest?

R.5 The photons striking a particular solar cell do not produce an electric current in the cell. Why is this? Would more photons of the same energy produce a current?

Chapter 3: Electromagnetic Waves – Radiant Energy II

Goals of Period 3

Section 3.1: To examine some applications of the quantum model of radiant energy including photon emission, fluorescence, and spectral lines

Section 3.2: To describe the transfer of energy and information

Section 3.3: To discuss radio and television signal transmission

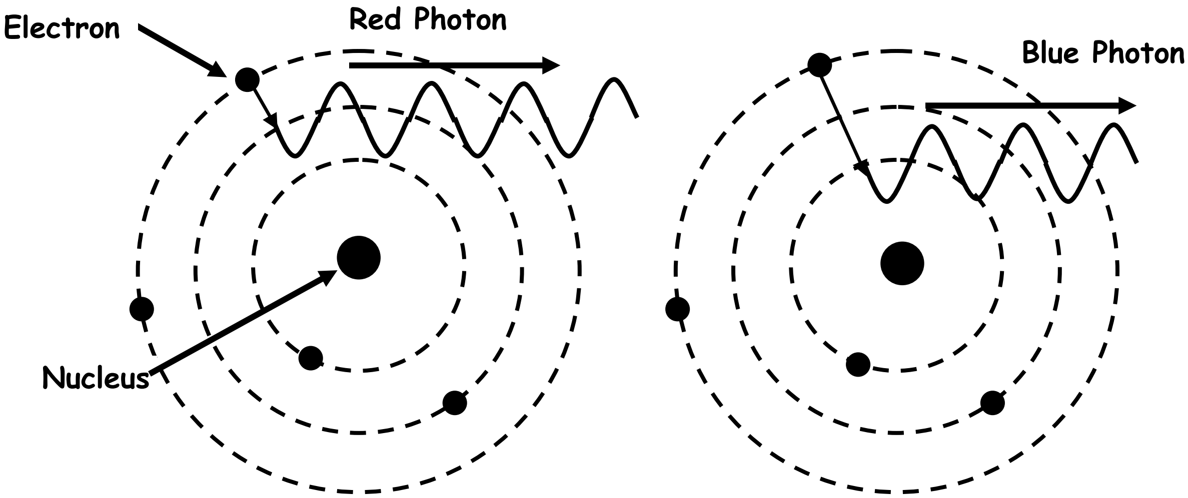
As described in Chapter 2, some properties of electromagnetic radiation can best be described by the quantum model, which treats radiant energy as being composed of small packets of energy called photons or quanta. As radiant energy interacts with matter, it absorbs or deposits energy in amounts that are integer multiples of this photon energy. In Chapter 3, we use the quantum model to explain photon absorption and emission by electrons.

3.1 Applications of the Quantum Model of Radiant Energy

Photon Absorption and Emission

A photon is emitted when an electron drops from a higher to a lower energy level in the shell of an atomic nucleus as illustrated in Figure 3.1.

Figure 3.1 Photons Emitted from an Atom



An electron dropping one energy level emits a lower energy photon of red visible light.

An electron dropping two energy levels emits a higher energy photon of blue visible light.

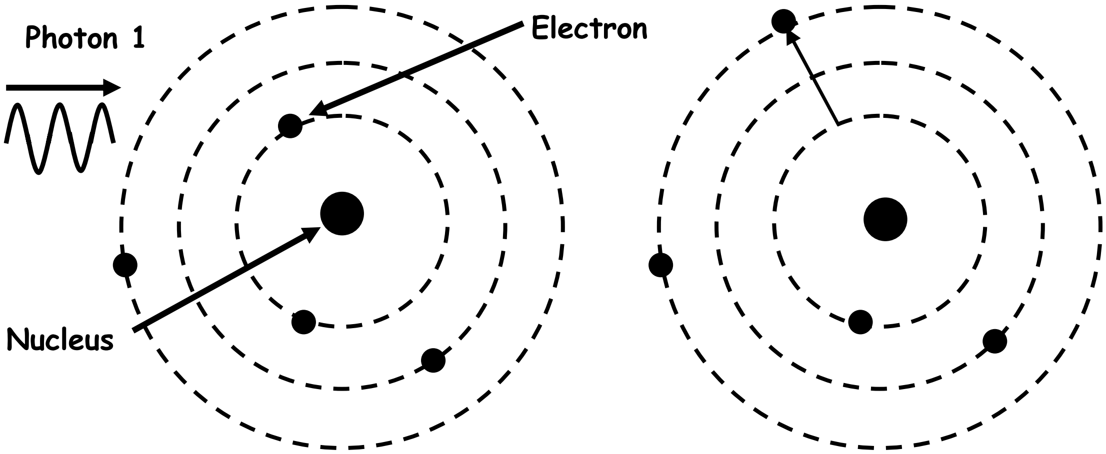
The Law of Conservation of Energy tells us that the energy of the atom before the photon emission must equal the energy of the emitted photon plus the atom after the emission. The photon's energy is determined by the difference in energy of the electron before and after it drops to a lower level. Since the electron must drop between discrete energy levels, the energy of the emitted photons is limited to discrete amounts called quanta. For photons of visible light, each quanta of energy corresponds to a bright line of color called a spectral emission line.

Ultraviolet Light and Fluorescence

Photons in the ultraviolet region of the spectrum 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 3.2.

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.

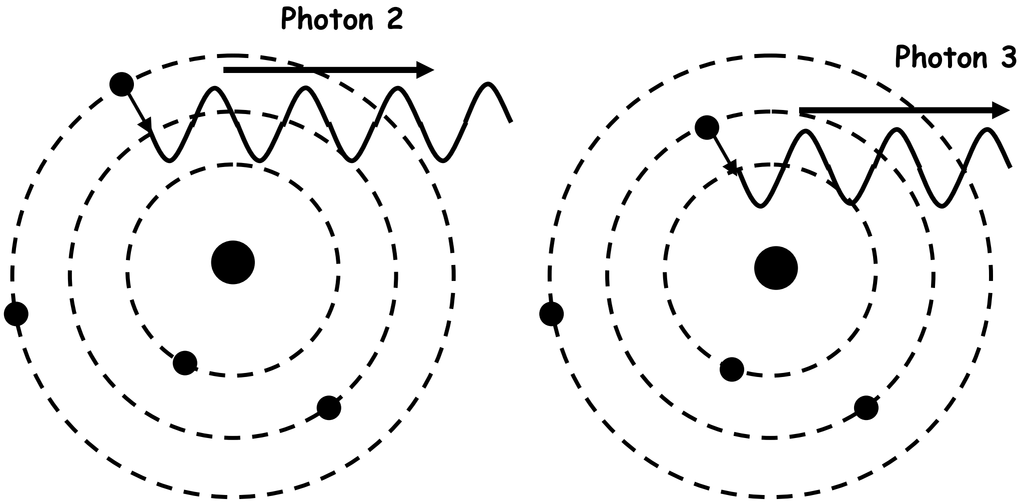
Figure 3.2 A Fluorescing Atom Absorbs a Photon



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

Time 2: The electron moves up two energy levels.

Figure 3.2, Continued A Fluorescing Atom Emits Two Photons



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.

(Example 3.1)

An electron absorbs a photon that has 6.67 x 10^{-18} joules of energy, and the electron moves to a higher energy level. Subsequently, the electron drops to a lower energy level and emits a photon with 4.48 x 10^{-19} joules of energy. What must happen to the electron to satisfy the law of conservation of energy?

The total energy emitted by the electron must equal the total energy absorbed. We subtract to find the difference between the energy absorbed and the energy emitted by the first photon. When adding or subtracting numbers written in scientific notation, each term must have the same power of ten.

$$\begin{array}{r} 6.67 \times 10^{-18}\ \text{J} \\ \underline{-\,4.48 \times 10^{-19}}\ \text{J} \end{array} \quad \text{becomes} \quad \begin{array}{r} 6.67 \times 10^{-18}\ \text{J} \\ \underline{-0.448 \times 10^{-18}}\ \text{J} \\ 6.22 \times 10^{-18}\ \text{J} \end{array}$$

or

$$\begin{array}{r} 6.67 \times 10^{-18}\ \text{J} \\ \underline{-\,4.48 \times 10^{-19}}\ \text{J} \end{array} \quad \text{becomes} \quad \begin{array}{l} 66.7 \times 10^{-19}\ \text{J} \\ \underline{-\,4.48 \times 10^{-19}}\ \text{J} \\ 62.2 \times 10^{-19}\ \text{J} = 6.22 \times 10^{-18}\ \text{J} \end{array}$$

This electron must emit one or more photons with a total energy of 6.22 x 10^{-18} J.

The photon emitted in Example 3.1 above is a photon of ultraviolet radiation. Photons in the ultraviolet region 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.

Visible Light Spectrum from a Gas

The process of photon emission from atoms, as illustrated by Figure 3.1, can explain the presence of spectral emission lines from a glowing gas. For photons of visible light, each quanta of energy corresponds to a bright line of color called a spectral emission line. Electrical energy raises electrons in the gas atoms to a higher energy level. When the electrons fall back down to lower energy levels, they emit photons of light characteristic of the atoms.

In class we will view tubes of glowing neon and mercury gas through diffraction gratings. When visible light passes through a prism or diffraction grating, the light is refracted or bent and is separated into a rainbow of color called a spectrum. Neon and mercury gases emit photons of only a few distinct wavelengths that produce bright lines when viewed through the diffraction gratings. The colors seen depend on the energy of the emitted photons. Atoms of different gases produce different patterns of spectral emission lines as illustrated in Figure 3.3. Since each chemical element has its own characteristic emission lines, observing these spectral lines identifies the chemical composition of a gas.

Figure 3.3 Spectral Emission Lines of Two Gases

Visible Light Spectrum from a Solid

When viewed through a diffraction grating, glowing gas molecules emit bright bands of color, or spectral lines. When molecules are compressed into a solid, the glowing object emits radiation that forms a continuous spectrum of color when viewed through a diffraction grating. The red end of this visible spectrum consists of lower energy, longer wavelength photons and the blue-violet end consists of higher energy, shorter wavelength photons. If the light source is a bulb filament, the brightness of the red and the blue end of the spectrum can be changed by increasing or decreasing the brightness of the filament. Light from a brighter, hotter filament produces a spectrum with a bright blue portion, while a cooler filament produces a bright red portion.

After a light bulb has been turned off, its warm filament continues to emit photons of infrared radiation and all other frequencies, too. Most of the radiation is infrared. Although the wavelength of infrared photons is too long to be detected by the human eye, these photons are visible through an infrared camera. As the filament cools further, it emits photons of longer wavelengths – microwave or radio wavelengths. In fact, all objects emit radiation of wavelengths proportional to the object's temperature. This radiation is produced by the internal kinetic energy of the molecules of the object.

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.

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

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

(Example 3.2)

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.

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

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.

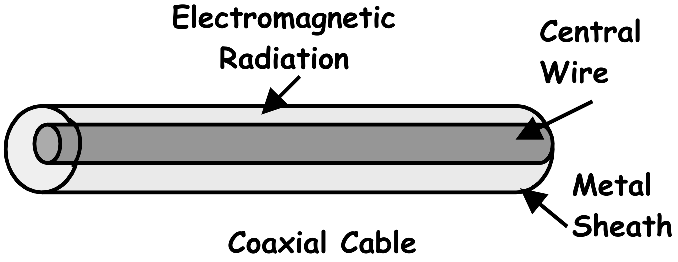
Modern communication utilizes modulated electromagnetic radiation in the form of radio waves for radio and TV broadcasts, microwaves for cellular phones, infrared waves for remote controls, and visible light for fiber optic cables. There are many ways in which the flow of energy can be modulated to transfer 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.

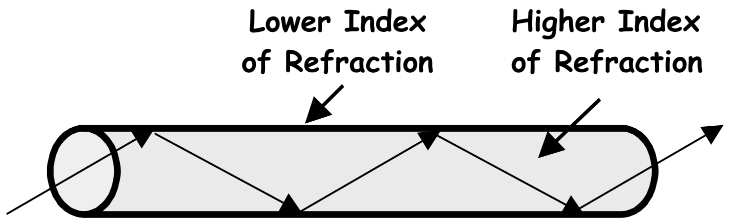
One of the most effective methods of sending signals is by ***coaxial cable***. Coaxial cables are used in television and internet connections. A coaxial cable consists of an insulated central conducting wire surrounded by a conducting tube. Electromagnetic radiation from the broadcasting station or 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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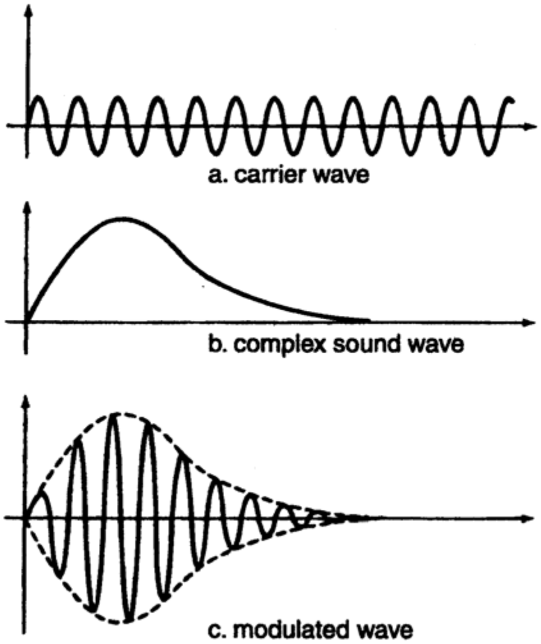
If you do not have cable or satellite television service, when you choose channel 4 you will get channel 4. If you do not have cable or satellite service, channel 4 may be on channel 62. You may wonder why this happens. It is because the carrier wave frequency is often changed by the cable or satellite 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



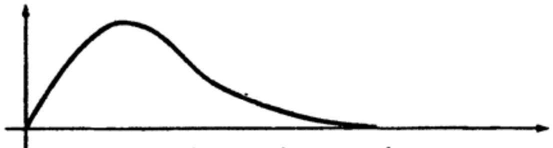
AM broadcasts have several limitations. The amplitude of a carrier wave is subject to disturbance by lightning, which introduces noise into an AM signal. Also, the human ear is capable of hearing a much wider range of frequencies than the range of frequencies that can be used to modulate the amplitude 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

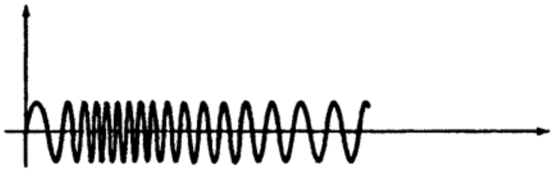
FM radio operates on the principle of modulating the frequency of the carrier wave rather than modulating the amplitude of the wave. Figure 3.7 illustrates a carrier wave whose frequency has been modulated to encode the signal of a complex sound wave.

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 quantum model describes radiant energy as composed of small packets of energy called photons or quanta.

If an electron in the shell of an atomic nucleus absorbs a photon, the electron is raised to a higher energy level. The electron can emit one or more photons by dropping back to a lower energy level in the shell of an atomic nucleus.

The law of conservation of energy requires that the total energy absorbed by the electron must equal the total energy emitted.

If an ultraviolet photon is absorbed and visible light photons are emitted, the electron is said to fluoresce. If there is a time delay between the absorption of the ultraviolet photon and the emission of the visible photons, the electron is said to phosphoresce.

When a glowing gas is viewed through a diffraction grating, bright spectral emission lines characteristic of the gas are seen. When a glowing solid object is viewed through a diffraction grating, a continuous spectrum of color is observed.

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

3.2: Information transfer involves a sender, a receiver, and the modulation or change of some form of energy in a meaningful way to produce a signal. The signal-to-noise ratio can be improved by increasing the energy in the signal or by decrease the energy in the noise.

A digital signal is produced by sequentially stopping and starting the energy being transferred. Morse Code is an example of a digital signal.

All forms of radiant energy can be modulated to transfer information. Radio waves are modulated to transfer radio and television signals. These signals can also be distributed to viewers through coaxial cable.

3.3: A carrier wave is a continuous sine wave of a single amplitude, wavelength, and frequency that is modulated to carry information from radio and TV broadcasts.

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 An electron absorbs a photon that has 5.0 x 10^{-21} joules of energy and the electron moves to a higher energy level. The electron later drops to a lower energy level and emits a photon that has 3.3 x 10^{-22} joules of energy. How much more energy must be emitted to satisfy the law of conservation of energy?

a) 1.7 x 10^{-22} joules
b) 4.7 x 10^{-22} joules
c) 1.7 x 10^{-21} joules
d) 4.7 x 10^{-21} joules
e) 4.7 x 10^{-20} joules

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 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.4 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.5 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.6 You are attending a concert and have a seat at the back of the auditorium, 50 meters from the stage. Your friend is listing to the same concert on her radio at home, 10 kilometers from the concert hall. If there is no delay in the broadcast of the concert, who do you think hears the sound first? (Hint: Use speed = distance/time. Assume that the speed of sound is 340 meters/second.)

Period 3 Review Questions

R.1 What is fluorescence? What causes an atom to fluoresce?

R.2 You view a glowing gas and a glowing solid through a diffraction grating. What is the difference between the images you see through the grating?

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 the differences 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?