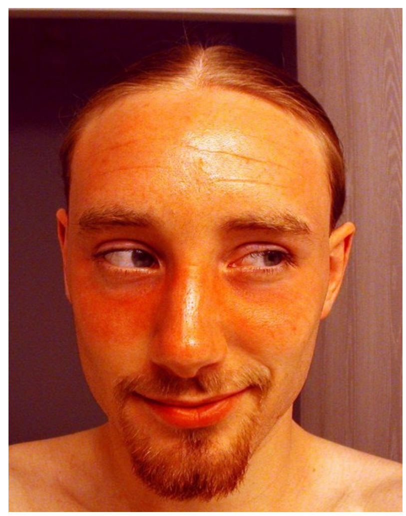
Chapter 7

Energy and Chemical Reactions

Energy…it makes things happen. To get an idea of the role energy plays in our lives, let's spend some time with John, a college student in one of the coastal towns in California. He wakes up in the morning to a beautiful sunny day and decides to take his chemistry book to the beach. Before leaving, he fries up some scrambled eggs, burns some toast, and pops a cup of day-old coffee in the microwave oven. After finishing his breakfast, he shoves his chemistry textbook into his backpack and jumps on his bike for the short ride to the seashore. Once at the beach, he reads two pages of his chemistry assignment, and despite the fascinating topic, gets drowsy and drops off to sleep. When he wakes up an hour later, he's real sorry that he forgot to put on his sunscreen. His painful sunburn drives him off the beach and back to his apartment to spend the rest of the day inside.

All of John's actions required energy. It took energy to get out of bed, make breakfast, pedal to the beach, and (as you well know) read his chemistry book. John gets that energy from the chemical changes that his body induces in the food he eats. It took heat energy to cook his eggs and burn his toast. The radiant energy from microwaves raised the temperature of his coffee, and the radiant energy from the sun caused his sunburn.

What is energy, and what different forms does it take? Why do some chemical changes release energy while others absorb it? This chapter attempts to answer such questions and then apply our understanding of energy to some of the important environmental issues that people face today.



Radiant energy from the sun causes sunburn

Photo by Dean Tersigni

Review Skills

The presentation of information in this chapter assumes that you can already perform the tasks listed below. You can test your readiness to proceed by answering the Review Questions at the end of the chapter. This might also be a good time to read the Chapter Objectives, which precede the Review Questions.

- Describe the similarities and differences between solids, liquids, and gases with reference to the particle nature of matter, the degree of motion of the particles, and the degree of attraction between the particles. (Section 2.1)
- Describe the relationship between temperature and motion. (Section 2.1)

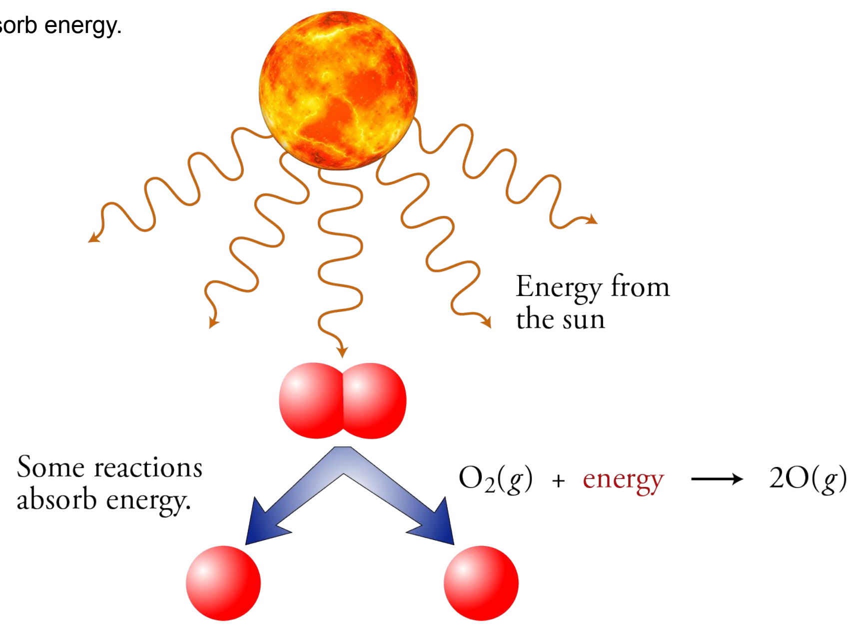
7.1 Energy

All chemical changes are accompanied by energy changes. Some reactions, such as the combustion of methane (a component of natural gas) release energy. This is why natural gas can be used to heat our homes:

$$CH_4(g) + 2O_2(g) \longrightarrow CO_2(g) + 2H_2O(l) + \text{Energy}$$

Other reactions absorb energy. For example, when energy from the sun strikes oxygen molecules, O_2, in the Earth's atmosphere, some of the energy is absorbed by the molecules, causing them to break apart into separate atoms (Figure 7.1).

Figure 7.1
Some reactions absorb energy.

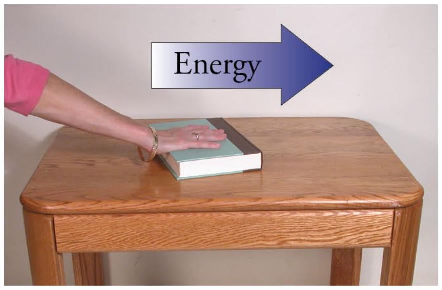


Before we can begin to explain the role that energy plays in these and other chemical reactions, we need to get a better understanding of what energy is and the different forms it can take.

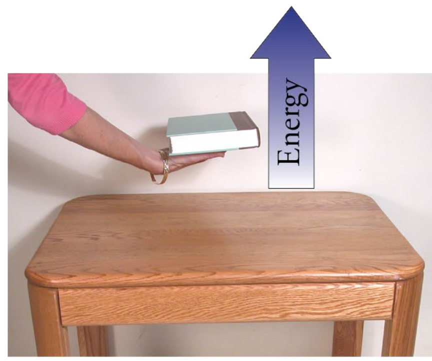
You probably have a general sense of what energy is. When you get up in the morning after a good night's sleep, you feel that you have plenty of energy to get your day's work done. After a long day of studying chemistry, you might feel like you hardly have the energy necessary to drag yourself to bed. The main goal of this section is to give you a more specific, scientific understanding of energy.

The simplest definition of **energy** is that it is the capacity to do work. Work, in this context, may be defined as what is done to move an object against some sort of resistance. For example, when you push this book across a table, the work you do overcomes the resistance caused by the contact between the book and the table. Likewise, when you lift this book, you do work to overcome the gravitational attraction that causes the book and the earth to resist being separated. When two oxygen atoms are linked together in a covalent bond, work must be done to separate them. Anything that has the capacity to do such work must, by definition, have energy (Figure 7.2).

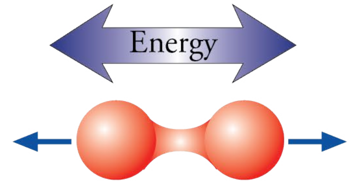
Figure 7.2
Energy: the Capacity to Do Work



Energy is required to push a book across a table and overcome the resistance to movement due to friction.



Energy is required to lift a book and overcome the resistance to movement due to gravity.



Energy is required to separate two atoms in a molecule and overcome the resistance to movement due to the chemical bond between them.

Kinetic Energy

It takes work to move a brick wall. A bulldozer moving at 20 miles per hour has the capacity to do this work, but when the same bulldozer is sitting still, it's not going to get the work done. The movement of the bulldozer gives it the capacity to do work, so this movement must be a form of energy. Any object that is in motion can collide with another object and move it, so any object in motion has the capacity to do work. This capacity to do work resulting from the motion of an object is called **kinetic energy, KE**.

Objective 2

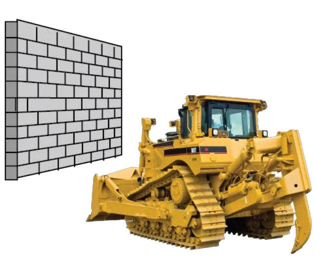
The amount of an object's kinetic energy is related to its mass and its velocity. If two objects are moving at the same velocity, the one with the greater mass will have a greater capacity to do work and thus a greater kinetic energy. For example, a bulldozer moving at 20 miles per hour can do more work than a scooter moving at the same velocity. If these two objects were to collide with a brick wall, the bulldozer would do more of the work of moving the wall than the scooter.

Objective 3

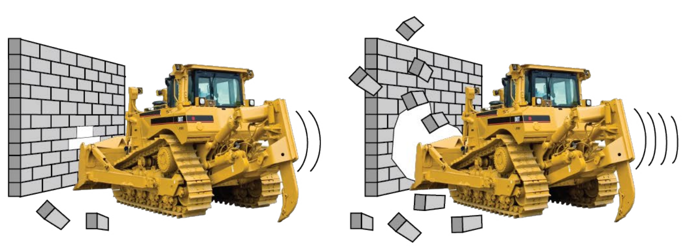
If two objects have equal mass but different velocities, the one with the greater velocity has the greater kinetic energy. A bulldozer moving at 20 miles per hour can do more work than an identical bulldozer moving at 5 miles per hour (Figure 7.3).

Objective 2 Objective 3

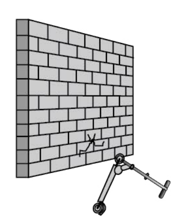
Figure 7.3
Factors that Affect Kinetic Energy



A stationary bulldozer does not have the capacity to do the work of moving a wall.



The faster moving bulldozer does more of the work of moving the wall. The faster an object moves, the more work it can do, and the more kinetic energy it has.



A scooter moving at the same velocity as a bulldozer will do less work and therefore has less energy.

Potential Energy

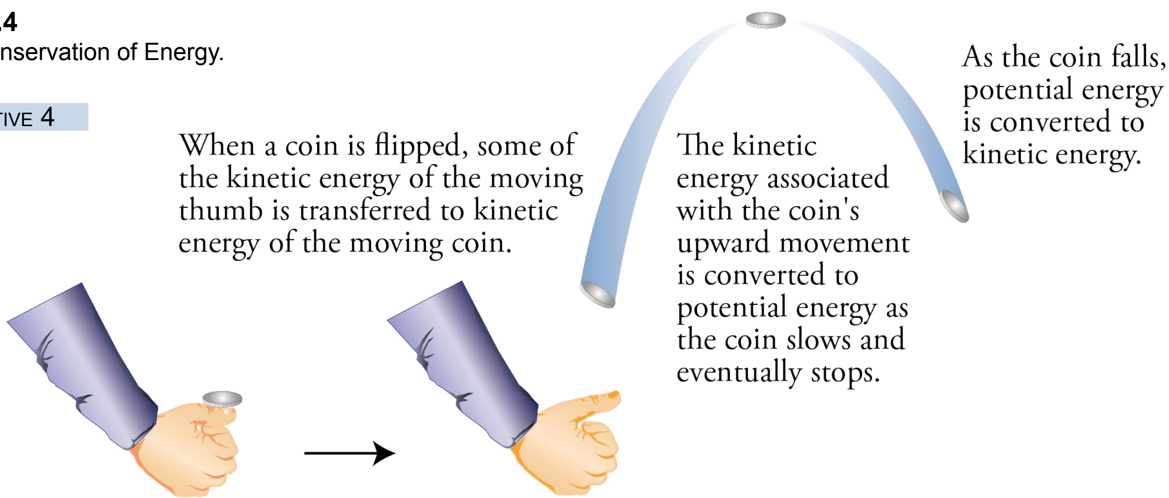
Energy can be transferred from one object to another. Picture the coin-toss that precedes a football game. A coin starts out resting in the referee's hand. After he flips it, sending it moving up into the air, it has some kinetic energy that it did not have before it was flipped. Where did the coin get this energy? From the referee's moving thumb. When scientists analyze such energy transfers, they find that all of the energy still exists. The **Law of Conservation of Energy** states that energy can be neither created nor destroyed, but it can be transferred from one system to another and changed from one form to another.[1]

Objective 4

As the coin rises, it slows down and eventually stops. At this point, the kinetic energy it got from the referee's moving thumb is gone, but the Law of Conservation of Energy says that energy cannot be destroyed. Where did the kinetic energy go? Although some of it has been transferred to the air particles it bumps into on its flight, most of the energy is still there in the coin in a form called **potential energy (PE)**, which is the retrievable, stored form of energy an object possesses by virtue of its position or state. We get evidence of this transformation when the coin falls back down toward the grass on the field. The potential energy it had at the peak of its flight is converted into kinetic energy of its downward movement, and this kinetic energy does the work of flattening a few blades of grass when the coin hits the field (Figure 7.4).

Figure 7.4
Law of Conservation of Energy.

Objective 4



There are many kinds of potential energy. An alkaline battery contains potential energy that can be used to move a toy car. A plate of pasta provides potential energy to allow your body to move. Knowing the relationships between potential energy and stability can help you to recognize changes in potential energy and to decide whether the potential energy has increased or decreased as a result of each change.

Objective 5

Objective 6

Let's look at the relationship between potential energy and stability. A system's stability is a measure of its tendency to change. A more stable system is less likely to change than a less stable system. As an object moves from a less stable state to a more stable state, it can do work. Thus, as an object becomes less stable, it gains a greater capacity to do work and, therefore, a greater potential energy. For example, a coin in your hand is less likely to move than a flipped coin at the peak of its flight, so we say that the coin in the hand is more stable than the coin in the air. As the coin moves

[1] Although chemists recognize that matter can be converted into energy and energy into matter, this matter-energy conversion is small enough to be disregarded.

from its less stable state in the air to a more stable state on the ground, it collides with and moves particles in the air and blades of grass. Therefore, the coin at the peak of its flight has a greater capacity to do the work of moving the objects, and, therefore, a greater potential energy than the more stable coin in the hand (Figure 7.5). *Any time a system shifts from a more stable state to a less stable state, the potential energy of the system increases.* We have already seen that kinetic energy is converted into potential energy as the coin is moved from the more stable position in the hand to the less stable position in the air.

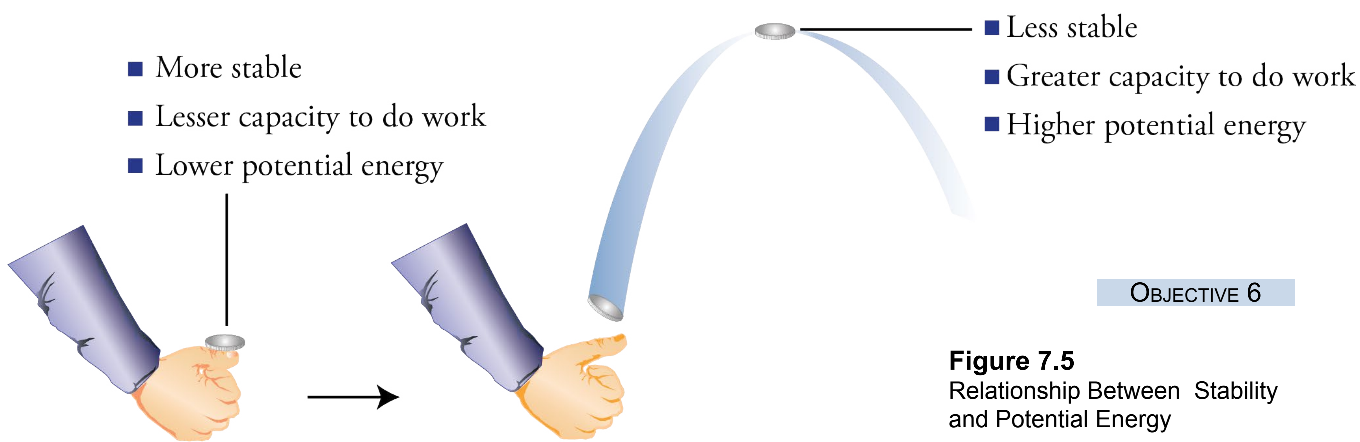
OBJECTIVE 5

more stable + **energy** → less stable system

lesser capacity to do work + **energy** → greater capacity to do work

lower PE + **energy** → higher PE

coin in hand + **energy** → coin in air above hand

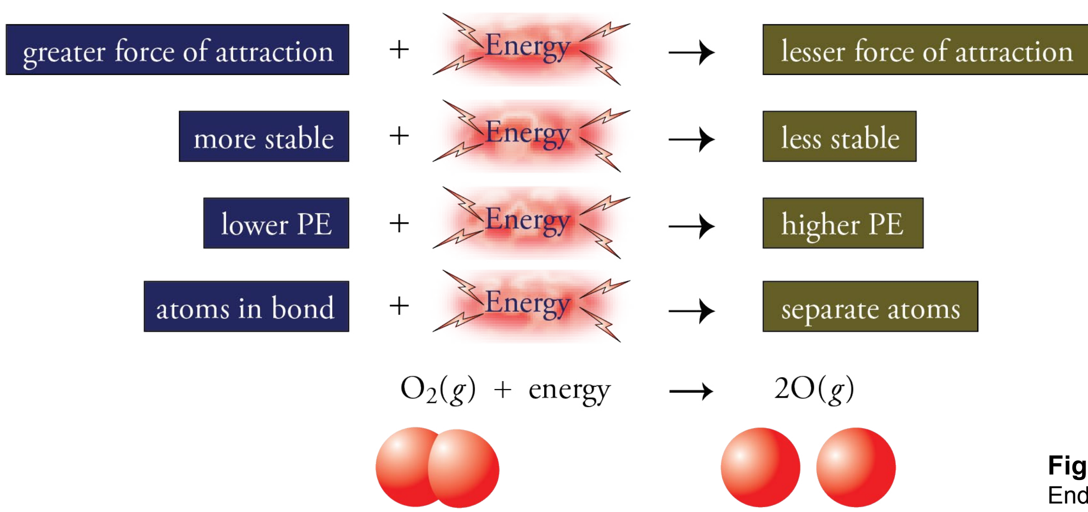


OBJECTIVE 6

Figure 7.5
Relationship Between Stability and Potential Energy

OBJECTIVE 7

Just as energy is needed to propel a coin into the air and increase its potential energy, energy is also necessary to separate two atoms being held together by mutual attraction in a chemical bond. The energy supplied increases the potential energy of the less stable separate atoms compared to the more stable atoms in the bond. For example, the first step in the formation of ozone in the earth's atmosphere is the breaking of the oxygen-oxygen covalent bonds in more stable oxygen molecules, O_2, to form less stable separate oxygen atoms. This change could not occur without an input of considerable energy, in this case, radiant energy from the sun. We call changes that absorb energy **endergonic** (or endogonic) changes (Figure 7.6).



OBJECTIVE 7

Figure 7.6
Endergonic Change

Objective 7

The attraction between the separated atoms makes it possible that they will change from their less stable separated state to the more stable bonded state. As they move together, they could bump into and move something (such as another atom), so the separated atoms have a greater capacity to do work and a greater potential energy than the atoms in the bond. This is why energy must be supplied to break chemical bonds.

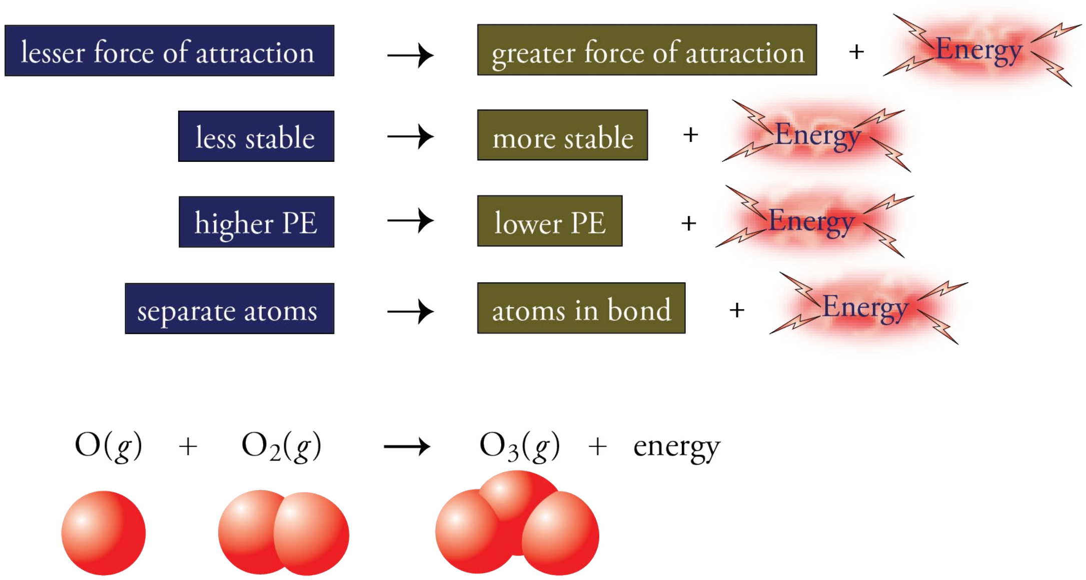
Objective 5

Objective 8

When objects shift from less stable states to more stable states, energy is released. For example, when a coin moves from the less stable peak of its flight to the more stable position on the ground, potential energy is released as kinetic energy. Likewise, energy is released when separate atoms come together to form a chemical bond. Because the less stable separate atoms have higher potential energy than the more stable atoms that participate in a bond, the change from separate atoms to atoms in a bond corresponds to a decrease in potential energy. Ozone, O_3, forms in the stratosphere when an oxygen atom, O, and an oxygen molecule, O_2, collide. The energy released in this change comes from the formation of a new O–O bond in ozone, O_3. We call changes that release energy **exergonic** (or exogonic) changes (Figure 7.7).

Figure 7.7
Exergonic Change

Objective 8



Some bonds are more stable than others. The products of the chemical reactions that take place in an alkaline battery, and in our bodies when the chemicals in pasta are converted into other substances, have more stable chemical bonds between their atoms than the reactants do. Therefore, in each case, the potential energy of the products is lower than that of the reactants, and the lost potential energy supplies the energy to move a toy car across the carpet and propel a four-year-old along behind it.

Example 7.1 - Energy

Objective 2
Objective 3
Objective 5

For each of the following situations, you are asked which of two objects or substances has the higher energy. Explain your answer with reference to the capacity of each to do work and say whether the energy that distinguishes them is kinetic energy or potential energy.

a. Incandescent light bulbs burn out because their tungsten filament gradually evaporates, weakening until it breaks. Argon gas is added to these bulbs to reduce the rate of evaporation. Which has greater energy, (1) an argon atom, Ar, with a velocity of 428 m/s or (2) the same atom moving with a velocity of 456 m/s? (These are the average velocities of argon atoms at 20 °C and 60 °C.)

b. Krypton, Kr, gas does a better job than argon of reducing the rate of evaporation of the tungsten filament in an incandescent light bulb. Because of its higher cost, however, krypton is only used when longer life is worth the extra cost. Which has higher energy, (1) an argon atom with a velocity of 428 m/s or (2) a krypton atom moving at the same velocity?

c. According to our model for ionic solids, the ions at the surface of the crystal are constantly moving out and away from the other ions and then being attracted back to the surface. Which has more energy, (1) a stationary sodium ion well separated from the chloride ions at the surface of a sodium chloride crystal or (2) a stationary sodium ion located quite close to the chloride ions on the surface of the crystal?

d. The chemical reactions that lead to the formation of polyvinyl chloride (PVC), which is used to make rigid plastic pipes, are initiated by the decomposition of peroxides. The general reaction is shown below. The simplest peroxide is hydrogen peroxide, H_2O_2 or HOOH. Which has more energy, (1) a hydrogen peroxide molecule or (2) two separate HO molecules that form when the relatively weak O–O bond in an HOOH molecule is broken?

$$\text{HOOH} \rightarrow 2\text{HO}$$

e. Hydrogen atoms react with oxygen molecules in the earth's upper atmosphere to form HO_2 molecules. Which has higher energy, (1) a separate H atom and O_2 molecule or (2) an HO_2 molecule?

$$\text{H}(g) + \text{O}_2(g) \rightarrow \text{HO}_2(g)$$

f. Dry ice—solid carbon dioxide—sublimes, which means that it changes directly from solid to gas. Assuming that the temperature of the system remains constant, which has higher energy, (1) the dry ice or (2) the gaseous carbon dioxide?

Solution

a. Any object in motion can collide with another object and move it, so any object in motion has the capacity to do work. This capacity to do work resulting from the motion of an object is called kinetic energy, KE. The particle with the higher velocity will move another object (such as another atom) farther, so it can do more work. It must therefore have more energy. In short, an **argon atom with a velocity of 456 m/s has greater kinetic energy** than the same atom with a velocity of 428 m/s.

b. The moving particle with the higher mass can move another object (such as another molecule) farther, so it can do more work and must therefore have more energy. Thus the **more massive krypton atoms moving at 428 m/s have greater kinetic energy** than the less massive argon atoms with the same velocity.

c. Separated ions are less stable than atoms in an ionic bond, so the **separated sodium and chloride ions have higher potential energy** than the ions that are closer together. The attraction between the separated sodium cation and the chloride anion pulls them together; as they approach each other, they could conceivably bump into another object, move it, and do work.

d. Separated atoms are less stable and have higher potential energy than atoms in a chemical bond, so energy is required to break a chemical bond. Thus energy is required to separate the two oxygen atoms of HOOH being held together by mutual attraction in a chemical bond. The energy supplied is represented in the higher potential energy of separate HO molecules compared to the HOOH molecule. If the bond were reformed, the potential energy would be converted into a form of energy that could be used to do work. In short, **two HO molecules have higher potential energy** than an HOOH molecule.

e. Atoms in a chemical bond are more stable and have lower potential energy than separated atoms, so energy is released when chemical bonds form. When H and O_2 are converted into an HO_2 molecule, a new bond is formed, and some of the potential energy of the separate particles is released. The energy could be used to do some work.

$$H(g) + O_2(g) \rightarrow HO_2(g)$$

Therefore, **separated hydrogen atoms and oxygen molecules have higher potential energy** than the HO_2 molecules that they form.

f. When carbon dioxide sublimes, the attractions that link the CO_2 molecules together are broken. The energy that the dry ice must absorb to break these attractions goes to increase the potential energy of the CO_2 as a gas. If the CO_2 returns to the solid form, attractions are reformed, and the potential energy is converted into a form of energy that could be used to do work. Therefore, **gaseous CO_2 has higher potential energy** than solid CO_2.

Exercise 7.1 - Energy

Objective 2
Objective 3
Objective 5

For each of the following situations, you are asked which of two objects or substances has the higher energy. Explain your answer with reference to the capacity of each to do work and say whether the energy that distinguishes them is kinetic energy or potential energy.

a. Nitric acid molecules, HNO_3, in the upper atmosphere decompose to form HO molecules and NO_2 molecules by the breaking of a bond between the nitrogen atom and one of the oxygen atoms. Which has higher energy, (1) a nitric acid molecule or (2) the HO molecule and NO_2 molecule that come from its decomposition?

$$HNO_3(g) \rightarrow HO(g) + NO_2(g)$$

b. Nitrogen oxides, $NO(g)$ and $NO_2(g)$, are released into the atmosphere in the exhaust of our cars. Which has higher energy, (1) a NO_2 molecule moving at 439 m/s or (2) the same NO_2 molecule moving at 399 m/s. (These are the average velocities of NO_2 molecules at 80 °C and 20 °C, respectively.)

c. Which has higher energy, (1) a nitrogen monoxide molecule, NO, emitted from your car's tailpipe at 450 m/s or (2) a nitrogen dioxide molecule, NO_2, moving at the same velocity?

d. Liquid nitrogen is used for a number of purposes, including the removal (by freezing) of warts. Assuming that the temperature remains constant, which has higher energy, (1) liquid nitrogen or (2) gaseous nitrogen?

e. Halons, such as halon-1301 (CF_3Br) and halon-1211 (CF_2ClBr), which have been used as fire extinguishing agents, are a potential threat to the Earth's protective ozone layer, partly because they lead to the production of $BrONO_2$, which is created from the combination of BrO and NO_2. Which has higher energy, (1) separate BrO and NO_2 molecules or (2) the $BrONO_2$ that they form?

f. The so-called alpha particles released by large radioactive elements such as uranium are helium nuclei consisting of two protons and two neutrons. Which has higher energy, (1) an uncharged helium atom or (2) an alpha particle and two separate electrons?

Units of Energy

Objective 9

The accepted SI unit for energy is the **joule (J)**, but another common unit is the **calorie (cal)**. The calorie has been defined in several different ways. One early definition described it as the energy necessary to increase the temperature of 1 gram of water from 14.5 °C to 15.5 °C. There are 4.186 J/cal according to this definition. Today, however, the U.S. National Institute of Standards and Technology defines the calorie as 4.184 joules:

Objective 10

$$4.184\ J = 1\ cal \quad \text{or} \quad 4.184\ kJ = 1\ kcal$$

The "calories" spoken of in the context of dietary energy—the energy supplied by food—are actually kilocalories, kcal, equivalent to 4184 J or 4.184 kJ. This dietary calorie is often written **Calorie** (using an uppercase C) and abbreviated Cal.

Objective 10

$$4184\ J = 1\ Cal \quad \text{or} \quad 4.184\ kJ = 1\ Cal$$

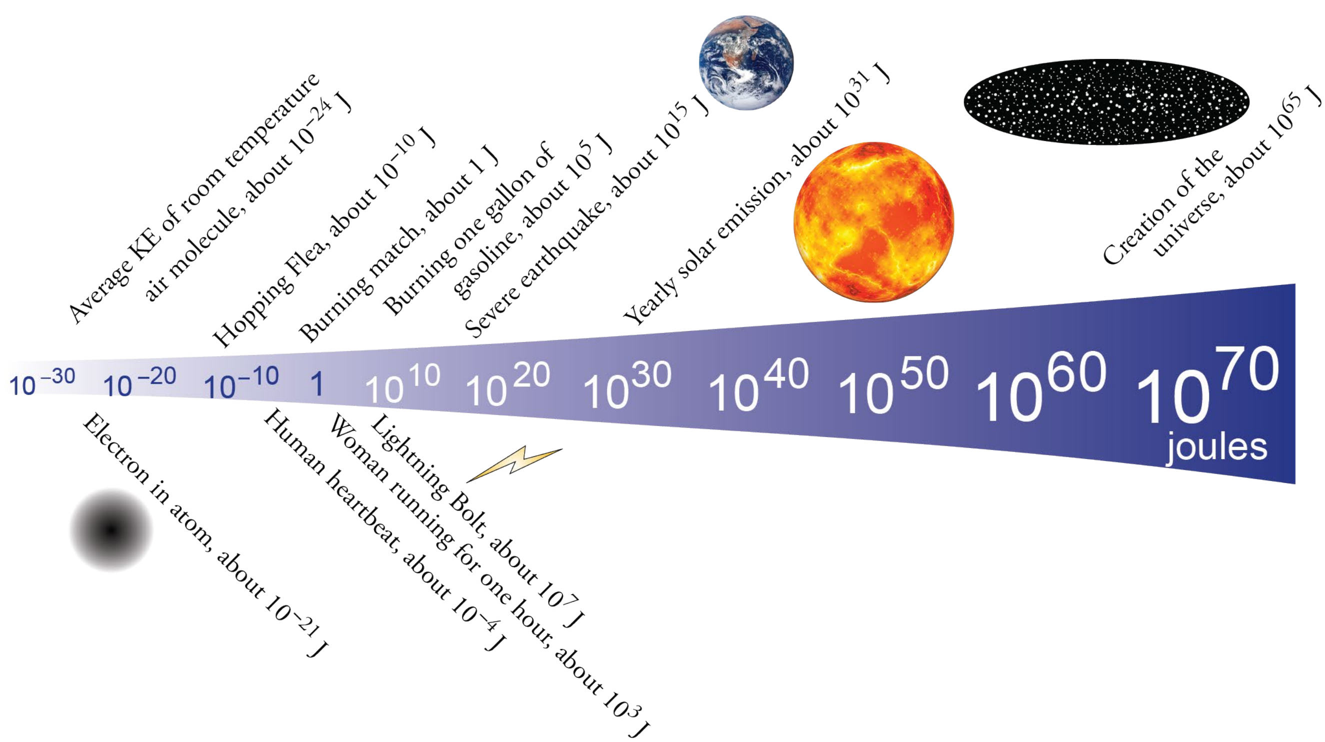
A meal of about 1000 dietary calories (Calories) provides about 4184 kJ of energy. Table 7.1 shows the energy provided by various foods. We will use joules and kilojoules to describe energy in this text. Figure 7.8 shows some approximate values in kilojoules for the energy represented by various events.

Table 7.1 Approximate Energy Provided by Various Foods

Food	Dietary Calories (kcal)	kilojoules (kJ)	Food	Dietary Calories (kcal)	kilojoules (kJ)
Cheese pizza (12 inch diameter)	1180	4940	Unsweetened apple juice (1 cup)	120	500
Roasted cashew nuts (1 cup)	780	3260	Butter (1 tablespoon)	100	420
White granular sugar (1 cup)	770	3220	Raw apple (medium sized)	100	420
Raw black beans (1 cup)	680	2850	Beer (8 fl oz glass)	100	420
Dry rice (1 cup)	680	2850	Chicken's egg (extra large)	90	380
Wheat flour (1 cup)	400	1670	Cheddar cheese (1 inch cube)	70	290
Ice cream - 10% fat (1 cup)	260	1090	Whole wheat bread (1 slice)	60	250
Raw broccoli (1 pound)	140	590	Black coffee (6 fl oz cup)	2	8

Figure 7.8

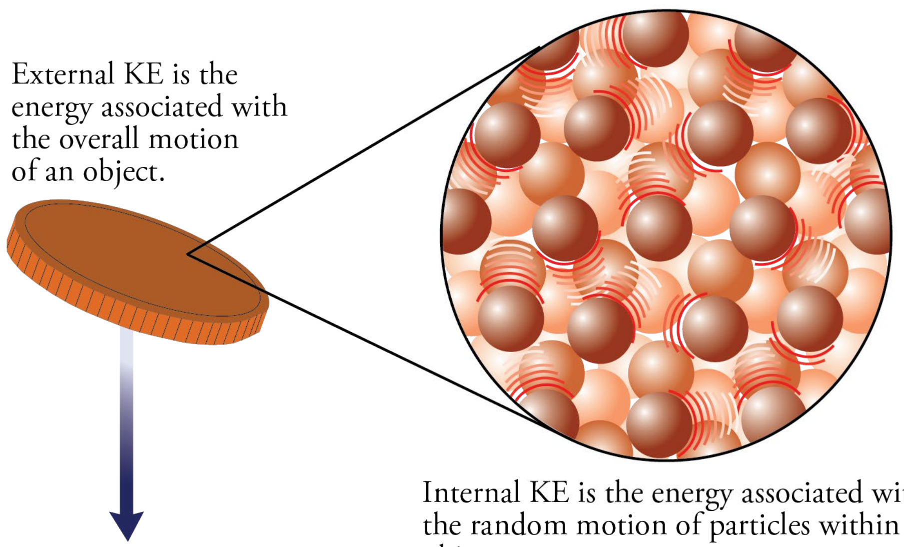
Approximate Energy of Various Events (The relative sizes of these measurements cannot be shown on such a small page. The wedge and the numbers of increasing size are to remind you that each numbered measurement on the scale represents 10,000,000,000 times the magnitude of the preceding numbered measurement.)



Kinetic Energy and Heat

An object's kinetic energy can be classified as internal or external. For example, a falling coin has a certain external kinetic energy that is related to its overall mass and to its velocity as it falls. The coin is also composed of particles that, like all particles, are moving in a random way, independent of the overall motion (or position) of the coin. The particles in the coin are constantly moving, colliding, changing direction, and changing their velocities. The energy associated with this internal motion is **internal kinetic energy** (Figure 7.9). OBJECTIVE 11

Figure 7.9
External Kinetic Energy and Internal Kinetic Energy

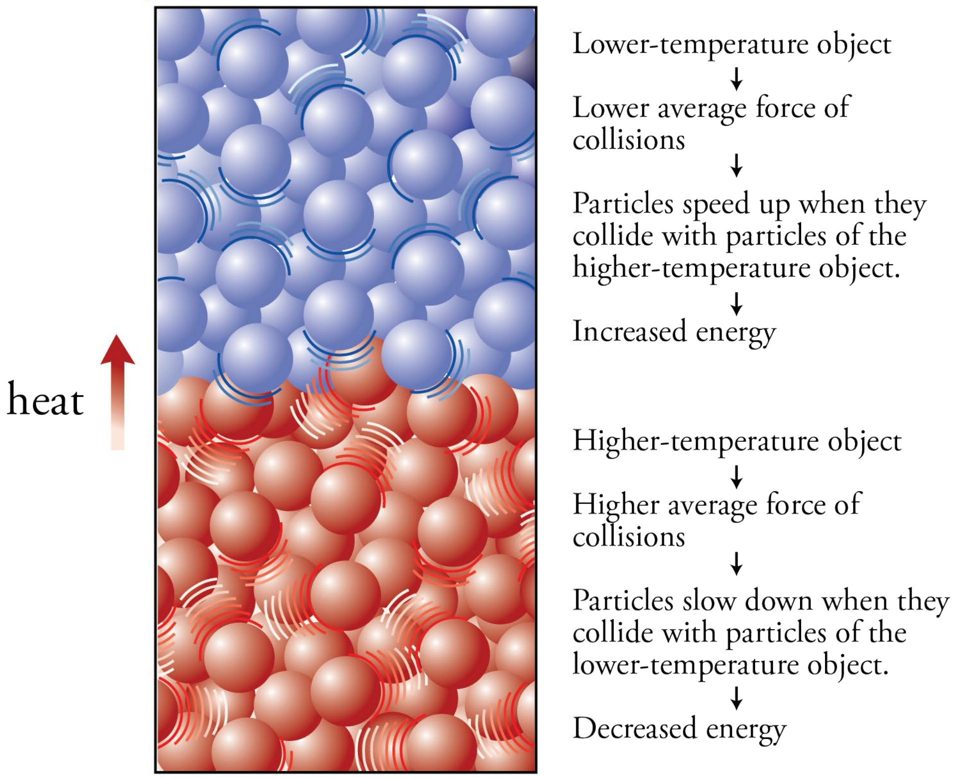


The amount of internal kinetic energy in an object can be increased in three general ways. The first way is to rub, compress, or distort the object. For example, after a good snowball fight, you can warm your hands by rubbing them together. Likewise, if you beat on metal with a hammer, it will get hot. OBJECTIVE 12

The second way to increase the internal kinetic energy of an object is to put it in contact with another object at a higher temperature. **Temperature** is proportional the average internal kinetic energy of an object, so higher temperature means a greater average internal energy for the particles within the object. The particles in a higher-temperature object collide with other particles with greater average force than the particles of a lower-temperature object. Thus collisions between the particles of two objects at different temperatures cause the particles of the lower-temperature object to speed up, increasing the object's energy, and cause the particles of the higher-temperature object to slow down, decreasing this object's energy. In this way, energy is transferred from the higher-temperature object to the lower-temperature object. We call energy OBJECTIVE 12 OBJECTIVE 13 OBJECTIVE 14 that is transferred in this way heat. The energy that is transferred through an object, as from the bottom of a cooking pan to its handle, is also called heat. **Heat** is the energy that is transferred from a region of higher temperature to a region of lower temperature as a consequence of the collisions of particles (Figure 7.10).

Figure 7.10
Heat Transfer

Objective 14



Objective 12

The third way an object's internal kinetic energy is increased is by exposure to radiant energy, such as the energy coming from the sun. The radiant energy is converted to kinetic energy of the particles in the object. This is why we get hot in the sun.

Radiant Energy

Gamma rays, X rays, ultraviolet radiation, visible light, infrared radiation, microwaves, and radio and TV waves are all examples of radiant energy. Although we know a great deal about radiant energy, we still have trouble describing what it is. For example, it seems to have a dual nature, with both particle and wave characteristics. It is difficult to visualize both of these two aspects of radiant energy at the same time, so sometimes we focus on its particle nature and sometimes on its wave character, depending on which is more suitable in a given context. Accordingly, we can describe the light that comes from a typical flashlight either as a flow of about 10^{17} particles of energy leaving the bulb per second or as waves of a certain length.

Objective 15

In the particle view, radiant energy is a stream of tiny, massless packets of energy called **photons**. The light from the flashlight contains photons of many different energies, so you might try to picture the beam as a stream of photons of many different sizes. (It is difficult to picture a particle without mass, but that is just one of the problems we have in describing what light is.)

The wave view says that as radiant energy moves away from its source, it has an effect on the space around it that can be described as a wave consisting of an oscillating electric field perpendicular to an oscillating magnetic field (Figure 7.11).

Objective 16

Because radiant energy seems to have both wave and particle characteristics, some experts have suggested that it is probably neither a wave nor a stream of particles. Perhaps the simplest model that includes both aspects of radiant energy says that as the photons travel, they somehow affect the space around them in such a way as to create the electric and magnetic fields.

Radiant energy, then, is energy that can be described in terms of oscillating electric and magnetic fields or in terms of photons. It is often called **electromagnetic radiation**. Because all forms of radiant energy have these qualities, we can distinguish one form of radiant energy from another either by the energy of its photons or the characteristics of its waves. The energies of the photons of radiant energy range from about 10^{-8} J per photon for the very high-energy gamma rays released in radioactive decay to about 10^{-31} J per photon or even smaller for low-energy radio waves. The different forms of radiant energy are listed in Figure 7.12 on the next page.

One distinguishing characteristic of the waves of radiant energy is wavelength, λ, the distance between two peaks on the wave of electromagnetic radiation. A more specific definition of **wavelength** is the distance in space over which a wave completes one cycle of its repeated form. Between two successive peaks, the wave has gone through all of its possible combinations of magnitude and direction and has begun to repeat the cycle again (Figure 7.11).

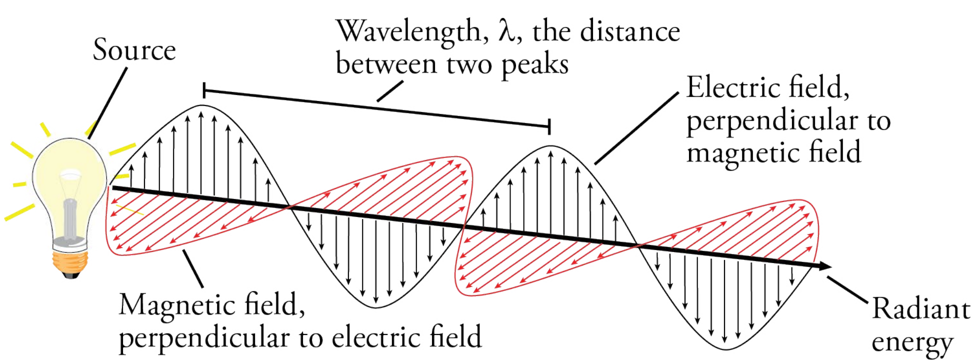


Figure 7.11
A Light Wave's Electric and Magnetic Fields

Objective 16

Gamma rays, with very high-energy photons, have very short wavelengths (Figure 7.12), on the order of 10^{-14} meters (or 10^{-5} nm). Short wavelengths are often described with nanometers, nm, which are 10^{-9} m. In contrast, the radio waves on the low-energy end of the AM radio spectrum have wavelengths of about 500 m (about one-third of a mile). If you look at the energy and wavelength scales in Figure 7.12, you will see that longer wavelength corresponds to lower-energy photons. The shorter the wavelength of a wave of electromagnetic radiation, the greater the energy of its photons. In other words, the energy, ε, of a photon is inversely proportional to the radiation's wavelength, λ. (The symbol ε is a lower case Greek epsilon, and the λ is a lowercase Greek lambda.)

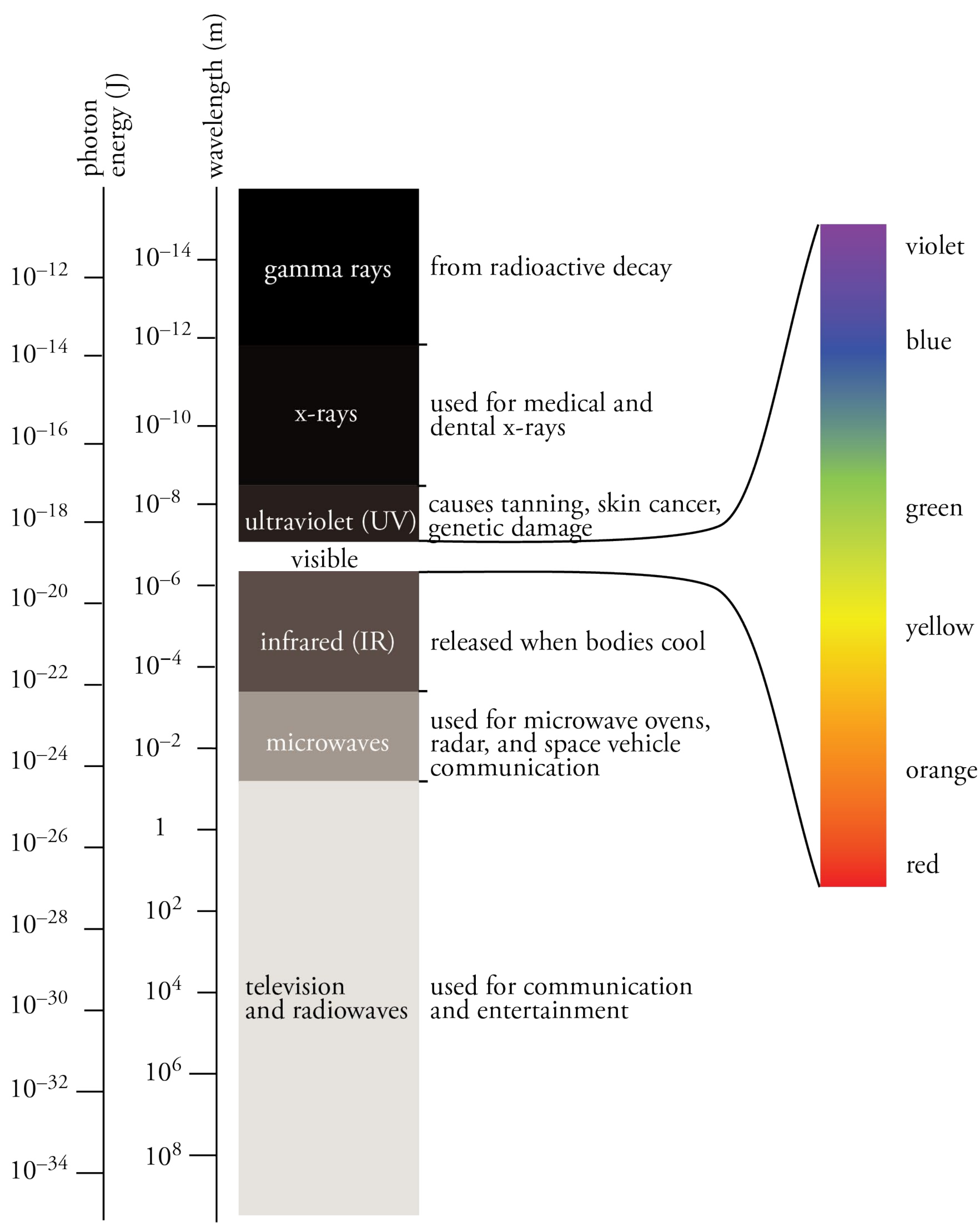
Objective 17

$$\varepsilon \propto \frac{1}{\lambda}$$

As Figure 7.12 illustrates, all forms of radiant energy are part of a continuum with no precise dividing lines between one form and the next. In fact, there is some overlap between categories. Note that visible light is only a small portion of the radiant energy spectrum. The different colors of visible light are due to different photon energies and associated wavelengths.

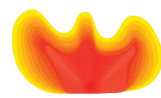
Figure 7.12
Radiant-Energy Spectrum

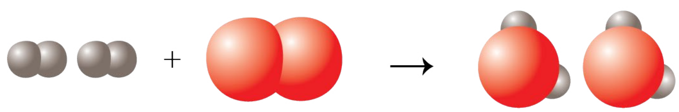
Objective 18 Objective 19



7.2 Chemical Changes and Energy

In most chemical reactions, bonds are broken and new ones formed. Section 7.1 showed us that the breaking of bonds requires energy and the formation of bonds releases it. If in a chemical reaction, more energy is released in the formation of new bonds than was necessary to break old bonds, energy is released overall, and the reaction is exergonic. The burning of hydrogen gas is an exergonic process: OBJECTIVE 20

$$2H_2(g) \quad + \quad O_2(g) \quad \longrightarrow \quad 2H_2O(l) \quad +$$ 



On the one hand, energy is required to break the bonds between the hydrogen atoms in the hydrogen molecules, H_2, and between the oxygen atoms in the oxygen molecules, O_2. On the other hand, energy is released in the formation of the H–O bonds in water. Because the bonds in the product are more stable, we say that they are stronger than the bonds in the reactants, and the product has lower potential energy than the reactants. Energy is released overall.

weaker bonds → stronger bonds + **energy**

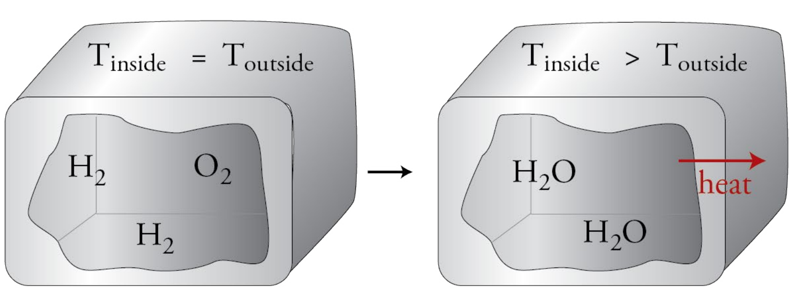
higher PE → lower PE + **energy** OBJECTIVE 20

$2H_2(g) + O_2(g) \rightarrow 2H_2O(g) +$ **energy**

To visualize these energy changes at the molecular level, let's picture a container of hydrogen and oxygen that is initially at the same temperature as its surroundings (Figure 7.13). As the reaction proceeds and forms water molecules, some of the potential energy of the system is converted into kinetic energy. (This is similar to the conversion of potential energy to kinetic energy when a coin falls toward the ground.) The higher average kinetic energy of the particles in the product mixture means that the product mixture is at a higher temperature than the initial reactant mixture and therefore at a higher temperature than the surroundings. Thus the higher-temperature products transfer heat to the surroundings. Because the conversion of potential energy OBJECTIVE 20

OBJECTIVE 20

Figure 7.13
Exothermic Reaction



Stronger bonds → More stable
↓
Energy released ← Lower PE
↓
Increases KE_{ave} of product particles
↓
Increased T → $T_{inside} > T_{outside}$
↓
Heat transferred to surroundings
↓
Exothermic

to kinetic energy in the reaction can lead to heat being released from the system, the energy associated with a chemical reaction is often called the *heat of reaction*. A change that leads to heat energy being released from the system to the surroundings is called **exothermic**. (Exergonic means *any form of energy* released, and exothermic means *heat* energy released.)

Objective 21

If less energy is released in the formation of the new bonds than is necessary to break the old bonds, energy must be absorbed from the surroundings for the reaction to proceed. The reaction that forms calcium oxide, often called quicklime, from calcium carbonate is an example of this sort of change. (Quicklime has been used as a building material since 1500 BC. It is used today to remove impurities in iron ores. Calcium oxide is also used in air pollution control and water treatment.) In the industrial production of quicklime, this reaction is run at over 2000 °C to provide enough energy to convert the calcium carbonate into calcium oxide and carbon dioxide.

Objective 21

$$\text{stronger bonds} + \textbf{energy} \rightarrow \text{weaker bonds}$$

$$\text{lower PE} + \textbf{energy} \rightarrow \text{higher PE}$$

$$CaCO_3(s) + \textbf{energy} \rightarrow CaO(s) + CO_2(g)$$

Objective 21

Collectively, the bonds formed in the products are weaker and, therefore, less stable than those of the reactant, so the products have higher potential energy than the reactants. The high temperature is necessary to provide energy for the change to the greater-potential-energy products. Because energy is absorbed in the reaction, it is endergonic.

Endergonic changes can lead to a transfer of heat *from* the surroundings. Cold packs used to quickly cool a sprained ankle are an example of this kind of change. One kind of cold pack contains a small pouch of ammonium nitrate, NH_4NO_3, inside a larger pouch of water. When the cold pack is twisted, ammonium nitrate is released into the water, and as it dissolves, the water cools (Figure 7.14).

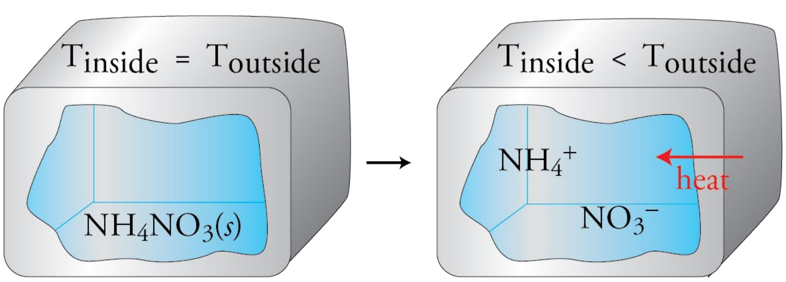
$$NH_4NO_3(s) + \textbf{energy} \rightarrow NH_4^+(aq) + NO_3^-(aq)$$

Objective 21

The attractions between the particles in the final mixture are less stable and have higher potential energy than the attractions in the separate ammonium nitrate solid and liquid water. The energy necessary to increase the potential energy of the system comes from some of the kinetic energy of the moving particles, so the particles in the final mixture have a lower average kinetic energy and a lower temperature than the

Figure 7.14
Endothermic Reaction

Objective 21



Weaker bonds → Less stable
↓
Energy absorbed ← Higher PE
↓
Decreases KE_{ave} of product particles
↓
Decreased T → $T_{inside} < T_{outside}$
↓
Heat transferred to system → Endothermic

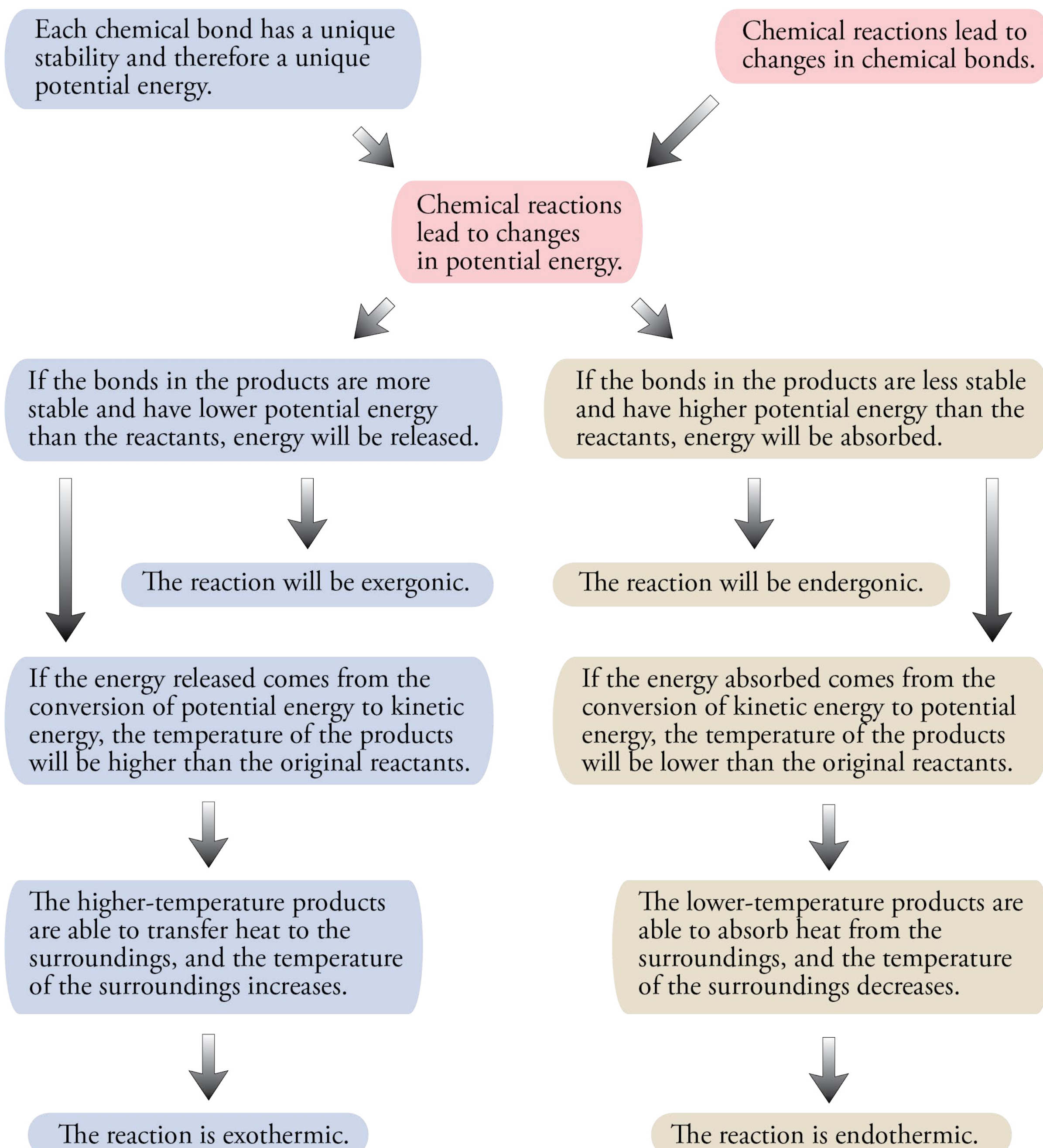
original substances. Heat is transferred from the higher-temperature sprained ankle to the lower-temperature cold pack. A change, such as the one in the cold pack, which leads a system to absorb heat energy from the surroundings, is called an **endothermic** change. (Endergonic means *any form of energy* absorbed, and endothermic means *heat* energy absorbed.)

OBJECTIVE 22

Figure 7.15 shows the logic sequence that summarizes why chemical reactions either release or absorb energy. It also shows why, in many cases, the change leads to a transfer of heat either to or from the surroundings, with a corresponding increase or decrease in the temperature of the surroundings.

OBJECTIVE 22

Figure 7.15
Energy and Chemical Reactions



7.3 Ozone: Pollutant and Protector

The discoveries that have caused scientists to worry about ozone levels in the Earth's atmosphere offer some excellent examples of the relationship between energy and chemical changes. Perhaps the news media's handling of these issues has caused you some confusion. One day you might see a newspaper headline about an ozone alert in Los Angeles, triggered by the concentration of ozone in the air rising to *too high* a level. Schoolteachers are warned to keep students off the playgrounds to prevent damage to their lungs. Turning the page in the same newspaper, you discover another article that describes problems resulting from *decreasing* amounts of ozone in the "ozone layer" of the upper atmosphere. *So, which is it?…too much or too little?* Is ozone a pollutant or a protector? What is this substance, and why are we so worried about it?

Leaves can be damaged by ozone.

Two forms of the element oxygen are found in nature: the life-sustaining diatomic oxygen, O_2, and ozone, O_3, which is a pale blue gas with a strong odor. The concentrations of ozone in the air around us are usually too low for the color and the odor to be apparent, but sometimes when we stand next to an electric motor, we notice ozone's characteristic smell. This is because an electric spark passing through oxygen gas creates ozone.

Objective 23

Ozone is a very powerful oxidizing agent. Sometimes this property can be used to our benefit, and sometimes it is a problem. Ozone mixed with oxygen can be used to sanitize hot tubs, and it is used in industry to bleach waxes, oils, and textiles, but when the levels in the air get too high, ozone's high reactivity becomes a problem. For example, O_3 is a very strong respiratory irritant that can lead to shortness of breath, chest pain when inhaling, wheezing, and coughing. Anyone who has lived in a smoggy city will recognize these symptoms. Not only can ozone oxidize lung tissue, but it also damages rubber and plastics, leading to premature deterioration of products made with these materials. Furthermore, ozone causes significant damage to plants.

Objective 24
Objective 25

The highest concentrations of O_3 in the air we breathe are found in large industrial cities with lots of cars and lots of sun. The explanation why this is true begins with a description of the source of nitrogen oxides. Any time air (which contains nitrogen and oxygen) is heated to high temperature (as occurs in the cylinders of our cars and in many industrial processes), nitrogen oxides are formed (NO and NO_2).

$$N_2(g) + O_2(g) \rightarrow 2NO(g)$$

$$2NO(g) + O_2(g) \rightarrow 2NO_2(g)$$

Nitrogen dioxide, NO_2, is a red-brown gas that contributes to the brown haze associated with smog.

Objective 24
Objective 26

The radiant energy that passes through the air on sunny days can supply the energy necessary to break covalent bonds between nitrogen atoms and oxygen atoms in NO_2 molecules, converting NO_2 molecules into NO molecules and oxygen atoms. Remember that the shorter the wavelength of light is, the higher the energy. Radiant energy of wavelengths less than 400 nm has enough energy to break N–O bonds in NO_2 molecules, but radiant energy with wavelengths longer than 400 nm does not supply enough energy to separate the atoms.

$$NO_2(g) \xrightarrow{\lambda < 400\text{ nm}} NO(g) + O(g)$$

The oxygen atoms react with oxygen molecules to form ozone molecules.

$$O(g) + O_2(g) \rightarrow O_3(g)$$

Objective 26

Because the process of ozone formation is initiated by light photons, the pollutant mixture is called photochemical smog. Figure 7.16 shows typical ozone levels in different areas of the United States. Note that the concentrations are highest in southern California. Cities such as Los Angeles, with its sunny weather and hundreds of thousands of cars, have ideal conditions for the production of photochemical smog. This smog is worst from May to September, when the days are long and the sunlight intense.

Objective 25

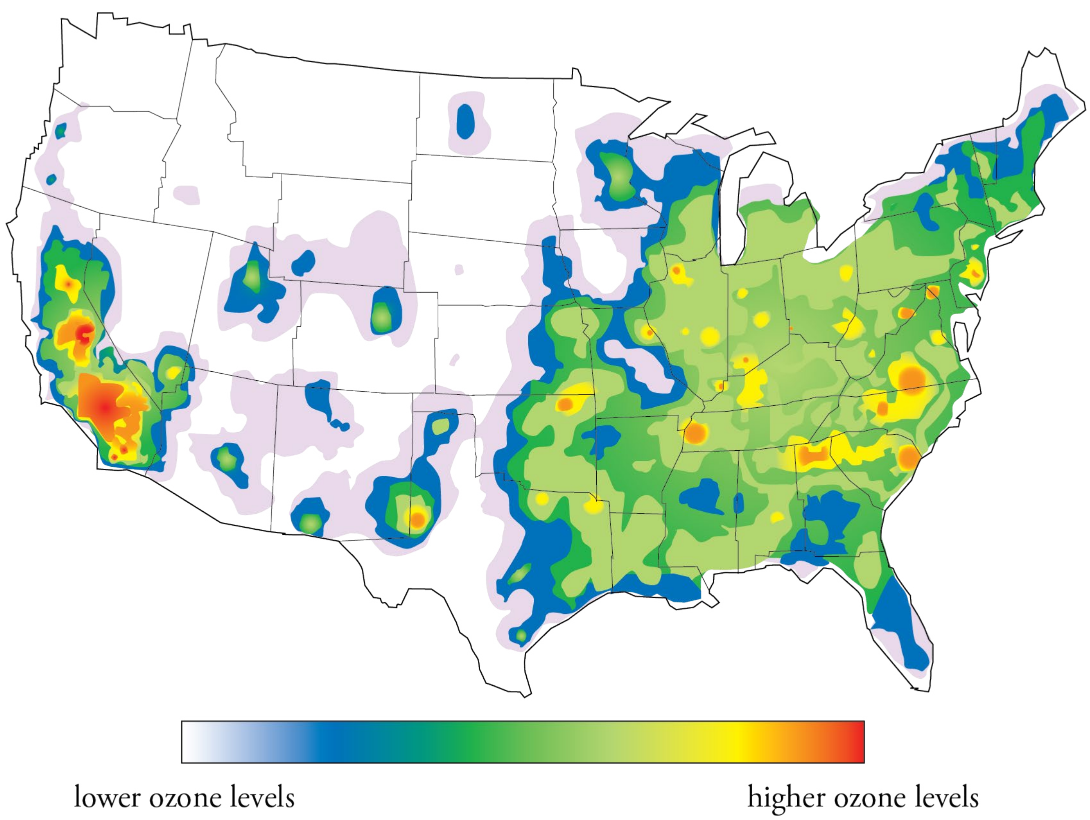
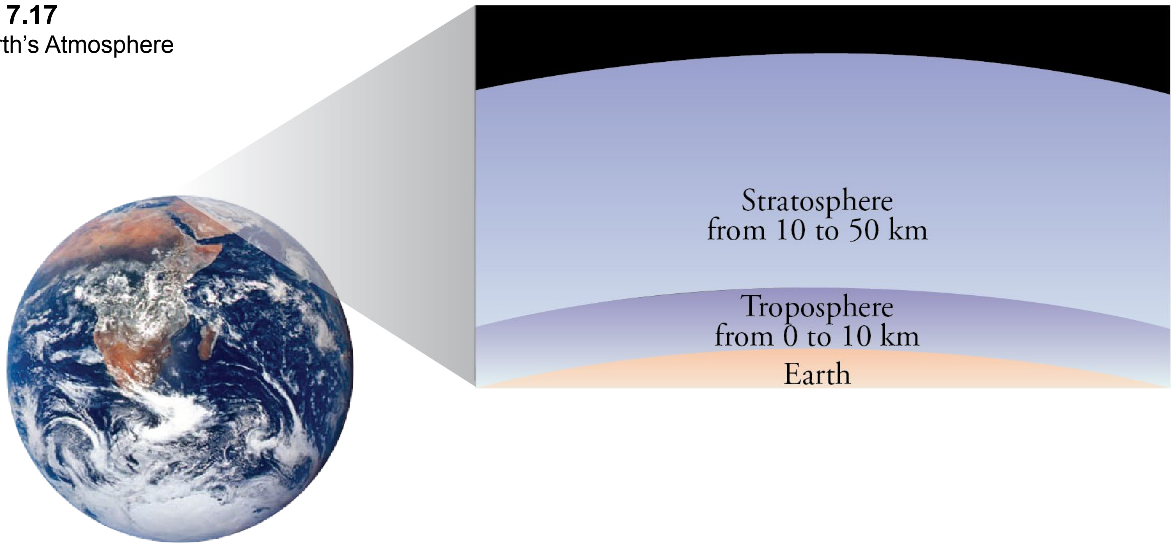


Figure 7.16
Typical Ozone Concentrations in the United States

Now that we have seen the conditions that lead to *too much* O_3 in the air we breathe and why that is a problem, we need to know why depleting the ozone in the upper atmosphere, creating *too little* ozone there, can also be a problem. Let's start with a little information about our atmosphere. Atmospheric scientists view the atmosphere as consisting of layers, each with its own characteristics. The lowest layer, which extends from the surface of the earth to about 10 km (about 6 miles) above sea level, is called the **troposphere**. For our discussion of ozone, we are more interested in the next lowest layer, the **stratosphere**, which extends from about 10 km to about 50 km above sea level (Figure 7.17).

Figure 7.17
The Earth's Atmosphere



The stratosphere contains a mixture of gases, including oxygen molecules, O_2, and ozone molecules, O_3, that play a very important role in protecting the earth from the sun's high-energy ultraviolet radiation. The ultraviolet portion of the sun's energy spectrum can be divided into three parts: UV-A, UV-B, and UV-C. Not all UV radiation is harmful. **UV-A**, which includes radiant energy of wavelengths from about 320 to 400 nm, passes through the stratosphere and reaches us on the surface of the earth. We are glad it does, because UV-A radiation provides energy that our bodies use to produce vitamin D.

Objective 27

Objective 28

Objective 27

Objective 29

The shorter-wavelength **UV-B** radiation (from about 290 to 320 nm) has greater energy than the UV-A radiation. Some UV-B radiation is removed by the gases in the stratosphere, but some of it reaches the surface of the earth. Radiation in this portion of the spectrum has energy great enough that excessive exposure can cause sunburn, premature skin aging, and skin cancer.

Objective 27

Objective 30

The highest-energy ultraviolet radiation is **UV-C**, with wavelengths from about 40 to 290 nm. We are very fortunate that this radiant energy is almost completely removed by the gases in the atmosphere, because UV-C is energetic enough to cause serious damage not only to us but to all life on earth. One reason it is so dangerous is that DNA, the substance that carries genetic information in living cells, absorbs UV radiation of about 260 nm. Likewise, proteins, which are vital structural and functional components of living systems, absorb radiation with wavelengths of about 280 nm. If these wavelengths were to reach the earth in significant quantity, the changes they would cause by altering DNA and protein molecules would lead to massive crop damage and general ecological disaster.

Removal of UV Radiation by Oxygen and Ozone Molecules

Objective 31

Some of the dangerous radiation removed in the stratosphere is absorbed by the O_2 molecules there. Radiant-energy wavelengths must be shorter than 242 nm to have enough energy to break the O-O bond, and UV-C radiation has wavelengths in the proper range.

$$O_2(g) \xrightarrow{\text{UV with } \lambda < 242 \text{ nm}} 2O(g)$$

Objective 31

UV radiation can also provide the energy to break a bond between oxygen atoms in ozone molecules. Because less energy is needed to break a bond in the O_3 molecule than to break the bond in O_2, the UV photons that break the bond in O_3 are associated with longer wavelengths. The O_3 molecules will absorb UV radiation of wavelengths from 240 nm to 320 nm.

$$O_3(g) \xrightarrow{\text{UV with } \lambda \text{ from 240 to 320 nm}} O(g) + O_2(g)$$

Objective 31

Thus oxygen molecules, O_2, and ozone molecules, O_3, work together to absorb high-energy UV radiation. Oxygen molecules absorb UV radiation with wavelengths less than 242 nm, and ozone molecules absorb radiant energy with wavelengths from 240 nm to 320 nm (Figure 7.18). We have seen that wavelengths in the range of 240 to 320 nm can cause problems that include skin aging, skin cancer, and crop failure. Because O_2 does not remove this radiation from the atmosphere, it is extremely important that the ozone layer be preserved.

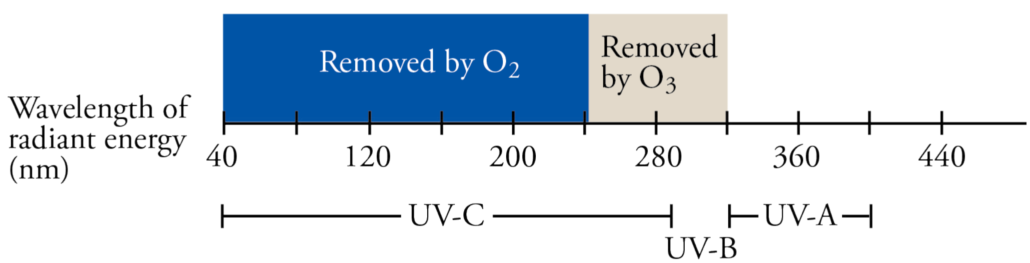


Figure 7.18 Removal of Ultraviolet Radiation in the Stratosphere

Objective 31

The Natural Destruction of Ozone

Ozone is constantly being generated and destroyed in the stratosphere as part of a natural cycle. The reactions for the synthesis of ozone are

$$O_2(g) \xrightarrow{\text{UV radiation}} 2O(g)$$

$$O(g) + O_2(g) \rightarrow O_3(g)$$

Objective 32

Several natural processes destroy ozone in the stratosphere. Perhaps the most important are:

$$NO(g) + O_3(g) \rightarrow NO_2(g) + O_2(g)$$

$$\text{and} \quad NO_2(g) + O(g) \rightarrow NO(g) + O_2(g)$$

The first reaction destroys one ozone molecule directly. The second reaction destroys an oxygen atom that might have become part of an ozone molecule. (Because oxygen atoms can collide with oxygen molecules to form ozone molecules, the ozone concentration is depleted indirectly through the removal of oxygen atoms.) The main reason that this pair of reactions is so efficient at destroying ozone molecules, however, is that the $NO(g)$ that is destroyed in the first reaction is regenerated in the second reaction. Therefore, in the overall reaction, an ozone molecule and an oxygen atom are converted into two oxygen molecules with no change in the number of NO molecules. This makes $NO(g)$ a catalyst for the reaction. A **catalyst** is a substance that speeds a chemical reaction without being permanently altered itself. The equation for the net reaction is

$$O_3(g) + O(g) \xrightarrow{\text{NO catalyst}} 2O_2(g)$$

7.4 Chlorofluorocarbons: A Chemical Success Story Gone Wrong

The announcement today, suggesting a worse situation than we thought, affirms the warning I issued last Spring: Upper atmosphere ozone depletion remains one of the world's most pressing environmental threats.

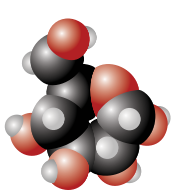
William K. Reilly, Administrator of the U.S. Environmental Protection Agency, 1991

In 1972 the chemical industry was producing about 700,000 metric tons (about 1.5 billion pounds) of **chlorofluorocarbons** (CFCs) per year, compounds composed entirely of carbon, chlorine, and fluorine. Most of the CFCs produced in the early 70's were either CFC-11, which is $CFCl_3$, or CFC-12, which is CF_2Cl_2. The development of these chemicals was considered a major triumph for the industry because they seemed to be perfect for use as aerosol propellants, solvents, expansion gases in foams, heat-exchanging fluids in air conditioners, and temperature-reducing fluids in refrigerators.

One of the reasons why CFCs were so successful is that they are extremely stable compounds; very few substances react with them. As a result, they are nontoxic and nonflammable. Another important characteristic is that they are gases at normal room temperatures and pressures, but they become liquids at pressures slightly above normal. These were precisely the characteristics needed for the applications listed above.

CFCs and the Ozone Layer

Objective 33



Web Molecules

Objective 34

Generally, gases are removed from the lower atmosphere in two ways. They either dissolve in the clouds and are rained out, or they react chemically to be converted into other substances. Neither of these mechanisms is important for CFCs. Chlorofluorocarbons are insoluble in water, and they are so stable that they can persist in the lower atmosphere for years. For example, CFC-11 molecules have an average life of 50 years in the atmosphere, and CFC-12 molecules have an average life of about 102 years. During this time, the CFC molecules wander about, moving wherever the air currents take them. They can eventually make their way into the stratosphere, where they encounter radiation with enough energy to break them down. For example, radiant energy of wavelength less than 215 nm will break the covalent bond between a chlorine atom and the carbon atom in CF_2Cl_2.

$$CF_2Cl_2(g) \xrightarrow{\lambda < 215\text{ nm}} CF_2Cl(g) + Cl(g)$$

Objective 35

The chlorine atoms released in this sort of reaction can destroy ozone molecules, in a process similar to the catalytic reactions between NO, O_3, and O described in the last section:

$$2Cl(g) + 2O_3(g) \rightarrow 2ClO(g) + 2O_2(g)$$

$$2ClO(g) \rightarrow ClOOCl(g)$$

Objective 35

$$ClOOCl(g) \rightarrow ClOO(g) + Cl(g)$$

$$ClOO(g) \rightarrow Cl(g) + O_2(g)$$

In one cycle, each chlorine atom destroys one ozone molecule. Because the chlorine atom is regenerated in the last two reactions, its role is that of a catalyst for the reaction. The equation for the net reaction is

$$\text{Net reaction:} \quad 2O_3(g) \xrightarrow{\text{Cl catalyst}} 3O_2(g)$$

Each chlorine atom is thought to destroy an average of 1000 ozone molecules before being temporarily incorporated into a compound such as HCl or $ClONO_2$.

$$CH_4(g) + Cl(g) \rightarrow CH_3(g) + HCl(g)$$

$$\text{and} \quad ClO(g) + NO_2(g) \rightarrow ClONO_2(g)$$

In 1985, scientists discovered a large decrease in the atmospheric concentration of ozone over Antarctica. This "ozone hole" could not be explained with the models used to describe atmospheric chemistry at that time, but it has since been explained in terms of an unexpectedly rapid reformation of chlorine atoms from chlorine compounds such as HCl and $ClONO_2$. The new model suggests that reactions such as the following take place on the surface of ice crystals that form in the cold air of the stratosphere over Antarctica.

$$ClONO_2(g) + HCl(s) \rightarrow Cl_2(g) + HNO_3(s)$$

$$ClONO_2(g) + H_2O(s) \rightarrow HOCl(g) + HNO_3(s)$$

$$HOCl(g) + HCl(s) \rightarrow Cl_2(g) + H_2O(s)$$

$$HOCl(g) \xrightarrow{\text{radiant energy}} Cl(g) + OH(g)$$

$$Cl_2(g) \xrightarrow{\text{radiant energy}} 2Cl(g)$$

The chlorine atoms freed in these reactions can once again react with ozone molecules and oxygen atoms. Many scientists fear that each chlorine atom that reaches the stratosphere may destroy tens of thousands of ozone molecules before escaping from the stratosphere. One way they finally escape is by migrating back into the lower atmosphere in HCl molecules that dissolve in the clouds and return to the earth in rain.

Special Topic 7.1 *Green Chemistry—Substitutes for Chlorofluorocarbons* describes substitutes for chlorofluorocarbons, and Special Topic 7.2 *Other Ozone-Depleting Chemicals* describes other ozone-depleting chemicals.

Special Topic 7.1 Green Chemistry - Substitutes for Chlorofluorocarbons

Any television, computer, or other fragile item you have purchased in recent years has probably come packaged in polystyrene foam (Styrofoam) for protection. The same foam is likely to be serving as insulation in the cooler you take along on a picnic. It is a stiff, low-density, non-heat-conducting solid produced by blowing gas into polystyrene liquid as it solidifies. Over 700 million pounds were manufactured in 1995.

Chlorofluorocarbons have been used as the blowing agents in the production of polystyrene foam, but because of the damage CFCs may be causing to the ozone layer, chemists are actively seeking other ways of doing the job. In 1996, the Dow Chemical Company received a Presidential Green Chemistry Challenge Award, specifically the Alternative Solvents/Reaction Conditions Award, for developing a process that makes polystyrene foam using 100% carbon dioxide, CO_2, as the blowing agent. (See Special Topic 1.1: *Green Chemistry*.) Carbon dioxide is nonflammable and nontoxic and does not deplete the ozone layer. The process does not even increase the level of CO_2 in the atmosphere, because the carbon dioxide it uses comes from other commercial or natural sources, such as ammonia plants or natural gas wells. This new technology reduces the use of CFCs by 3.5 million pounds per year.

Special Topic 7.2 Other Ozone-Depleting Chemicals

Although CFCs have gotten the most attention as a threat to the ozone layer, there are other chemicals that are also thought to pose a danger to it. Halons, which are similar to CFCs but contain at least one bromine atom, are one such group of compounds. Halon-1301 (CF_3Br) and halon-1211 (CF_2ClBr) have been used as fire-extinguishing agents, but the bromine atoms they release have been shown to be even more efficient at destroying ozone than chlorine atoms are.

While governments are in general agreement that halons should be banned, the status of another bromine-containing compound is more ambiguous. This compound is methyl bromide, CH_3Br. The controversy revolves around whether or not methyl bromide has a significant effect on the ozone layer and whether the benefits of using it outweigh the potential hazards. This ozone-depleting compound is different from CFCs and halons because it is not produced by humans only, but by many prolific natural sources. For example, the ocean is thought to both release and absorb significant amounts of CH_3Br, and wildfires generate methyl bromide as well. The actual contribution of the various sources of methyl bromide to the atmosphere is still uncertain, but many scientists agree that significant amounts do come from human activities (so-called *anthropogenic sources*) such as the burning of rain forests, the use of insecticides, herbicides, and fungicides, and the use of leaded gasoline that contains ethylene dibromide. One of the reasons methyl bromide has been considered less threatening to the ozone layer than CFCs or halons is that it has a much shorter lifetime. The best estimates predict its average lifetime to be 1 to 2 years compared to over 50 years for the shortest-lived common CFC and over 20 years for the most common halons. Although research on the possible effects of methyl bromide continues, experts now consider it damaging enough that steps have been taken to begin phasing it out.

With the discovery of the damaging effects of CFCs, alternatives were developed that have many of the desirable characteristics of CFCs but are less stable in the lower atmosphere and less likely to reach the stratosphere. These chemicals, called hydrochlorofluorocarbons (HCFCs), are similar in structure to CFCs but contain at least one hydrogen atom. For example, HCFC-22 is CF_2HCl, and HCFC-123 is CF_3CHCl_2. Although these chemicals are thought to be less damaging to the ozone layer, they too can reach the stratosphere and lead to some depletion of O_3. Thus they are viewed as transitional compounds to be used until better substitutes have been found.

Chapter Glossary

Energy The capacity to do work.

Kinetic energy The capacity to do work due to the motion of an object.

Law of Conservation of Energy Energy can neither be created nor destroyed, but it can be transferred from one system to another and changed from one form to another.

Potential energy A retrievable, stored form of energy an object possesses by virtue of its position or state.

Endergonic (endogonic) change Change that absorbs energy.

Exergonic (exogonic) change Change that releases energy.

Joule (J) The accepted international unit for energy.

calorie (with a lowercase c) A common energy unit. There are 4.184 joules per calorie (abbreviated *cal*).

Calorie (with an upper case C) The dietary calorie (abbreviated Cal). In fact, it is a kilocalorie, the equivalent of 4184 joules.

Internal kinetic energy The energy associated with the random motion of particles.

Temperature A measure of the average internal kinetic energy of an object.

Heat The energy transferred from a region of higher temperature to a region of lower temperature due to collisions between particles.

Radiant energy or electromagnetic radiation Energy that can be described in terms of either oscillating electric and magnetic fields or in terms of a stream of tiny packets of energy with no mass.

Photons Tiny packets or particles of radiant energy.

Wavelength (λ) The distance in space over which a wave completes one cycle of its repeated form.

Exothermic change Change that leads to heat energy being released from the system to the surroundings.

Endothermic change Change that leads the system to absorb heat energy from the surroundings.

Troposphere The lowest layer of the earth's atmosphere. It extends from the surface of the earth to about 10 km above the earth.

Stratosphere The second layer of the earth's atmosphere, which extends from about 10 km to about 50 km above sea level.

UV-A Ultraviolet radiation in the range of about 320 to 400 nm wavelengths. This is the part of the ultraviolet spectrum that reaches the earth and provides energy for the production of vitamin D.

UV-B Ultraviolet radiation in the range of about 290 to 320 nm wavelengths. Most of this radiation is filtered out by the earth's atmosphere, but some reaches the surface of the earth. Excessive exposure can cause sunburn, premature skin aging, and skin cancer.

UV-C Ultraviolet radiation in the range of about 40 to 290 nm wavelengths. Almost all UV-C is filtered out by our atmosphere. Because DNA and proteins absorb radiation in this range, UV-C could cause crop damage and general ecological disaster if it were to reach the earth's surface in significant quantities.

Catalyst A substance that speeds a chemical reaction without being permanently altered itself.

Chlorofluorocarbon (CFC) A compound composed of just carbon, chlorine, and fluorine.

You can test yourself on the glossary terms at the textbook's Web site.

Chapter Objectives

The goal of this chapter is to teach you to do the following.

1. Define all of the terms in the Chapter Glossary.

Section 7.1 Energy

2. Explain why a more massive object, such as a bulldozer, has a more energy than a less massive object, such as a scooter, moving at the same velocity.
3. Explain why an object, such as a bulldozer, has more energy when it is moving at a higher velocity than the same object moving at a lower velocity.
4. State the Law of Conservation of Energy.
5. Describe the relationship between stability, capacity to do work, and potential energy.
6. Explain why an object, such as a coin, gains potential energy as it moves farther from the earth.
7. Explain why energy must be absorbed to break a chemical bond.
8. Explain why energy is released when a chemical bond is formed.
9. Convert between the names and abbreviations for joule (J), calorie (cal), and dietary calorie (Calorie or Cal).
10. Write or identify the relative sizes of the joule, calorie, and dietary calorie (Calorie).
11. Explain the difference between external kinetic energy and internal kinetic energy.
12. List the three ways that an object's internal kinetic energy can be increased.
13. Write or identify what is meant in terms of average internal kinetic energy when we say that one object has a higher temperature than another object.
14. Describe the changes that take place during heat transfer between objects at different temperatures.
15. Write a brief description of radiant energy in terms of its particle nature.
16. Write a brief description of radiant energy in terms of its wave nature.
17. Write or identify the relationship between the wavelength of radiant energy and the energy of its photons.
18. Write or identify the relative energies and wavelengths of the following forms of radiant energy: gamma rays, X rays, ultraviolet (UV), visible, infrared (IR), microwaves, and radio waves.
19. Write or identify the relative energies and wavelengths of the following colors of visible light: violet, blue, green, yellow, orange, and red.

Section 7.2 Energy and Chemical Reactions

20. Explain why some chemical reactions release heat to their surroundings.
21. Explain why some chemical reactions absorb heat from their surroundings.
22. Explain why chemical reactions either absorb or release energy.

Section 7.3 Ozone: Pollutant and Protector

23. Explain why the same characteristic that makes ozone useful in industry also leads to health problems.
24. Describe how ozone is produced in the air we breathe.
25. Explain why the highest concentrations of ozone in the air we breathe are found in large industrial cities with lots of cars and lots of sun.

26. Explain why UV radiation of wavelength less than 400 nm is able to break N–O bonds in NO_2 molecules, and explain why radiant energy of wavelength longer than 400 nm cannot break these bonds.
27. Describe the three types of ultraviolet radiation—UV-A, UV-B, and UV-C—including their relative wavelengths and energies.
28. Explain why it is beneficial to humans for UV-A radiation to reach the surface of the earth.
29. Explain why UV-B radiation can be damaging to us and our environment if it reaches the earth in higher quantities than it does now.
30. Explain why we are fortunate that UV-C radiation is almost completely filtered out by the gases in the atmosphere.
31. Explain how oxygen molecules, O_2, and ozone molecules, O_3, work together to protect us from high-energy ultraviolet radiation.
32. Explain how nitrogen monoxide, NO, is able to catalyze the conversion of ozone molecules, O_3, and oxygen atoms, O, to oxygen molecules, O_2.

Section 7.4 Chlorofluorocarbons: A Chemical Success Story Gone Wrong

33. Explain why CFCs eventually make their way into the stratosphere even though most chemicals released into the atmosphere do not.
34. Explain why the radiant energy found in the troposphere is unable to liberate chlorine atoms from CFC molecules, but the radiant energy in the stratosphere is able to do this.
35. Explain why the chlorine atoms liberated from CFCs are thought to be a serious threat to the ozone layer.

Review Questions

For questions 1 and 2, illustrate your answers with simple drawings of the particles that form the structures of the substances mentioned. You do not need to be specific about the nature of the particles. Think of them as simple spheres, and draw them as circles. Provide a general description of the arrangement of the particles, the degree of interaction between them, and their freedom of movement.

1. A pressurized can of a commercial product used to blow the dust off computer components contains tetrafluoroethane, $C_2H_2F_4$. At room temperature, this substance is a liquid at pressures slightly above normal pressure and a gas at normal pressures. Although most of the tetrafluoroethane in the can is in the liquid form, $C_2H_2F_4$ evaporates rapidly, resulting in a significant amount of vapor above the liquid. When the valve on the top of the can is pushed, the tetrafluoroethane gas rushes out, blowing dust off the computer. When the valve closes, more of the liquid $C_2H_2F_4$ evaporates to replace the vapor released. If the can is heated, the liquid evaporates more quickly, and the increase in gas causes the pressure to build up to possibly dangerous levels.
    a. Describe the general structure of liquids, such as liquid tetrafluoroethane.
    b. Describe the general structure of gases, such as gaseous tetrafluoroethane.
    c. Describe the process by which particles move from liquid to gas.
    d. Describe the changes that take place in the liquid when it is heated, and explain why these changes lead to a greater rate of evaporation of the liquid.

2. Sodium metal can be made by running an electric current through molten sodium chloride.
    a. Describe the general structure of solid sodium chloride.
    b. Describe the changes that take place when the temperature of NaCl solid increases.
    c. Describe the changes that take place when sodium chloride melts.

Key Ideas

Complete the following statements by writing one of these words or phrases in each blank.

4.184	internal kinetic
absorbed	joule
average	less
calorie	magnetic
change	mass
changed	massless
collisions	more
created	motion
cycle	particle
decrease	peaks
destroyed	position or state
electric	potential
energy	released
external	resistance
from	retrievable, stored
greater	shorter
heat	transferred
increases	wave

3. The simplest definition of ______________ is that it is the capacity to do work. Work, in this context, may be defined as what is done to move an object against some sort of ______________.
4. The capacity to do work resulting from the ______________ of an object is called kinetic energy, KE.
5. If two objects are moving at the same velocity, the one with the greater ______________ will have a greater capacity to do work and thus a greater kinetic energy.
6. If two objects have equal mass but different velocities, the one with the greater velocity has the ______________ kinetic energy.
7. The Law of Conservation of Energy states that energy can be neither ______________ nor ______________, but it can be ______________ from one system to another and ______________ from one form to another.
8. Potential energy (PE) is a(n) ______________ form of energy an object possesses by virtue of its ______________.
9. A system's stability is a measure of its tendency to ______________.
10. As an object moves from a(n) ______________ stable state to a(n) ______________ stable state, it can do work.
11. Any time a system shifts from a more stable state to a less stable state, the potential energy of the system ______________.

12. Energy is necessary to separate two atoms being held together by mutual attraction in a chemical bond. The energy supplied increases the ______________ energy of the less stable separate atoms compared to the more stable atoms in the bond.
13. Because less stable separate atoms have higher potential energy than the more stable atoms that participate in a bond, the change from separate atoms to atoms in a bond corresponds to a(n) ______________ in potential energy.
14. The accepted SI unit for energy is the ______________, but another common unit is the ______________.
15. The U.S. National Institute of Standards and Technology defines the calorie as ______________ joules.
16. A falling coin has a certain ______________ kinetic energy that is related to its overall mass and to its velocity as it falls.
17. The energy associated with internal motion of particles that compose an object can be called ______________ energy.
18. Temperature is a measure of the ______________ internal kinetic energy of an object.
19. Heat is the energy that is transferred from a region of higher temperature to a region of lower temperature as a consequence of the ______________ of particles.
20. Radiant energy seems to have a dual nature, with both ______________ and ______________ characteristics.
21. Radiant energy can be viewed as a stream of tiny, ______________ packets of energy called photons.
22. The wave view says that as radiant energy moves away from its source, it has an effect on the space around it that can be described as a wave consisting of an oscillating ______________ field perpendicular to an oscillating ______________ field.
23. One distinguishing characteristic of the waves of radiant energy is wavelength, λ, the distance between two ______________ on the wave of electromagnetic radiation. A more specific definition of wavelength is the distance in space over which a wave completes one ______________ of its repeated form.
24. The ______________ the wavelength of a wave of electromagnetic radiation, the greater the energy of its photons.
25. If in a chemical reaction, more energy is released in the formation of new bonds than was necessary to break old bonds, energy is ______________ overall, and the reaction is exergonic.
26. A change that leads to ______________ energy being released from the system to the surroundings is called exothermic.
27. If less energy is released in the formation of the new bonds than is necessary to break the old bonds, energy must be ______________ from the surroundings for the reaction to proceed.
28. Endergonic changes can lead to a transfer of heat ______________ the surroundings.

Complete the following statements by writing one of these words or phrases in each blank.

10	permanently
242 nm	premature aging
240 nm to 320 nm	proteins
50	shorter
1000	skin cancer
DNA	speeds
cars	stable
light photons	sun
longer	sunburn
nitrogen oxides	UV-A
oxidizing	UV-B
oxygen, O_2	UV-C
ozone, O_3	

29. Two forms of the element oxygen are found in nature: the life-sustaining diatomic ______________ and ______________ which is a pale blue gas with a strong odor.

30. Ozone is a very powerful ______________ agent.

31. The highest concentrations of O_3 in the air we breathe are found in large industrial cities with lots of ______________ and lots of ______________.

32. Any time air (which contains nitrogen and oxygen) is heated to high temperature (as occurs in the cylinders of our cars and in many industrial processes), ______________ are formed.

33. Radiant energy of wavelengths ______________ than 400 nm has enough energy to break N–O bonds in NO_2 molecules, but radiant energy with wavelengths ______________ than 400 nm does not supply enough energy to separate the atoms.

34. Because the process of ozone formation is initiated by ______________, the pollutant mixture is called photochemical smog.

35. The stratosphere extends from about ______________ km to about ______________ km above sea level.

36. ______________ radiation, which includes radiant energy of wavelengths from about 320 to 400 nm, passes through the stratosphere and reaches us on the surface of the earth. We are glad it does, because it provides energy that our bodies use to produce vitamin D.

37. ______________ radiation has wavelengths from about 290 to 320 nm. Some of it is removed by the gases in the stratosphere, but some of it reaches the surface of the earth. Radiation in this portion of the spectrum has energy great enough that excessive exposure can cause ______________, ______________, and ______________.

38. The highest-energy ultraviolet radiation is ______________, with wavelengths from about 40 to 290 nm. It is energetic enough to cause serious damage not only to us but to all life on earth. One reason it is so dangerous is that ______________, the substance that carries genetic information in living cells, absorbs UV radiation of about 260 nm. Likewise, ______________, vital structural and functional components of living systems, absorb(s) radiation with wavelengths of about 280 nm. If these wavelengths were to reach the earth in significant quantity, the changes they would cause would lead to massive crop damage and general ecological disaster.

39. Oxygen molecules, O_2, and ozone molecules, O_3, work together to absorb high-energy UV radiation. Oxygen molecules absorb UV radiation with wavelengths less than ______________, and ozone molecules absorb radiant energy with wavelengths from ______________.

40. A catalyst is a substance that ______________ a chemical reaction without being ______________ altered itself.

41. One of the reasons why CFCs were so successful is that they are extremely ______________ compounds; very few substances react with them.

42. Each chlorine atom is thought to destroy an average of ______________ ozone molecules before being temporarily incorporated into a compound such as HCl or $ClONO_2$.

Chapter Problems

Section 7.1 Energy

43. For each of the following situations, you are asked which of two objects or substances has the higher energy. Explain your answer with reference to the capacity of each to do work and say whether the energy that distinguishes them is kinetic energy or potential energy.

OBJECTIVE 2
OBJECTIVE 3
OBJECTIVE 5

a. (1) An ozone molecule, O_3, with a velocity of 393 m/s or (2) the same molecule moving with a velocity of 410 m/s. (These are the average velocities of ozone molecules at 25 °C and 50 °C.)
b. (1) An ozone molecule, O_3, moving at 300 m/s or (2) an oxygen molecule, O_2, moving at the same velocity.
c. (1) A proton and an electron close together or (2) a proton and an electron farther apart.
d. (1) An HOCl molecule or (2) an OH molecule and a chlorine atom formed from breaking the chlorine-oxygen bond in the HOCl molecule. (The conversion of HOCl into Cl and OH takes place in the stratosphere.)
e. (1) Two separate chlorine atoms in the stratosphere or (2) a chlorine molecule, Cl_2, that can form when they collide.
f. (1) Water in the liquid form or (2) water in the gaseous form. (Assume that the two systems are at the same temperature.)

Objective 2
Objective 3
Objective 5

44. For each of the following situations, you are asked which of two objects or substances has the higher energy. Explain your answer with reference to the capacity of each to do work and say whether the energy that distinguishes them is kinetic energy or potential energy.
    a. (1) A methane molecule, CH_4, in the stratosphere or (2) a CH_3 molecule and a hydrogen atom formed from breaking one of the carbon-hydrogen bonds in a CH_4 molecule.
    b. (1) A water molecule moving at 1.63×10^3 mi/h or (2) the same water molecule moving at 1.81×10^3 mi/h. (These are the average velocities of water molecules at 110 °C and 200 °C.)
    c. (1) Iodine solid or (2) iodine gas. (Assume that the two systems are at the same temperature.)
    d. (1) A nitrogen monoxide, NO, molecule and an oxygen atom in the stratosphere or (2) the NO_2 molecule that can form when they collide.
    e. (1) Two bar magnets pushed together with the north pole of one magnet almost touching the south pole of the other magnet or (2) the same magnets farther apart.
    f. (1) A water molecule moving at 1.63×10^3 mi/h or (2) a uranium hexafluoride, UF_6, molecule moving at the same velocity.
45. At 20 °C, ozone molecules, O_3, have an average velocity of 390 m/s, and oxygen molecules, O_2, have an average velocity of 478 m/s. If these gases are at the same temperature, they have the same average kinetic energy. Explain in qualitative terms how these gases could have the same average kinetic energy but different average velocities.
46. Energy is the capacity to do work. With reference to this definition, describe how you would demonstrate that each of the following has potential energy. (There is no one correct answer in these cases. There are many ways to demonstrate that a system has potential energy.)
    a. A brick on the top of a tall building
    b. A stretched rubber band
    c. Alcohol molecules added to gasoline
47. Energy is the capacity to do work. With reference to this definition, describe how you would demonstrate that each of the following has potential energy. (There is no one correct answer in these cases. There are many ways to demonstrate that a system has potential energy.)
    a. A paper clip an inch away from a magnet
    b. A candy bar
    c. A baseball popped up to the catcher at the peak of its flight.
48. For each of the following changes, describe whether (1) kinetic energy is being converted into potential energy, (2) potential energy is being converted into kinetic energy, or (3) kinetic energy is transferred from one object to another. (More than one of these changes may be occurring.)
    a. An archer pulls back a bow with the arrow in place.
    b. The archer releases the arrow, and it speeds toward the target.

49. For each of the following changes, describe whether (1) kinetic energy is being converted into potential energy, (2) potential energy is being converted into kinetic energy, or (3) kinetic energy is transferred from one object to another. (More than one of these changes may be occurring.)
    a. A car in an old wooden roller coaster is slowly dragged up a steep incline to the top of the first big drop.
    b. After the car passes the peak of the first hill, it falls down the backside at high speed.
    c. As it goes down the hill, the car makes the whole wooden structure shake.
    d. By the time the car reaches the bottom of the first drop, it is moving fast enough to go up to the top of the next smaller hill on its own.
50. When a child swings on a swing, energy is constantly being converted back and forth between kinetic energy and potential energy. At what point (or points) in the child's motion is the potential energy at a maximum? At what point (or points) is the kinetic energy at a maximum? If a parent stops pushing a swinging child, why does the child eventually stop? Where has the energy of the swinging child gone?
51. Methyl bromide is an agricultural soil fumigant that can make its way into the stratosphere, where bromine atoms are stripped away by radiant energy from the sun. The bromine atoms react with ozone molecules (thus diminishing the earth's protective ozone layer) to produce BrO, which in turn reacts with nitrogen dioxide , NO_2, to form $BrONO_2$. For each of these reactions, identify whether energy would be absorbed or released. Explain why. Describe how energy is conserved in each reaction. OBJECTIVE 7 OBJECTIVE 8
    a. $CH_3Br(g) \rightarrow CH_3(g) + Br(g)$
    b. $BrO(g) + NO_2(g) \rightarrow BrONO_2(g)$
52. The following chemical changes take place in the air over sunny industrial cities, such as Los Angeles. Identify whether energy would be absorbed or released in each reaction. Explain why. Describe how energy is conserved in each reaction. OBJECTIVE 7 OBJECTIVE 8
    a. $2O(g) \rightarrow O_2(g)$
    b. $NO_2(g) \rightarrow NO(g) + O(g)$
53. A silver bullet speeding toward a vampire's heart has both external kinetic energy and internal kinetic energy. Explain the difference between the two. OBJECTIVE 11
54. Describe three different ways to increase the internal kinetic energy of your skin. OBJECTIVE 12
55. When a room-temperature thermometer is placed in a beaker of boiling water, heat is transferred from the hot water to the glass of the thermometer and then to the liquid mercury inside the thermometer. With reference to the motion of the particles in the water, glass, and mercury, describe the changes that are taking place during this heat transfer. What changes in total energy and average internal kinetic energy are happening for each substance? Why do you think the mercury moves up the thermometer? OBJECTIVE 14
56. With reference to both their particle and their wave nature, describe the similarities and differences between visible light and ultraviolet radiation. OBJECTIVE 15 & 16 OBJECTIVE 17 & 18
57. With reference to both their particle and their wave nature, describe the similarities and differences between red light and blue light. OBJECTIVE 15 & 16 OBJECTIVE 17 & 19

Objective 18

58. Consider the following forms of radiant energy: microwaves, infrared, ultraviolet, X rays, visible light, radio waves, and gamma rays.
   a. List them in order of increasing energy.
   b. List them in order of increasing wavelength.

Objective 19

59. Consider the following colors of visible light: green, yellow, violet, red, blue, and orange.
   a. List these in order of increasing energy.
   b. List these in order of increasing wavelength.

Section 7.2 Energy and Chemical Reactions

Objective 21

60. Consider the following endergonic reaction. In general terms, explain why energy is absorbed in the process of this reaction.

$$N_2(g) + O_2(g) \rightarrow 2NO(g)$$

Objective 20

61. The combustion of propane is an exergonic reaction. In general terms, explain why energy is released in the process of this reaction.

$$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(l)$$

Objective 14
Objective 20

62. Hydrazine, N_2H_4, is used as rocket fuel. Consider a system in which a sample of hydrazine is burned in a closed container, followed by heat transfer from the container to the surroundings.

$$N_2H_4(g) + O_2(g) \rightarrow N_2(g) + 2H_2O(g)$$

   a. In general terms, explain why energy is released in the reaction.
   b. Before heat energy is transferred to the surroundings, describe the average internal kinetic energy of the product particles compared to the reactant particles. If the product's average internal kinetic energy is higher than for the reactants, from where did this energy come? If the average internal kinetic energy is lower than for the reactants, to where did this energy go?
   c. Describe the changes in particle motion as heat is transferred from the products to the surroundings.

Objective 14
Objective 20

63. Cinnabar is a natural mercury(II) sulfide, HgS, found near volcanic rocks and hot springs. It is the only important source of mercury, which has many uses, including dental amalgams, thermometers, and mercury vapor lamps. Mercury is formed in the following endothermic reaction when mercury(II) sulfide is heated. Consider a system in which a sample of HgS in a closed container is heated with a Bunsen burner flame.

$$8HgS(s) \rightarrow 8Hg(l) + S_8(s)$$

   a. Describe the changes in particle motion as heat is transferred from the hot gases of the Bunsen burner flame to the container to the HgS(*s*).
   b. In general terms, explain why energy is absorbed in the reaction.
   c. Into what form of energy is the heat energy converted for this reaction?

64. Even on a hot day, you get cold when you step out of a swimming pool. Suggest a reason why your skin cools as water evaporates from it. Is evaporation an exothermic or endothermic process?

65. Classify each of the following changes as exothermic or endothermic.
   a. Leaves decaying in a compost heap.
   b. Dry ice (solid carbon dioxide) changing to carbon dioxide gas.
   c. Dew forming on a lawn at night.
66. Classify each of the following changes as exothermic or endothermic.
   a. The nuclear reaction that takes place in a nuclear electrical generating plant.
   b. Cooking an egg in boiling water.
   c. The breakdown of plastic in the hot sun.
67. Explain why chemical reactions either absorb or evolve energy. OBJECTIVE 22

Section 7.3 Ozone: Pollutant and Protector

68. What characteristic of ozone makes it useful for some purposes and a problem in other situations? What do people use it for in industry? What health problems does it cause? OBJECTIVE 23
69. Having aced your finals, you decide to spend your summer vacation visiting a friend in Southern California. Unfortunately, during your first day at an amusement park there, you begin to have some chest pain, slight wheezing, and shortness of breath. This reminds you of what you read about ozone in Chapter 7 of your chemistry textbook. When you tell your friend that ozone is the likely cause of your problems, she asks you to explain how the ozone you are breathing is created and why the ozone levels are higher in Los Angeles than where you live, in rural Minnesota. What do you tell her? How did you contribute to the increase in ozone as you drove your rental car from your hotel to the park? OBJECTIVE 24 OBJECTIVE 25
70. Explain why UV radiation of wavelength less than 400 nm is able to break N–O bonds in NO_2 molecules, and explain why radiant energy of wavelength longer than 400 nm cannot break these bonds. OBJECTIVE 26
71. Explain why it is beneficial to us to have UV-A radiation reach the surface of the earth. OBJECTIVE 28
72. Explain why UV-B radiation can be damaging to us and our environment if it reaches the earth in higher quantities than it does now. OBJECTIVE 29
73. Explain why we are fortunate that UV-C radiation is almost completely filtered out by the gases in the atmosphere. OBJECTIVE 30
74. Explain how oxygen molecules, O_2, and ozone molecules, O_3, work together to protect us from high-energy ultraviolet radiation. OBJECTIVE 31
75. Explain how nitrogen monoxide, NO, is able to catalyze the conversion of ozone molecules, O_3, and oxygen atoms, O, to oxygen molecules, O_2. OBJECTIVE 32

Section 7.4 Chlorofluorocarbons: A Chemical Success Story Gone Wrong

76. Explain why CFCs eventually make their way into the stratosphere even though most chemicals released into the atmosphere do not. OBJECTIVE 33
77. Explain why the radiant energy found in the troposphere is unable to liberate chlorine atoms from CFC molecules but the radiant energy in the stratosphere is able to do this. OBJECTIVE 34
78. Explain why the chlorine atoms liberated from CFCs are thought to be a serious threat to the ozone layer. OBJECTIVE 35

Additional Problems

79. Energy is the capacity to do work. With reference to this definition, describe how you would demonstrate that each of the following objects or substances has potential energy. (There is no one correct answer in these cases. There are many ways to demonstrate that a system has potential energy.)
    a. Natural gas used to fuel a city bus
    b. A compressed spring
    c. A pinecone at the top of a tall tree
80. Energy is the capacity to do work. With reference to this definition, describe how you would demonstrate that each of the following objects or substances has potential energy. (There is no one correct answer in these cases. There are many ways to demonstrate that a system has potential energy.)
    a. Two bar magnets with the north pole of one magnet about an inch away from the north pole of the second magnet (like poles of two magnets repel each other.)
    b. Uranium atoms in the reactor fuel of a nuclear power plant
    c. A suitcase on the top shelf of a garage
81. For each of the following changes, describe whether (1) kinetic energy is being converted into potential energy, (2) potential energy is being converted into kinetic energy, or (3) kinetic energy is transferred from one object to another. (More than one of these changes may be occurring.)
    a. Using an elaborate system of ropes and pulleys, a piano mover hoists a piano up from the sidewalk to outside a large third floor window of a city apartment building.
    b. His hands slip and the piano drops 6 feet before he is able to stop the rope from unwinding.
82. For each of the following changes, describe whether (1) kinetic energy is being converted into potential energy, (2) potential energy is being converted into kinetic energy, or (3) kinetic energy is transferred from one object to another. (More than one of these changes may be occurring.)
    a. A pinball player pulls back the knob, compressing a spring, in preparation for releasing the ball into the machine.
    b. The player releases the knob, and the ball shoots into the machine.
83. The following changes combine to help move a car down the street. For each change, describe whether (1) kinetic energy is being converted into potential energy, (2) potential energy is being converted into kinetic energy, or (3) kinetic energy is transferred from one object to another. (More than one of these changes may be occurring.)
    a. The combustion of gasoline in the cylinder releases heat energy, increasing the temperature of the gaseous products of the reaction.
    b. The hot gaseous products push the piston down in the cylinder.
    c. The moving piston turns the crankshaft, which ultimately turns the wheels.

84. For each of the following changes, describe whether (1) kinetic energy is being converted into potential energy, (2) potential energy is being converted into kinetic energy, or (3) kinetic energy is transferred from one object to another. (More than one of these changes may be occurring.)
    a. Wind turns the arms of a windmill.
    b. The windmill pumps water from below the ground up into a storage tank at the top of a hill.
85. Classify each of the following changes as exothermic or endothermic.
    a. Fuel burning in a camp stove
    b. The melting of ice in a camp stove to provide water on a snow-camping trip
86. Classify each of the following changes as exothermic or endothermic.
    a. Fireworks exploding
    b. Water evaporating on a rain-drenched street
87. Why does your body temperature rise when you exercise?

Discussion Questions

88. You know that the Law of Conservation of Energy states that energy is conserved. When you put on the brakes of a car to stop it, where does the energy associated with the moving car go?
89. Only a fraction of the energy released in the combustion of gasoline is converted into kinetic energy of the moving car. Where does the rest go?