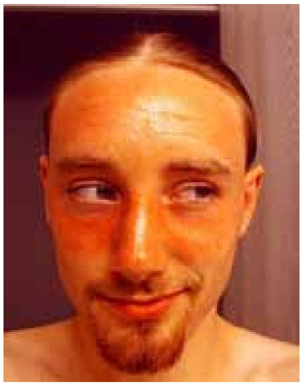
4.1 Energy

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.

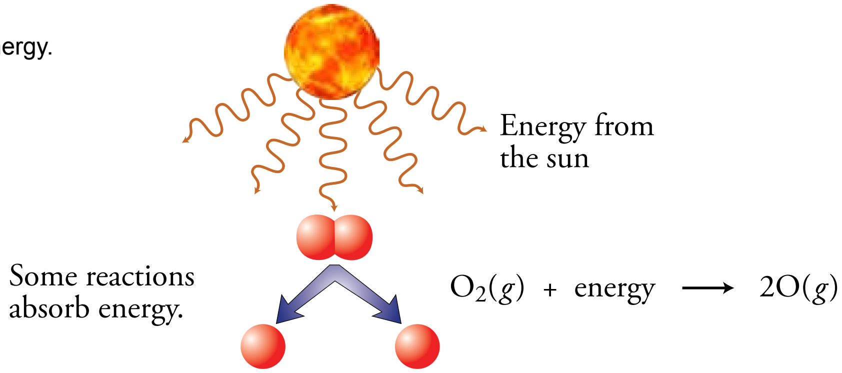


Radiant energy from the sun causes sunburn

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.

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. 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 4.1).

Figure 4.1
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 4.2).

Figure 4.2
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

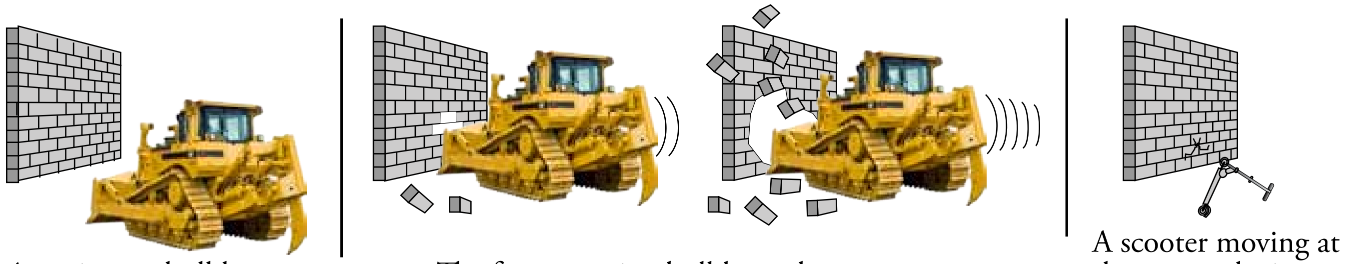
The amount of an object's kinetic energy is related to its mass and its velocity. If two objects are moving at the same velocity, the one with the greater mass will have a greater capacity to do work and thus a greater kinetic energy. For example, a bulldozer moving at 20 miles per hour can do more work 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 4.3).

Objective 2 Objective 3

Figure 4.3
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.

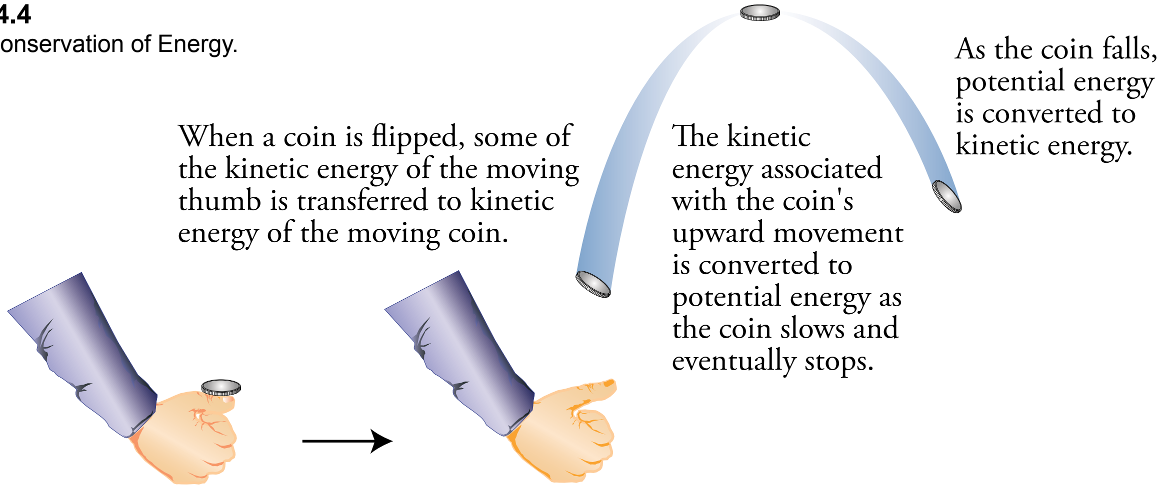
Potential Energy

Objective 4

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]

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 4.4).

Figure 4.4
Law of Conservation of Energy.



When a coin is flipped, some of the kinetic energy of the moving thumb is transferred to kinetic energy of the moving coin.

The kinetic energy associated with the coin's upward movement is converted to potential energy as the coin slows and eventually stops.

As the coin falls, potential energy is converted to kinetic energy.

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

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[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 4.5). *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.

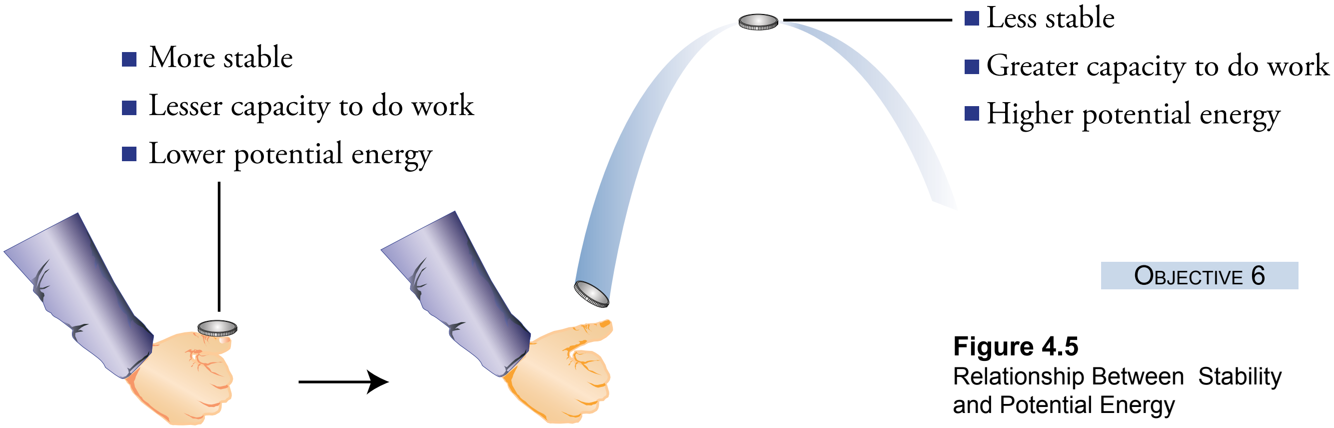
OBJECTIVE 5

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

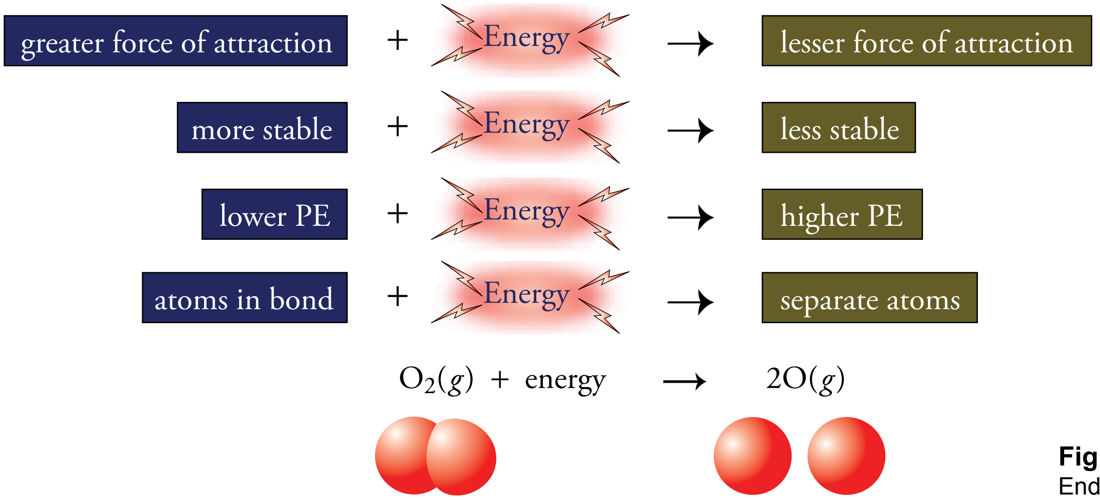


OBJECTIVE 6

Figure 4.5
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 4.6).



OBJECTIVE 7

Figure 4.6
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.

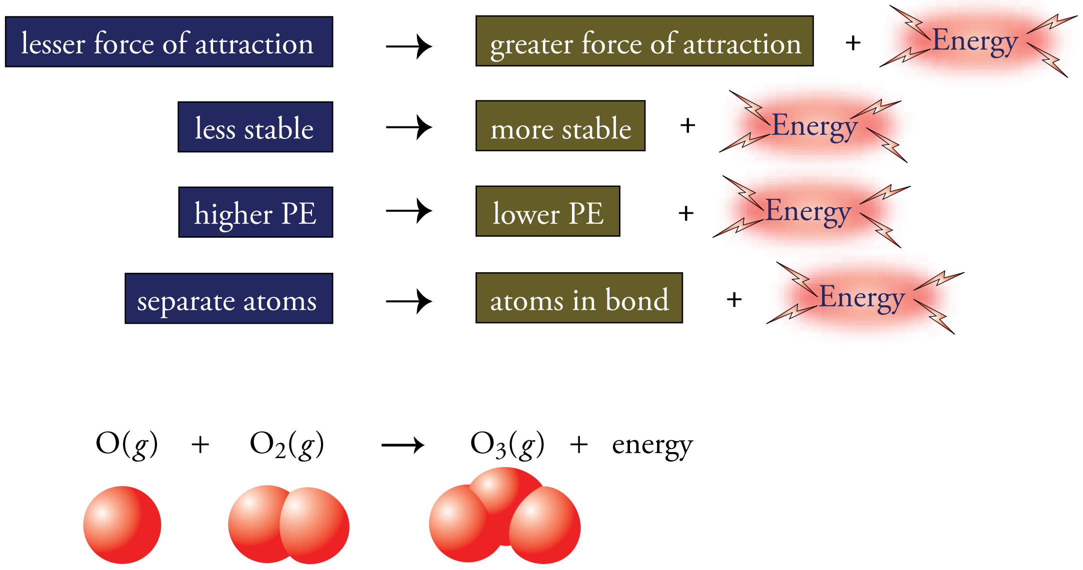
Objective 5

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 4.7).

Figure 4.7
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 4.1 - 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?

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

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?

$$\mathrm{H}(g) + \mathrm{O_2}(g) \rightarrow \mathrm{HO_2}(g)$$

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 4.1 - 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?
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

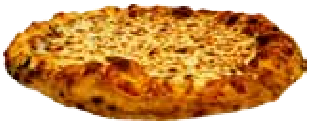
The accepted SI unit for energy is the **joule (J)**, but another common unit is the **calorie (cal)**. The calorie has been defined in several different ways. One early definition described it as the energy necessary to increase the temperature of 1 gram of water from 14.5 °C to 15.5 °C. There are 4.186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

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

OBJECTIVE 10

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.

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



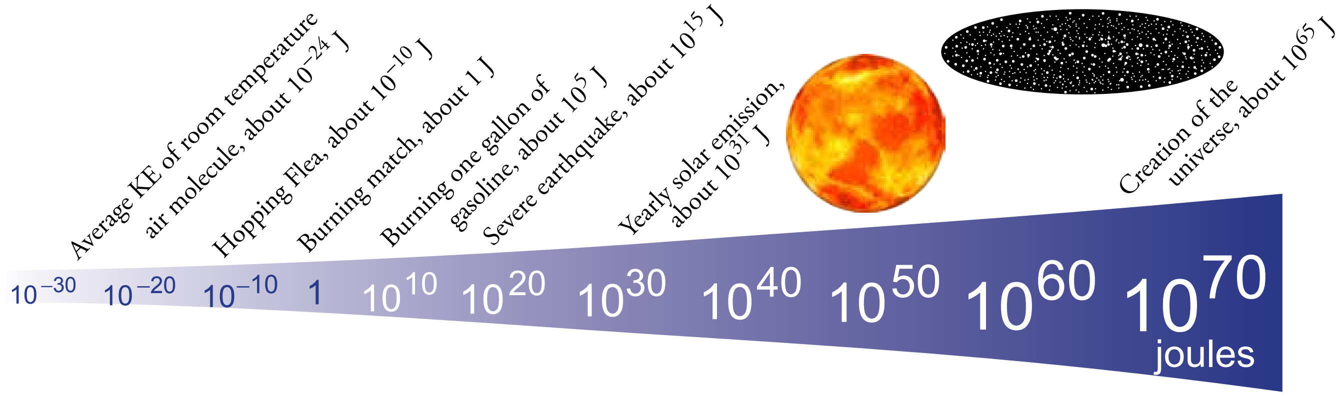
A meal of about 1000 dietary calories (Calories) provides about 4184 kJ of energy. Table 4.1 shows the energy provided by various foods.We will use joules and kilojoules to describe energy in this text. Figure 4.8 shows some approximate values in kilojoules for the energy represented by various events.

Table 4.1 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
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 4.8

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

Objective 11

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 called **internal kinetic energy** (Figure 4.9).

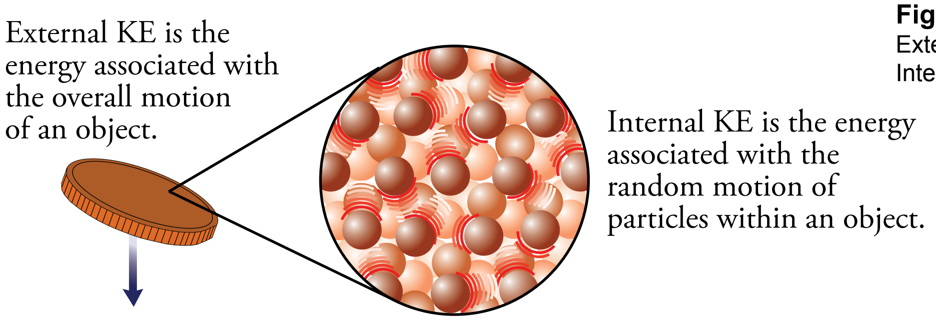


Figure 4.9
External Kinetic Energy and Internal Kinetic Energy

Objective 11

Objective 12

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 13

Objective 14

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 to 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 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 4.10).

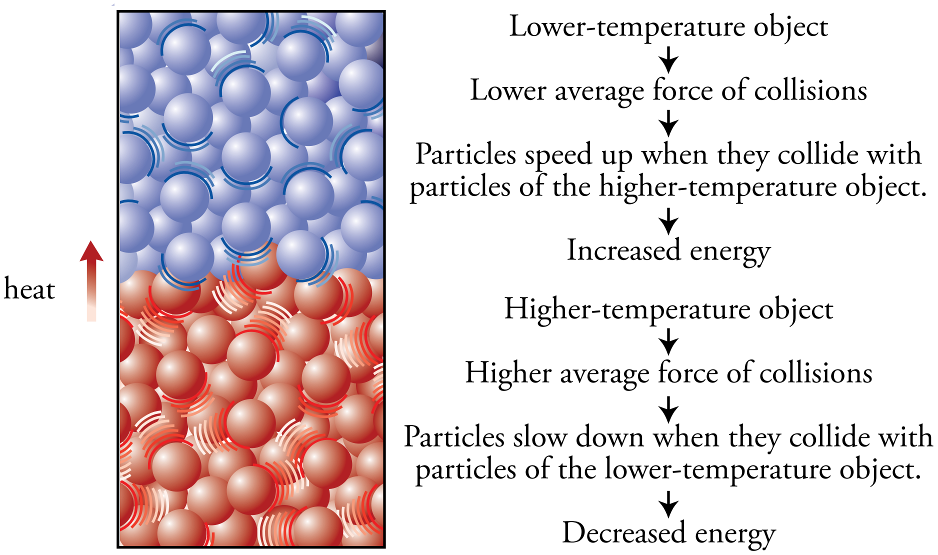


Figure 4.10
Heat Transfer

Objective 14

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.)

Objective 16

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 4.11).

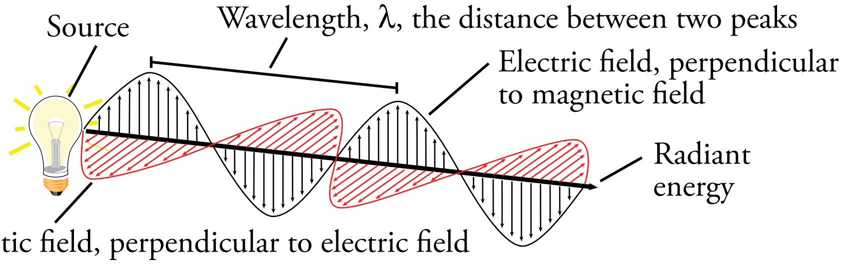
Because radiant energy seems to have both wave and particle characteristics, some experts have suggested that it is probably neither a wave nor a stream of particles. Perhaps the simplest model that includes both aspects of radiant energy says that as the photons travel, they somehow affect the space 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 4.12 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 4.11).

Figure 4.11
A Light Wave's Electric and Magnetic Fields

Objective 16



Gamma rays, with very high-energy photons, have very short wavelengths (Figure 4.12), 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 4.12, 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 4.12 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 4.12
Radiant-Energy Spectrum

OBJECTIVE 18
OBJECTIVE 19