8.2: The Basics of Energy

Learning Objectives

- Define energy, distinguish types of energy, and describe the nature of energy changes that accompany chemical and physical changes
- Distinguish the related properties of heat, thermal energy, and temperature.

Chemical changes and their accompanying changes in energy are important parts of our everyday world (Figure 8.2.1). The macronutrients in food (proteins, fats, and carbohydrates) undergo metabolic reactions that provide the energy to keep our bodies functioning. We burn a variety of fuels (gasoline, natural gas, coal) to produce energy for transportation, heating, and the generation of electricity. Industrial chemical reactions use enormous amounts of energy to produce raw materials (such as iron and aluminum). Energy is then used to manufacture those raw materials into useful products, such as cars, skyscrapers, and bridges.

Figure 8.2.1: The energy involved in chemical changes is important to our daily lives: (a) A cheeseburger for lunch provides the energy you need to get through the rest of the day; (b) the combustion of gasoline provides the energy that moves your car (and you) between home, work, and school; and (c) coke, a processed form of coal, provides the energy needed to convert iron ore into iron, which is essential for making many of the products we use daily. (credit a: modification of work by "Pink Sherbet Photography"/Flickr; credit b: modification of work by Jeffery Turner).

Over 90% of the energy we use comes originally from the sun. Every day, the sun provides the Earth with almost 10,000 times the amount of energy necessary to meet all of the world's energy needs for that day. Our challenge is to find ways to convert and store incoming solar energy so that it can be used in reactions or chemical processes that are both convenient and nonpolluting. Plants and many bacteria capture solar energy through photosynthesis. We release the energy stored in plants when we burn wood or plant products such as ethanol. We also use this energy to fuel our bodies by eating food that comes directly from plants or from animals that get their energy by eating plants. Burning coal and petroleum also releases stored solar energy: These fuels are fossilized plant and animal matter.

Energy is usually defined as the capability to do **work (w) or** supply heat. For example, a billiard ball can collide with a second ball, changing the direction or speed of motion of the latter. In such a process the motion of the first ball would also be altered. We would say that one billiard ball did work on (transferred energy to) the other.

Kinetic Energy

Figure $8.2.2$ Cartoon of a boy riding a bike downhill. The words "kinetic energy" and "due to motion" are also on the picture.

Image source: Smart Learning for All

Energy due to motion is called kinetic energy and is represented by E_k. For an object moving in a straight line, the kinetic energy is one-half the product of the mass and the square of the speed:

$$E_k = \frac{1}{2}mu^2 \tag{8.2.1}$$

where

- m = mass of the object
- u = speed of object

If the two billiard balls mentioned above were studied in outer space, where friction due to their collisions with air molecules or the surface of a pool table would be negligible, careful measurements would reveal that their total kinetic energy would be the same before and after they collided. This is an example of the **law of conservation of energy**, which states that *energy cannot be created or destroyed* under the usual conditions of everyday life. Whenever there appears to be a decrease in energy somewhere, there is a corresponding increase somewhere else.

Example $8.2.1$: Kinetic Energy

Calculate the kinetic energy of a Volkswagen Beetle of mass 844 kg (1860 lb) which is moving at 13.4 m s^{-1} (30 miles per hour).

Solution:

$$E_k = \frac{1}{2}mu^2 = \frac{1}{2} \times 844 \text{ kg} \times (13.4 \text{ m s}^{-1})^2 = 7.58 \times 10^4 \text{ kg m}^2 \text{ s}^{-2}$$

In other words the units for energy are derived from the SI base units kilogram for mass, meter for length, and second for time. A quantity of heat or any other form of energy may be expressed in kilogram meter squared per second squared. In honor of Joule's pioneering work this derived unit 1 kg m^2 s^{-2} called the **joule**, abbreviated J. The Volkswagen in question could do nearly 76 000 J of work on anything it happened to run into.

Potential Energy

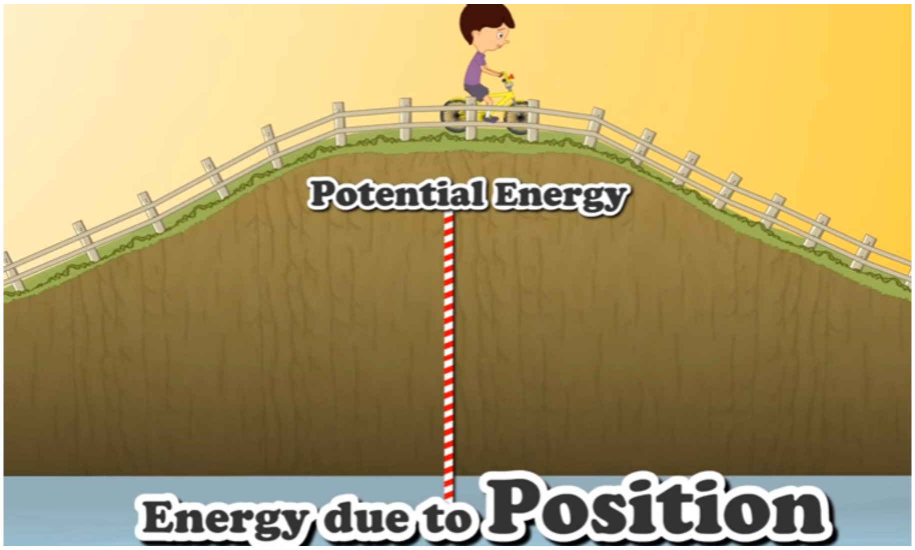


Figure 8.2.3Boy on a bike at the peak of a hill. The words "potential energy" and "energy due to position" are also in the picture.

Image source: Smart Learning for All

Potential Energy is energy that is stored by rising in height, or by other means. It frequently comes from separating things that attract, like rising birds are being separated from the Earth that attracts them, or by pulling magnets apart, or pulling an electrostatically charged balloon from an oppositely charged object to which it has clung. Potential Energy is abbreviated E_P and gravitational potential energy is calculated as follows:

$$E_P = mgh \tag{8.2.2}$$

where

- m = mass of the object in kg
- g = gravitational constant, 9.8 m s^2
- h = height in m

Notice that E_P has the same units, kg m^2 s^{-2} or ***Joule*** as kinetic energy.

Example 8.2.2: Kinetic Energy Application

How high would the VW weighing 844 kg and moving at 30 mph need to rise (vertically) on a hill to come to a complete stop, if none of the stopping power came from friction?

Solution:

The car's kinetic energy is 7.58×10^4 kg m^2 s^{-2}(from EXAMPLE 8.2.1), so all of this would have to be converted to E_P. Then we could calculate the vertical height:

$$E_P = mgh = 7.58 \times 10^4 \text{ kg m}^2 \text{ s}^{-2} = 844 \text{ kg} \times 9.8 \text{ms}^{-2} \times h$$
$$h = 9.2 \text{ m}$$

Even when there is a great deal of friction, the law of conservation of energy still applies. If you put a milkshake on a mixer and leave it there for 10 min, you will have a warm, rather unappetizing drink. The whirling mixer blades do work on (transfer energy to) the milkshake, raising its temperature. The same effect could be produced by heating the milkshake, a fact which suggests that heating also involves a transfer of energy. The first careful experiments to determine how much work was equivalent to a given quantity of heat were done by the English physicist James Joule (1818 to 1889) in the 1840s. In an experiment very similar to our milkshake example, Joule connected falling weights through a pulley system to a paddle wheel immersed in an insulated container of water. This allowed him to compare the temperature rise, which resulted from the work done by the weights, with that which resulted from heating. Units with which to measure energy may be derived from the SI base units of Table 1 from The International System of Units (SI)(opens in new window) by using Eq. 8.2.1.

Another unit of energy still widely used by chemists is the **calorie**. The calorie used to be defined as the energy needed to raise the temperature of one gram of water from 14.5°C to 15.5°C but now it is defined as exactly 4.184 J.

Like matter, energy comes in different types and is conserved. One scheme classifies energy into two types: potential energy, the energy an object has because of its relative position, composition, or condition, and kinetic energy, the energy that an object possesses because of its motion. Water at the top of a waterfall or dam has potential energy because of its position; when it flows downward through generators, it has kinetic energy that can be used to do work and produce electricity in a hydroelectric plant (Figure 8.2.4). A battery has potential energy because the chemicals within it can produce **electricity**, another form of energy, that can do work.

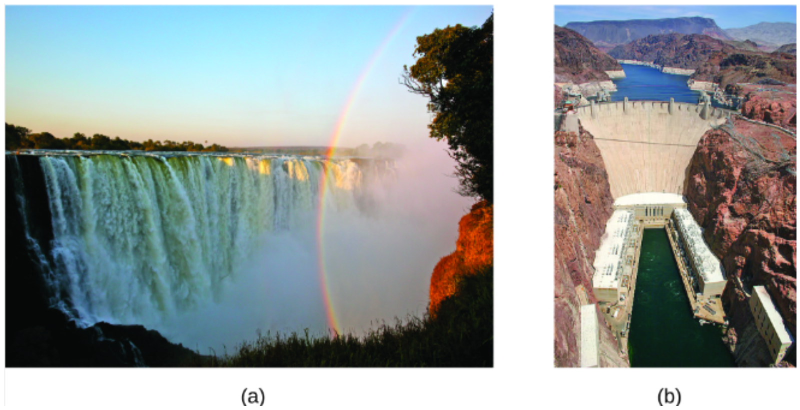


Figure 8.2.4: (a) Water that is higher in elevation, for example, at the top of Victoria Falls, has a higher potential energy than water at a lower elevation. As the water falls, some of its potential energy is converted into kinetic energy. (b) If the water flows through generators at the bottom of a dam, such as the Hoover Dam shown here, its kinetic energy is converted into electrical energy. (credit a: modification of work by Steve Jurvetson; credit b: modification of work by “curimedia”/Wikimedia commons).

Two pictures are shown and labeled a and b. Picture a shows a large waterfall with water falling from a high elevation at the top of the falls to a lower elevation. The second picture is a view looking down into the Hoover Dam. Water is shown behind the high wall of the dam on one side and at the base of the dam on the other.

Energy can be converted from one form into another, but all of the energy present before a change occurs always exists in some form after the change is completed. This observation is expressed in the law of conservation of energy: during a chemical or physical change, energy can be neither created nor destroyed, although it can be changed in form. (This is also one version of the first law of thermodynamics, as you will learn later.)

When one substance is converted into another, there is always an associated conversion of one form of energy into another. Heat is usually released or absorbed, but sometimes the conversion involves light, electrical energy, or some other form of energy. For example, chemical energy (a type of potential energy) is stored in the molecules that compose gasoline. When gasoline is combusted within the cylinders of a car’s engine, the rapidly expanding gaseous products of this chemical reaction generate mechanical energy (a type of kinetic energy) when they move the cylinders’ pistons.

According to the law of conservation of matter (seen in an earlier chapter), there is no detectable change in the total amount of matter during a chemical change. When chemical reactions occur, the energy changes are relatively modest and the mass changes are too small to measure, so the laws of conservation of matter and energy hold well. However, in nuclear reactions, the energy changes are much larger (by factors of a million or so), the mass changes are measurable, and matter-energy conversions are significant. This will be examined in more detail in a later chapter on nuclear chemistry. To encompass both chemical and nuclear changes, we combine these laws into one statement: The total quantity of matter and energy in the universe is fixed.

Thermal Energy, Temperature, and Heat

Thermal energy is kinetic energy associated with the random motion of atoms and molecules. Temperature is a quantitative measure of “hot” or “cold.” When the atoms and molecules in an object are moving or vibrating quickly, they have a higher average kinetic energy (KE), and we say that the object is “hot.” When the atoms and molecules are moving slowly, they have lower KE, and we say that the object is “cold” (Figure 8.2.5). Assuming that no chemical reaction or phase change (such as melting or vaporizing) occurs, increasing the amount of thermal energy in a sample of matter will cause its temperature to increase.

And, assuming that no chemical reaction or phase change (such as condensation or freezing) occurs, decreasing the amount of thermal energy in a sample of matter will cause its temperature to decrease.

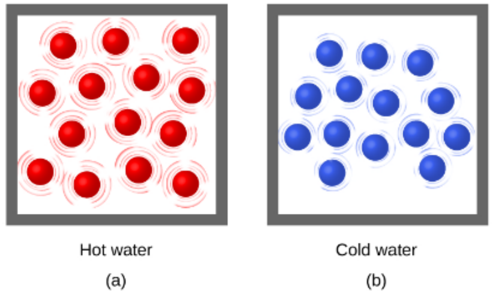
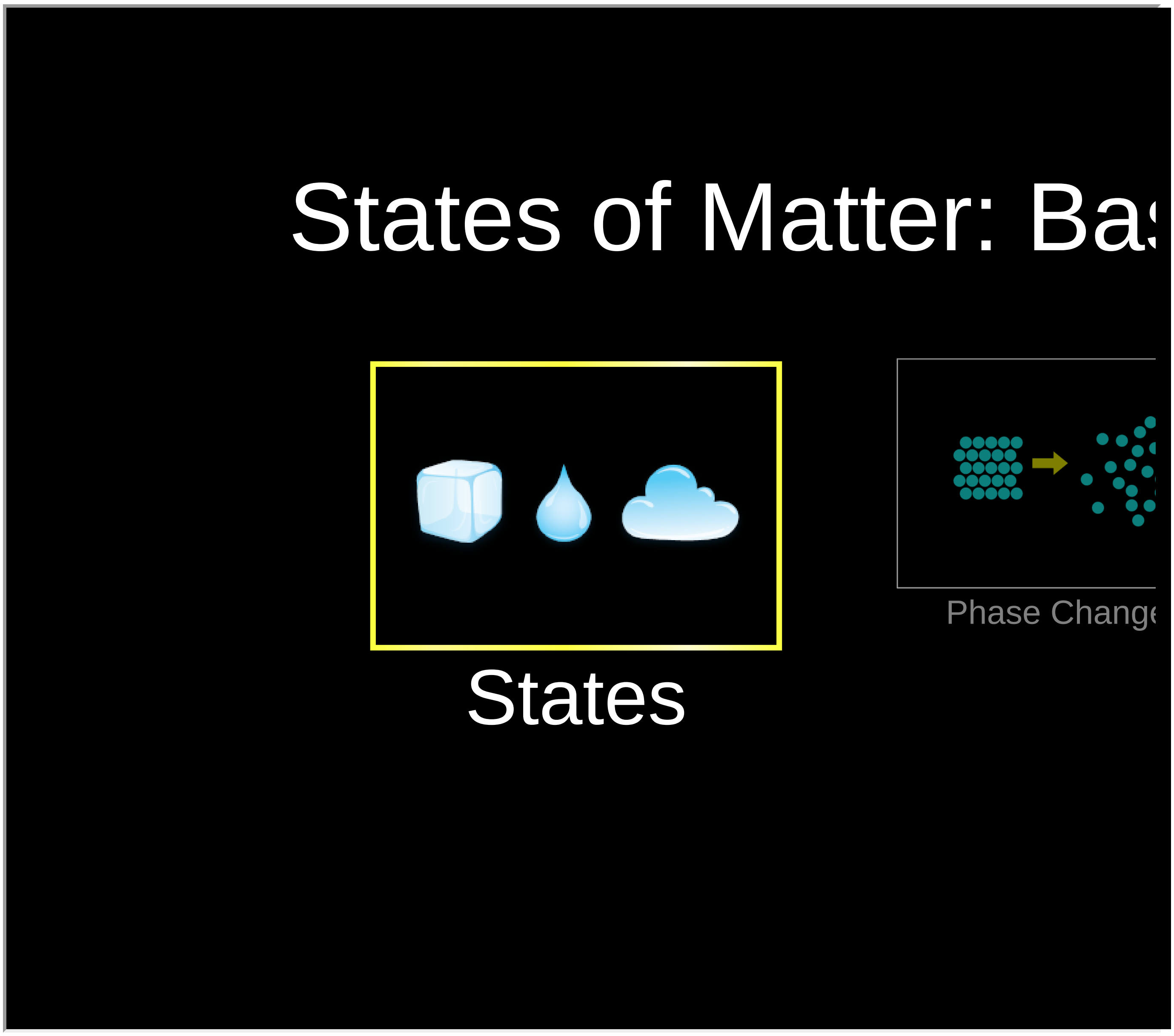
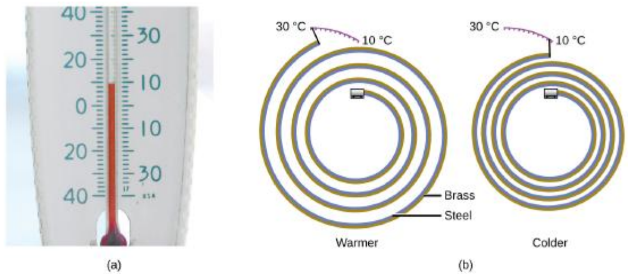


Figure 8.2.5: (a) The molecules in a sample of hot water move more rapidly than (b) those in a sample of cold water.Two molecular drawings are shown and labeled a and b. Drawing a is a box containing fourteen red spheres that are surrounded by lines indicating that the particles are moving rapidly. This drawing has a label that reads "Hot water." Drawing b depicts another box of equal size that also contains fourteen spheres, but these are blue. They are all surrounded by smaller lines that depict some particle motion, but not as much as in drawing a. This drawing has a label that reads "Cold water."



Most substances expand as their temperature increases and contract as their temperature decreases. This property can be used to measure temperature changes, as shown in Figure 8.2.6. The operation of many thermometers depends on the expansion and contraction of substances in response to temperature changes.



A picture labeled a is shown as well as a pair of drawings labeled b. Picture a shows the lower portion of an alcohol thermometer. The thermometer has a printed scale to the left of the tube in the center that reads from negative forty degrees at the bottom to forty degrees at the top. It also has a scale printed to the right of the tube that reads from negative thirty degrees at the bottom to thirty five degrees at the top. On both scales, the volume of the alcohol in the tube reads between nine and ten degrees. The two images labeled b both depict a metal strip coiled into a spiral and composed of brass and steel. The left coil, which is loosely coiled, is labeled along its upper edge with the 30 degrees C and 10 degrees C. The end of the coil is near the 30 degrees C label. The right hand coil is much more tightly wound and the end is near the 10 degree C label.

Figure 8.2.6: (a) In an alcohol or mercury thermometer, the liquid (dyed red for visibility) expands when heated and contracts when cooled, much more so than the glass tube that contains the liquid. (b) In a bimetallic thermometer, two different metals (such as brass and steel) form a two-layered strip. When heated or cooled, one of the metals (brass) expands or contracts more than the other metal (steel), causing the strip to coil or uncoil. Both types of thermometers have a calibrated scale that indicates the temperature. (credit a: modification of work by "dwstucke"/Flickr). (c) The demonstration allows one to view the effects of heating and cooling a coiled bimetallic strip.A bimetallic coil from a thermometer reacts to the heat from a lighter, by uncoiling and then coiling back up when the lighter is removed. Animation used with permission from Hustvedt (via Wikipedia).

Heat (q) is the transfer of thermal energy between two bodies at different temperatures. Heat flow (a redundant term, but one commonly used) increases the thermal energy of one body and decreases the thermal energy of the other. Suppose we initially have a high temperature (and high thermal energy) substance (H) and a low temperature (and low thermal energy) substance (L). The atoms and molecules in H have a higher average KE than those in L. If we place substance H in contact with substance L, the thermal energy will flow spontaneously from substance H to substance L. The temperature of substance H will decrease, as will the average KE of its molecules; the temperature of substance L will increase, along with the average KE of its molecules. Heat flow will continue until the two substances are at the same temperature (Figure 8.2.7).\

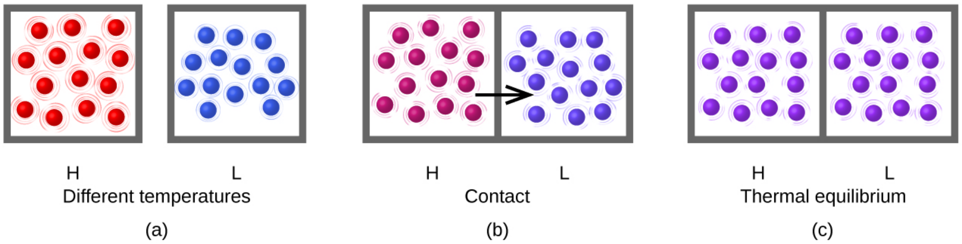


Figure 8.2.7: (a) Substances H and L are initially at different temperatures, and their atoms have different average kinetic energies. (b) When they are put into contact with each other, collisions between the molecules result in the transfer of kinetic (thermal) energy from the hotter to the cooler matter. (c) The two objects reach "thermal equilibrium" when both substances are at the same temperature, and their molecules have the same average kinetic energy.

Three drawings are shown and labeled a, b, and c, respectively. The first drawing labeled a depicts two boxes, with a space in between and the pair is captioned "Different temperatures." The left hand box is labeled H and holds fourteen well-spaced red spheres with lines drawn around them to indicate rapid motion. The right hand box is labeled L and depicts fourteen blue spheres that are closer together than the red spheres and have smaller lines around them showing less particle motion. The second drawing labeled b depicts two boxes that are touching one another. The left box is labeled H and contains fourteen maroon spheres that are spaced evenly apart. There are tiny lines around each sphere depicting particle movement. The right box is labeled L and holds fourteen purple spheres that are slightly closer together than the maroon spheres. There are also tiny lines around each sphere depicting particle movement. A black arrow points from the left box to the right box and the pair of diagrams is captioned "Contact." The third drawing labeled c, is labeled "Thermal equilibrium." There are two boxes shown in contact with one another. Both boxes contain fourteen purple spheres with small lines around them depicting moderate movement. The left box is labeled H and the right box is labeled L.

Matter undergoing chemical reactions and physical changes can release or absorb heat. A change that releases heat is called an exothermic process. For example, the combustion reaction that occurs when using an oxyacetylene torch is an exothermic process—this process also releases energy in the form of light as evidenced by the torch's flame (Figure $8.2.8a$). A reaction or change that absorbs heat is an endothermic process. A cold pack used to treat muscle strains provides an example of an endothermic process. When the substances in the cold pack (water and a salt like ammonium nitrate) are brought together, the resulting process absorbs heat, leading to the sensation of cold.

Figure 8.2.8: (a) An oxyacetylene torch produces heat by the combustion of acetylene in oxygen. The energy released by this exothermic reaction heats and then melts the metal being cut. The sparks are tiny bits of the molten metal flying away. (b) A cold pack uses an endothermic process to create the sensation of cold. (credit a: modification of work by "Skatebiker"/Wikimedia commons).

Two pictures are shown and labeled a and b. Picture a shows a metal railroad tie being cut with the flame of an acetylene torch. Picture b shows a chemical cold pack containing ammonium nitrate.

Units of Energy

Energy is measured in terms of its ability to perform work or to transfer heat. **Mechanical work** (w) is done when a **force** f displaces an object by a **distance** *d*:

$$w = f \times d \tag{8.2.3}$$

The basic unit of energy is the ***joule***. One joule is the amount of work done when a force of 1 newton acts over a distance of 1 m; thus 1 J = 1 N-m. The newton is the amount of force required to accelerate a 1-kg mass by 1 m/sec^2, so the basic dimensions of the joule are kg m^2 s^{-2}. Historically, energy was measured in units of calories (cal). A calorie is the amount of energy required to raise one gram of water by 1 degree C (1 kelvin). However, this quantity depends on the atmospheric pressure and the starting temperature of the water. The ease of measurement of energy changes in calories has meant that the calorie is still frequently used. The **Calorie** (with a capital C), or large calorie, commonly used in quantifying food energy content, is a kilocalorie. Another common unit of measurement of energy is the *BTU* (British thermal unit) which is defined in terms of the heating effect on water. Because of the many forms that energy can take, there are a correspondingly large number of units in which it can be expressed, a few of which are summarized below.

Effect of units of energy	Joule equivalents
1 calorie will raise the temperature of 1 g of water by 1 C°. The “dietary” calorie is actually 1 kcal. An average young adult expends about 1800 kcal per day just to stay alive. (you should know this definition)	1 cal = 4.184 J
1 BTU (British Thermal Unit) will raise the temperature of 1 lb of water by 1F°.	1 BTU = 1055 J
The electron-volt is even tinier: 1 eV is the work required to move a unit electric charge (1 C) through a potential difference of 1 volt.	1 J = 6.24 × 1018 eV
The watt is a unit of power, which measures the rate of energy flow in J sec^{-1}. Thus the watt-hour is a unit of energy. An average human consumes energy at a rate of about 100 watts; the brain alone runs at about 5 watts.	1 J = 2.78×10^{-4}watt-hr 1 w-h = 3.6 kJ
The liter-atmosphere is a variant of force-displacement work associated with volume changes in gases.	1 L-atm = 101.325 J
The huge quantities of energy consumed by cities and countries are expressed in quads; the therm is a similar but smaller unit.	1 quad = 1015 Btu = 1.05×10^{18} J
If the object is to obliterate cities or countries with nuclear weapons, the energy unit of choice is the ton of TNT equivalent.	1 ton of TNT = 4.184 GJ (by definition)

Summary

Video 8.2.1: *A video summary of Energy and Chemistry.*

Energy is the capacity to do work (applying a force to move matter). Kinetic energy (KE) is the energy of motion; potential energy is energy due to relative position, composition, or condition. When energy is converted from one form into another, energy is neither created nor destroyed (law of conservation of energy or first law of thermodynamics). Matter has thermal energy due to the KE of its molecules and temperature that corresponds to the average KE of its molecules. Heat is energy that is transferred between objects at different temperatures; it flows from a high to a low temperature. Chemical and physical processes can absorb heat (endothermic) or release heat (exothermic). The SI unit of energy, heat, and work is the joule (J). Specific heat and heat capacity are measures of the energy needed to change the temperature of a substance or object. The amount of heat absorbed or released by a substance depends directly on the type of substance, its mass, and the temperature change it undergoes.

Key Equations

- $q = c \times m \times \Delta T = c \times m \times (T_{\text{final}} - T_{\text{initial}})$
- $E_k = \frac{1}{2}mu^2$
- $E_P = mgh$
- $w = f \times d$

Glossary

calorie (cal)

unit of heat or other energy; the amount of energy required to raise 1 gram of water by 1 degree Celsius; 1 cal is defined as 4.184 J

endothermic process

chemical reaction or physical change that absorbs heat

energy

capacity to supply heat or do work

exothermic process

chemical reaction or physical change that releases heat

joule (J)

SI unit of energy; 1 joule is the kinetic energy of an object with a mass of 2 kilograms moving with a velocity of 1 meter per second, 1 J = 1 kg m^2/s and 4.184 J = 1 cal

kinetic energy

energy of a moving body, in joules, equal to $\frac{1}{2}mv^2$ (where *m* = mass and *v* = velocity)

potential energy

energy of a particle or system of particles derived from relative position, composition, or condition

temperature

intensive property of matter that is a quantitative measure of "hotness" and "coldness"

thermal energy

kinetic energy associated with the random motion of atoms and molecules

thermochemistry

study of measuring the amount of heat absorbed or released during a chemical reaction or a physical change

work (*w*)

energy transfer due to changes in external, macroscopic variables such as pressure and volume; or causing matter to move against an opposing force

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