

Chapter 5: Thermal Energy, the Microscopic Picture

Goals of Period 5

Section 5.1: To describe three states of matter - solid, liquid, and gas

Section 5.2: To discuss the relationship between temperature, thermal energy, and molecular motion

Section 5.3: To discuss the transfer of thermal energy at the molecular level

Section 5.4: To define thermal equilibrium and thermodynamic systems

Section 5.5: To examine four properties of matter

Section 5.6: To discuss the relationship of temperature and phase changes

In the previous period we discussed thermal energy and the concept of heat as thermal energy in transit. We defined *thermal energy* or *internal energy* as the kinetic energy involved in random molecular motion together with the potential energy stored in molecular attractions. We also saw that the temperature of an object is an indication of how hot or how cold an object is, but is not a measure of the amount of thermal energy the object has. In this period, we look in more detail at thermal phenomena in terms of the atomic theory of matter.

All matter is made of atoms or groups of atoms called molecules. So, it is not surprising that the study of thermal energy on an atomic or molecular basis is necessary in order to gain a fundamental understanding of the subject. In fact, we find that many phenomena such as diffusion, evaporation, thermal expansion, and changes of phase in matter can all be described on a molecular or atomic level. For brevity in the following discussions, we use the term "molecules" to refer either to molecules or to single atoms.

5.1 States of Matter

In a solid body, the molecules are tightly bound to each other by intermolecular forces (which are electromagnetic in nature) and can only vibrate about their equilibrium positions. In a liquid, the molecules are still close together and strongly attracted to each other, but they can freely slide past one another. In a gas, the molecules move so fast and are so far apart that they fly around relatively freely, experiencing intermolecular forces only when they are colliding with each other.

You might ask what happens if all of the molecules have the smallest amount of energy that they can have. In this case, the temperature corresponds to the lowest possible temperature, zero Kelvin, and is called absolute zero. Zero Kelvin occurs at very close to $-273\text{ }^{\circ}\text{C}$ and to $-460\text{ }^{\circ}\text{F}$. It is not true, however, that at this temperature all motion of the molecules of an object will cease. If we remove from an object all of the thermal energy that can be removed, the molecules of the object will still have some residual energy, known as the zero point energy.

5.2 Thermal Energy and Molecular Motion

Molecules are always in random motion, even when no motion is discernible to the naked eye. The fact that there is random molecular motion can be inferred from the motion of small dust particles suspended in air. The molecules or atoms making up the air are constantly in random motion. As air molecules strike dust particles in the air, the dust particles also move about in a random fashion. This random motion of the dust particles is known as Brownian motion. The observation of Brownian motion was one of the first accepted experimental proofs for the molecular or atomic theory of matter.

For gases, the thermal motion of molecules is random not only in direction, but also in speed. Some molecules are fast, some are slow. However, it is possible to speak of an average molecular speed applying to the entire group of molecules making up a gas. It is this average molecular speed that determines the temperature of the gas. The higher the average speed of the molecules, the higher the temperature. A graph of the molecular speed for the molecules of a gas at a temperature of 295 kelvin is shown in Figure 5.1. Note that the average speed is not equal to the most probable speed of the molecules.

Figure 5.1 Graph of Molecular Speeds of a Gas

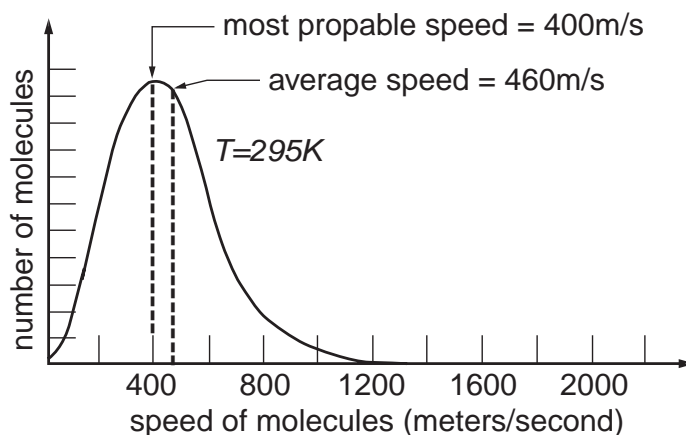
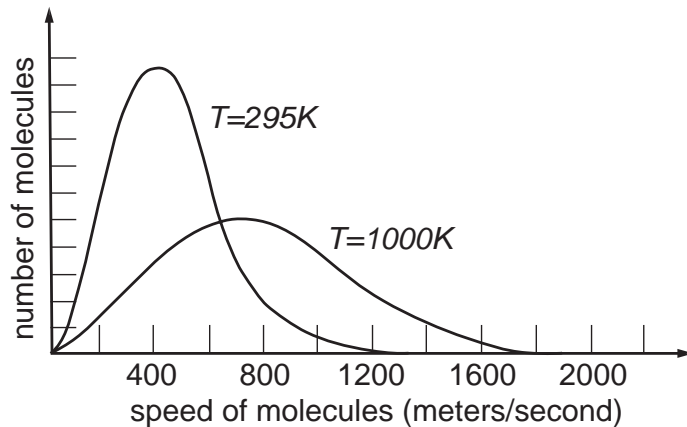


Figure 5.2 on the next page illustrates the change in the speed of the molecules of a gas when the gas temperature changes. The graph shows the distribution of molecular speeds for oxygen gas at a temperature of 295 K and 1000 K.

There is also a distribution of the speeds of molecules in a liquid or solid. However, this distribution of speeds differs from material to material, depending on the characteristics of the structure of that material. But for all materials – solid, liquid, or gas – the higher the temperature, the higher the average energy per molecule of the material.

Figure 5.2 Comparison of the Speeds of Gas Molecules at Different Temperatures

5.3 Transfer of Thermal Energy

In Chapter 4, we discussed the transfer of thermal energy by three methods: conduction, convection, and radiation. We now discuss each of these processes on a molecular level.

Conduction

The process of conduction occurs when one object is in physical contact with another object. We have seen that the molecules of the material at a higher temperature will have a higher average energy than the molecules of the material at a lower temperature. Because of the proximity of the materials, energy of the material at the higher temperature will be transferred to the molecules of the material at the lower temperature. As a result, the average energy of the molecules of the higher temperature object will decrease and the average energy of the molecules of the lower temperature object will increase. Thus, the temperature of the hotter object will decrease, and the temperature of the colder object will increase.

Convection

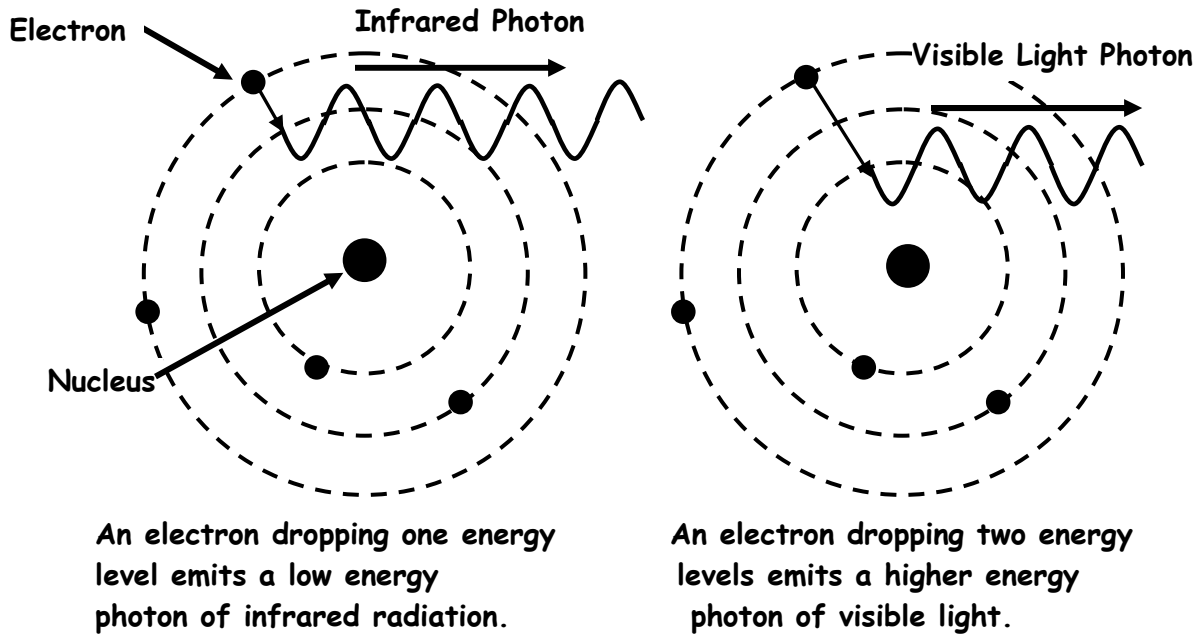
In the process of convection, which is limited to liquids and gases, the molecules of a higher temperature portion of a material will move so as to mix with the molecules of a lower temperature portion of the material. In this way, the average molecular energy of the cold portion of the material increases, while the average molecular energy of the warm portion of the material decreases. Thermal energy has been transferred.

Radiation

The third method of transfer of thermal energy, by radiation, takes place when electromagnetic radiation is produced by an object. In the case of a gas, the radiation will be produced by the individual atoms of that gas. In Chapter 2 we saw that the electromagnetic radiation from a single atom is characteristic of the energy levels of that atom. Figure 5.3 illustrates a single atom emitting a single photon and shows how the

frequency of the emitted radiation depends on the change of energy levels of the radiating electron.

Figure 5.3 Photons of Radiant Energy are Emitted from an Atom



When a substance is condensed from a gas into a liquid or a solid, the radiation mechanism gets much more complicated. In fact, the situation gets so complicated that it undergoes a profound simplification. As atoms are squeezed together to form a solid, the radiation from each atom is strongly affected by the presence of all the adjacent and close-by atoms. In 1900, even before the process of radiation from individual atoms was understood, a physicist named Planck realized that when many close-together atoms radiate, photons of all frequencies are produced, but in differing amounts. The amounts of the different photons produced depend on various properties of the radiating body, but depend most strongly of the temperature of the radiating material. A body for which the radiation is described solely by its temperature is known as a **black body**.

Radiation is produced by vibrating electric charge, and it should not be surprising that the greater the average kinetic energy of the molecules producing the radiation, the more radiation is produced. Since the temperature of a material is a measure of the average kinetic energy of the molecules of that material, it should also not be surprising that the distribution of the frequencies of the photons produced by the material can be characterized by the material's temperature. Therefore, since every object has some measurable temperature, we expect every object to emit some type of electromagnetic radiation. As also expected, on average a warm object radiates higher energy and higher frequency photons than does a cooler object. For example, when you turn on a toaster, you first detect heat from the infrared photons emitted. As the temperature of the toaster's element increases, your eyes can detect higher energy photons of visible red light.

An object that emits visible light is known as an *incandescent* object. The incandescent light bulb invented by Thomas Edison emits visible light from a glowing filament. We see incandescent objects because our eyes are sensitive to the visible light photons radiated from the object. We see cooler, room temperature objects when photons of visible light reflect from the object to our eyes. Room-temperature objects radiate primarily infrared photons, which are invisible to the human eye. However, infrared photons can be detected by infrared scanners and cameras, so that the presence and motion of people or animals can be observed even if there is no light available to reflect off of them.

Energy of Radiating Objects

The energy of the photons radiated from an object is proportional to the object's temperature as illustrated in Figure 5.4. This diagram also shows how the amount of radiation from an object increases as the temperature of that object increases.

Figure 5.4 Energy of Photons Radiated from Hot and Cool Solids

When an incandescent solid is viewed through a diffraction grating, the radiating solid produces a continuous spectrum of color. The dominant or brightest color in this spectrum depends on the temperature of the radiating object, with hotter objects radiating photons of higher frequency and energy. Within the visible portion of the spectrum, a cool object is radiating more red photons and a hotter object is radiating more blue-violet photons.

When photons strike an ideal radiating object, all of the photons are absorbed and none are reflected. This is probably why an ideal radiating solid is known as a black body. For such an ideal radiating solid, the average photon energy is proportional to the object's temperature, as shown by Equation 5.1.

(Equation 5.1)

$$E = 3 k T$$

where

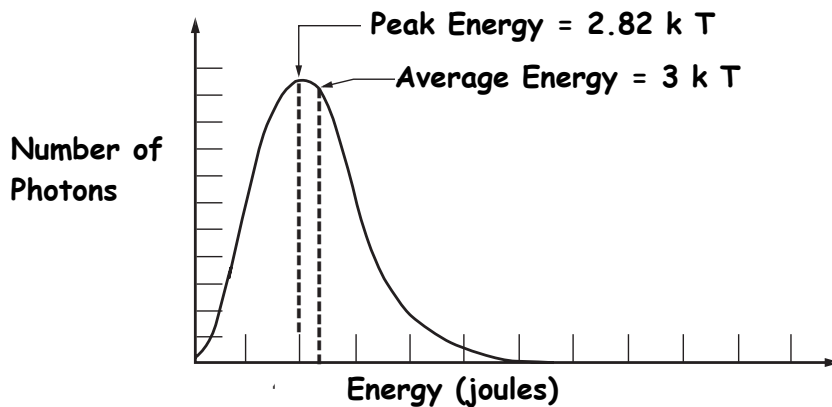
E = average photon energy (joules)

k = Boltzmann's constant = 1.38×10^{-23} J/K

T = temperature (kelvin)

Equation 5.1 describes the average energy of the photons emitted by an object at a temperature T . If we consider the peak photon energy, the relationship between energy and temperature is $E = 2.82 k T$. A comparison of the average and peak photon energies from an object at a temperature T is shown in Figure 5.5.

Figure 5.5 Relationship between Energy and Temperature



(Example 5.1)

When a particular 40-watt incandescent light bulb is lit, the average energy per photon of the photons radiated from its glowing filament is 1.325×10^{-19} J. What is the average temperature of the filament?

Solve $E = 3 k T$ for T .

$$T = \frac{E}{3 k} = \frac{1.325 \times 10^{-19} \text{ J}}{3 (1.38 \times 10^{-23} \text{ J/K})} = 3,200 \text{ K} \quad \text{or} \quad 5,300 \text{ }^\circ \text{F}$$

Concept Check 5.1

The light bulb in Example 5.1 is turned off and allowed to cool to room temperature of 70 °F (294 K). What is the average energy per photon of the infrared photons emitted by the bulb's filament at this temperature?

The photons emitted from an object radiate outward in all directions. If the object is placed in a closed, insulated box, the emitted photons bounce off of the box walls in all directions. The photons within the box can be thought of as a photon gas. A photon gas differs from a molecular gas in that the number of molecules of a gas in a container is fixed. However, as long as energy is conserved, the number of photons need not remain constant. For example, one photon of violet visible light with 5×10^{-19} joules of energy is equivalent to two photons of red visible light, each with 2.5×10^{-19} joules. As Figure 5.4 shows, the higher the temperature of an object, the more photons one would expect to be emitted from this source.

We can explain how energy is transferred between objects by radiation. The hotter an object is, the more energy it radiates. A cold object in the vicinity of a hot object also will radiate. But the hot object will radiate more energy than the colder object, with the net result that more energy is lost to the cold object by the hot object than by the cold object to the hot object. The average energy of the molecules of the cold object will increase, while the average energy of the molecules of the hot object will decrease.

5.4 Thermal Equilibrium and Thermodynamic Systems

Thermal equilibrium occurs when objects are at the same temperature as their surroundings. For example, a can of orange juice from your freezer and another from your table are placed inside of a well-insulated chest. After some time, the cans reach the same temperature because the two cans of OJ exchange heat. If the cans are at different temperatures, the thermal energy in one OJ can will increase and the thermal energy in the other can will decrease. It does not matter if one can was big and the other was small. They will still wind up at the same temperature.

If another object that is at the same temperature is very quickly put into the chest and the lid is shut, all three objects are in thermal equilibrium with each other. Two objects, each in thermal equilibrium with a third object, are all in equilibrium. This rule is called the Zeroth law of thermodynamics.

If the cans of OJ are touching in the insulated chest, they exchange heat primarily by conduction. If the cans are not touching, they exchange heat by radiation. When objects exchange heat via thermal radiation, they do so by an exchange of energy from radiated photons (electromagnetic radiation). If there is air in the chest, there may also be a transfer of energy between the cans by convection. When the cans reach

the same temperature, or thermal equilibrium, there has been a net transfer of thermal energy from the warmer can to the cooler can.

In learning about thermodynamics we use the word **system** when we consider the transfer of energy from one object to another by heat (thermal energy in transport) or work. Objects have characteristics that can be perceived by our senses, such as the size, mass and temperature of the object. Such objects are considered macroscopic (a piece of matter), not microscopic (atoms and molecules). The system could be any physical system such as a heat engine, which will be discussed in the next period, or a biological system such as your friend. Thermodynamics is the study of these systems.

A **thermodynamic system** is any collection of objects, and the rest of the universe is the system's environment. The thermodynamic system impacts the environment around it by heat and/or work. This causes an energy exchange with the environment, and the system's thermal energy, the internal energy of all objects in the system, may change. The **internal energy** is the total kinetic energy and potential energy of all objects that are in the system. In general, any thermodynamic system will include photons. The system may also have kinetic and potential energies due to outside forces such as gravity. We will discuss this when we look at changing the phase of an object, such as changing water to ice.

5.5 Some Properties of Matter

Most of the properties of matter follow from the characteristics of the states of matter and from the molecular picture. Next, we examine some of these properties.

Evaporative Cooling

We observe that a liquid in an open container will eventually disappear. This process is known as evaporation, and gives us more evidence for the motion of the molecules in the liquid. Consider the molecules just below the surface of a liquid. The fast ones are more likely to overcome the intermolecular forces and escape, while the slower molecules stay behind in the liquid. Without the fast molecules, the average molecular speed in the liquid is lower and that implies a lower temperature. The greater the rate of evaporation, the stronger this cooling effect will be. The evaporation rate of a liquid depends on what the liquid is, on the surface characteristics of the liquid, on the temperature of the liquid, and ultimately on the forces that exist between the atoms or molecules making up the liquid. Machine oil, for instance, evaporates so slowly that almost no cooling is noticeable. The cooling effect is more pronounced in liquids such as Freon (the working fluid in some air conditioners and refrigerators) that evaporate quickly, because less time is available for the liquid to gain back thermal energy from its environment. You will see several examples of evaporative cooling in class.

Diffusion

If a drop of ink is placed in one corner of a water tank, the ink will gradually spread out and distribute itself all through the water. This spreading out will take place even if the water is not stirred and the temperature of the water is held uniform to prevent convection currents. This process is called **diffusion**. Diffusion can be understood on the basis of the random motion of molecules in a substance. This is why

the drop of ink diffuses in the water. The concentration of the ink molecules is highest when the drop is first placed into the water. As time goes on, the ink molecules spread throughout the container. If the temperature of the water is higher, the diffusion takes place more rapidly. Diffusion takes place more rapidly in gases than in liquids and more rapidly in liquids than in solids.

Thermal Expansion

Molecules in hot matter move faster than molecules in cold matter, and usually the average intermolecular distances are larger. Thus, almost all matter expands when heated. In the classroom we shall see several examples of thermal expansion and contraction and observe that different materials exhibit different characteristics in this regard. There are many industrial applications of this effect, for example, in obtaining a very tight fit between machine parts.

One of the very few exceptions to the general rule that objects expand when heated is water near its freezing point. Between 0 °C and 4 °C decreases in volume. The result is that the water expands by about 10 percent when it freezes. The same is true of seawater. This fact makes ice less dense than water, so ice rises to the top and floats. While this effect may seem a nuisance to homeowners, forcing them to drain outdoor water pipes for the winter, it has tremendous ecological consequences because it prevents lakes and oceans from freezing solid. This is very good for fish and all other life forms.

Friction

In Physics 103 we discovered that the amount of friction between two surfaces depends on the smoothness of the surfaces, the types of materials in contact, and the amount of force pressing the surfaces together. Of these factors, the type of material is a property of the matter making up an object. Two equally smooth surfaces made of different matter may produce different amounts of friction. For example, a block made of rubber experiences more friction as it slides across a table top than does a wooden block of the same mass and smoothness. This difference in friction is due to their properties of matter – the different chemical composition of rubber and wood.

Regardless of the types of matter involved, the molecular picture explains how mechanical energy can be transformed into thermal energy by friction. When a block of wood slides across a table top, frictional forces do work to slow down the block. Some of the mechanical energy of the block is converted into random motion of the individual molecules in the block and the tabletop, that is, into thermal energy.

5.6 Temperature and Phase Changes

As thermal energy is added to, or taken away from, a substance, two things can happen. First, as you have already seen, the temperature can change. However, the amount that the temperature will change is not the same for all objects, even when the amount of thermal energy added is the same. You already know, for example, that a cup of water will get much hotter than a pan of water, if the same amount of thermal energy is added to each of them. This is because temperature change depends on the amount of matter being heated. Temperature change also depends on the type of

material being heated. It takes more energy to raise the temperature of water than to raise the temperature of an equal amount of metal, for example.

The amount of energy that must be added to an object to raise its temperature by one degree is known as the **heat capacity** (H_{cap}) of that object. The thermal energy required to change the temperature of an object by several degrees is given in Equation 5.2. If thermal energy is measured in calories and temperature in degrees Celsius, then heat capacity is given in calories/degree C or in joules/degree C.

$$\text{Change in thermal energy} = (\text{Heat capacity}) \times (\text{Change in Temperature})$$

(Equation 5.2)

$$Q = H_{cap} \times \Delta T$$

where

$$\begin{aligned} Q &= \text{heat added or subtracted (calories or joules)} \\ H_{cap} &= \text{heat capacity (calories/ } ^\circ\text{C or joules/ } ^\circ\text{C)} \\ \Delta T &= \text{change in temperature} = T_{final} - T_{initial} \text{ (Celsius degrees)} \end{aligned}$$

(Example 5.2)

What is the heat capacity of one kilogram of iron if 9,000 joules of thermal energy are required to increase the temperature of the iron by 20 °C?

Solve Equation 5.1 for the heat capacity, H_{cap}

$$H_{cap} = \frac{Q}{\Delta T} = \frac{9,000 \text{ J}}{20 \text{ } ^\circ\text{C}} = 450 \text{ J/}^\circ\text{C}$$

Concept Check 5.2

What is the heat capacity of one kilogram of copper if 7,800 joules of thermal energy are required to increase the temperature of the copper by 20 °C?

If we divide the heat capacity of an object by its mass, we obtain a quantity known as the **specific heat** (s_{heat}) of the object. The specific heat does not depend on the size or shape of an object, but only on the material from which it is made. Water has a large specific heat of 1 calorie per gram per degree Celsius or 4,186 joules per kilogram degree Celsius. Ice floats because the volume of water increases when it freezes. This is connected to the change in the specific heat of water near 0 °C. Table 5.1 lists the specific heat of some common materials.

Table 5.1 Specific Heat of Common Materials

Material	Specific Heat (J/g °C)	Specific Heat (cal/g °C)
Water (liquid, 15 °C)	4.186	1.00
Water (ice, - 5 °C)	2.100	0.50
Water (steam, 110 °C)	2.010	0.48
Wood	1.700	0.40
Aluminum	0.900	0.22
Glass	0.840	0.20
Iron	0.450	0.11
Copper	0.390	0.093
Silver	0.230	0.056

The heat required to change the temperature of an object can be expressed as

$$\text{Change in thermal energy} = (\text{Specific heat}) \times (\text{Mass}) \times (\text{Change in Temperature})$$

(Equation 5.3)

$$Q = s_{\text{heat}} \times M \times \Delta T$$

where

Q = heat added or subtracted (calories or joules)

s_{heat} = specific heat (calories/gram °C or joules/kilogram °C)

M = mass (grams or kilograms)

ΔT = change in temperature = $T_{\text{final}} - T_{\text{initial}}$ (Celsius degrees)

If thermal energy is given in calories, mass in grams and temperature in degrees Celsius, then specific heat is given in calories/(gram degree Celsius).

(Example 5.3)

How much thermal energy is needed to raise 2 kilograms of iron by 10 °C? The specific heat of iron is 450 J/kg °C.

$$Q = s_{\text{heat}} \times M \times \Delta T = (450 \text{ J/kg } ^\circ\text{C}) \times 2 \text{ kg} \times 10 \text{ } ^\circ\text{C} = 9,000 \text{ J}$$

What is the heat capacity of this object?

Solve Equation 5.2 for the heat capacity, H_{cap}

$$H_{\text{cap}} = \frac{Q}{\Delta T} = \frac{9,000 \text{ J}}{10 \text{ } ^\circ\text{C}} = 900 \text{ J/}^\circ\text{C}$$

The second thing that can happen when thermal energy is transferred to or from a system is that the state of the system can change. Changes from the solid to the liquid or from the liquid to the gaseous state, and vice versa, are called *phase changes*. They always involve a transfer of heat, even though the temperature of the substance undergoing the phase change stays constant. As discussed earlier, the heat flow from one object to another can change either the average kinetic energy of the random motion of the molecules, which changes the temperature of the object, or can change the average potential energy of the molecules, which causes the phase of the object to change. Consider what happens when, for instance, a pot of water is heated on a stove. At first, the temperature rises. Upon reaching 100 °C (212 °F) the temperature stops increasing, even though the flame keeps supplying heat at the same rate as before. We know that the thermal energy supplied goes into breaking the bonds between the molecules, while the kinetic energy of the molecules remains unchanged. Gradually, more and more molecules gain sufficient energy to overcome the intermolecular forces binding the molecules one to the other. A similar phenomenon occurs when ice melts.

We call the heat required to produce a phase change the *latent heat (L_{heat})*. Two examples of latent heat are the heat of freezing and the heat of vaporization. The heat of freezing is the amount of thermal energy *given off* as a liquid freezes, and the heat of vaporization is the amount of thermal energy that must be *added* to change a liquid to a gas.

Heat added or subtracted for a phase change = Latent heat x Mass

$$Q = L_{heat} M \quad \text{(Equation 5.4)}$$

where

$$\begin{aligned} Q &= \text{heat (calories or joules)} \\ L_{heat} &= \text{latent heat (calories/gram or joules/kilogram)} \\ M &= \text{mass (grams or kilograms)} \end{aligned}$$

If liquid water at 100 °C is changed into steam, the heat added (the latent heat of vaporization) is 540 calories for every gram of water. If steam at 100 °C is changed into water at 100 °C, 540 calories for every gram of steam must be subtracted. If ice at 0 °C is changed into liquid water at 0 °C, the heat added (the latent heat of melting) is 80 calories for every gram of ice. If liquid water at 0 °C is change into ice at 0 °C, 80 calories for every gram of liquid water must be subtracted.

Latent heats can be very large. For example, the latent heat of vaporization of water is 540 cal/g and the latent heat of freezing of water is 80 cal/g. Therefore, changing a given quantity of water to steam requires 5.4 times as much heat as warming it from 0 °C (+32 °F) to 100 °C (212 °F), and melting ice requires as much heat as warming water from 20 °C (68 °F) to 100 °C.

(Example 5.4)

How many calories of heat are required to convert 500 grams of water at a temperature of 25 °C into steam at 100 °C?

First, use Equation 5.3 to find the heat required to raise the temperature of the water to 100 °C. The specific heat of liquid water is 1.00 calories/gram °C.

$$Q = s_{heat} \times M \times \Delta T = (1.00 \text{ cal/g } ^\circ\text{C}) \times 500 \text{ g} \times (100 \text{ } ^\circ\text{C} - 25 \text{ } ^\circ\text{C}) = 37,500 \text{ cal}$$

Next, use Equation 5.4 to find the heat required for the phase change of 500 grams of water at 100 °C into steam at 100 °C. The latent heat of evaporation of water is 540 calories/gram.

$$Q = L_{heat} \times M = 540 \text{ cal/g} \times 500 \text{ g} = 270,000 \text{ cal}$$

The total heat is the sum of the heat required to heat the water to 100 °C and the heat required to convert the liquid water into steam.

$$\text{Total heat} = 37,500 \text{ cal} + 270,000 \text{ cal} = 307,500 \text{ cal}$$

Concept Check 5.3

How many calories heat are required to convert 200 grams of ice at 0 °C into liquid water at 30 °C ? The latent heat of melting of ice is 80 calories/gram. The specific heat of ice is 0.5 calories/gram °C .

Pressure can influence phase changes. Water expands when it becomes vapor, but by applying enough pressure one can compress the vapor to water. Therefore the boiling temperature of water depends on pressure, and is 100 °C only at normal atmospheric pressure. In a pressure cooker that is providing a pressure of twice the normal atmospheric pressure, the boiling point of water is raised to about 120 °C (248 °F), which shortens cooking times. At the top of Mount Everest, where the pressure is about one third that of normal atmospheric pressure, water boils at 71 °C (160 °F).

Similarly, ice can be melted by applying enough pressure. This facilitates ice skating. Under the pressure of a person's weight on the thin blade a little bit of ice melts and the water provides a good lubricant between the blade and the ice surface. If

a wire is looped around a piece of ice with the ends of the wire attached to weights, it will work its way through the ice. Under the pressure exerted on it by the wire, the ice beneath the wire melts and the wire moves down a little into the block of ice. The water resulting from the ice that was melted is pushed up above the wires and, since it is no longer under pressure, refreezes. By this process the wire can move through the ice, leaving solid ice again behind it.

Period 5 Summary

5.1: Matter can exist in a solid, liquid, or gaseous state.

In a solid, molecules are tightly bound. In a liquid, molecules are close together and strongly attracted to each other, but they can slide freely past one another. In a gas, molecules move so fast and are so far apart, that they move relatively freely and experience intermolecular forces only when they collide.

5.2: Temperature is the average kinetic energy of the molecules in a substance.

Heat is thermal energy in transit between two objects at different temperatures.

The molecules making up an object in any of the three states of matter are always in motion. The higher the temperature of the object, the faster the average speed of the molecules and the greater of average energy per molecule.

5.3: Thermal energy can be transferred via conduction, convection, or radiation.

Conduction transfers energy from hot to cold objects by decreasing the average energy of the molecules of the hot object and increasing the average energy of the molecules of the cold object.

Convection mixes the molecules of the higher temperature portion of a liquid or gas with the molecules of a lower temperature portion so that the average energy of the initially hot molecules decreases and the average energy of the initially cold molecules increases.

Radiation occurs when a vibrating electric charge drops to a lower energy level in an atomic shell and emits a photon. The average energy of the emitted photons is proportional the temperature of the emitting object: $E = k T$.

All objects emit and absorb photons. The hotter the object, the more photons it radiates. When a hot and cold object are near one another, thermal energy is transferred via radiation when the hot object emits more photons than it absorbs, lowering its temperature, and the cold object absorbs more photons than it emits, raising its temperature.

5.4: Thermal equilibrium occurs when a thermodynamic system (any collection of objects) is at the same temperature as its surroundings (the system's environment).

Period 5 Summary, Continued

Thermal energy (or internal energy) of a system is the kinetic energy involved in random molecular motion together with the potential energy stored in molecular attractions.

- 5.5:** Evaporation cools a substance because the molecules with the most kinetic energy are most likely to leave (evaporate) from the surface of a substance. When the molecules with the most energy leave, the average kinetic energy of the remaining molecules goes down and the temperature is lower.

Diffusion occurs due to the random (Brownian) motion of molecules. Diffusion occurs more rapidly at higher temperatures because warm molecules have greater average kinetic energy.

Thermal expansion occurs as the temperature of substances increases because molecules in hot matter move faster than molecules in cold matter. Water is an exception, decreasing in volume when it freezes.

The amount of friction between surfaces depends, in part, on the type of matter making up the surfaces. When a block moves across a table top, some of the kinetic energy of the block is converted in the motion of the molecules of the block and the table top, that is, into thermal energy.

- 5.6:** Phase changes occur when matter changes from one state of matter (solid, liquid, or gas) to another state.

Heat capacity: The amount of heat needed to change an object's temperature by one Celsius degree. $Q = H_{cap} \Delta T$

Specific heat: The amount of heat needed to change the temperature of one gram of a substance by one Celsius degree. $Q = s_{heat} M \Delta T$

Latent heat: The amount of heat needed to change the phase of one gram of a substance. $Q = L_{heat} M$

Period 5 Exercises

- E.1 An increase in the temperature of a solid usually
- decreases the average molecular separation.
 - causes the molecules to melt.
 - increases the average molecular separation.
 - causes the electrons to transfer to lower energy levels.
 - NONE of the statements is correct.

- E.2 Evaporation is a process
- that increases the temperature of liquids.
 - where slow molecules increase their speed.
 - caused by cooling.
 - that results in a decrease of the temperature of liquids.
 - NONE of the statements is correct.
- E.3 When water is cooled to form ice there is a decrease in
- the kinetic energy of the molecules.
 - the latent heat of the water.
 - the intermolecular force.
 - molecular contraction.
 - Both a) and b) are correct.
- E.4 When you transfer heat to a substance, you always increase its
- latent heat.
 - specific heat.
 - temperature.
 - energy.
 - heat capacity.
- E.5 Brownian motion provided evidence for
- electronic shells of atoms.
 - atomic weights of atoms.
 - molecular motion.
 - nuclear charges of atoms.
 - None of the above is correct.
- E.6 Container A contains air at a temperature of 100°C and container B contains air at a temperature of 200°C . Which of the following is true?
- The air molecules in container A are moving faster, on average than those in container B.
 - The air molecules in container B are moving faster, on average than those in container A.
 - There is not enough information to say anything about the average molecular speeds.
 - The air molecules in both containers have the same average speed.

- E.7 One can change a substance from a liquid to a solid by
- a) removing thermal energy from the substance.
 - b) adding thermal energy to the substance.
 - c) adding the latent heat of vaporization to the substance.
 - d) adding the latent heat of fusion to the substance.
 - e) Both a) and d) are necessary
- E.8 Absolute zero is
- a) defined as zero degrees on the Kelvin scale of temperature.
 - b) the temperature at which all motion stops.
 - c) the temperature of liquid nitrogen.
 - d) defined as zero on the Celsius scale.
 - e) Both a) and b) are correct.
- E.9 Consider two pails of water at the same temperature. Pail A contains 80 kg of water and Pail B contains 40 kg of water. Which one of the following statements is TRUE?
- a) The water in pail A has a larger specific heat than the water in pail B.
 - b) The water in pail A has a greater thermal conductivity than the water in pail B.
 - c) The water in pail A has a greater heat capacity than the water in pail B.
 - d) The water in pail A has a smaller specific heat than the water in pail B.
 - e) None of the statements is true.

Period 5 Review Questions

- R.1 In class, we discussed convection, conduction, and diffusion. Which of these three processes can occur in solids, liquids and in gases?
- R.2 "Wind chill" refers to the cooling effect of wind. Why does it feel colder on a windy day than it does on a calm day?
- R.3 Why do car tires require less air in summer than in winter?
- R.4 What does the specific heat of an object depend upon? The shape of the object? The material from which the object is made? The mass of the object? The temperature of the object?
- R.5 Which contains more thermal energy – a cup full of hot coffee or a bathtub full of warm water? Why?

