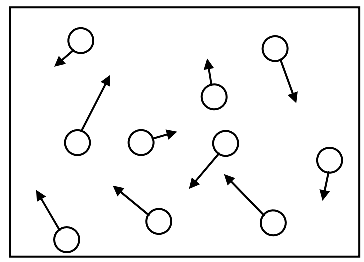
SUBAREA I. MATTER AND ENERGY; HEAT, THERMODYNAMICS, AND THERMOCHEMISTRY

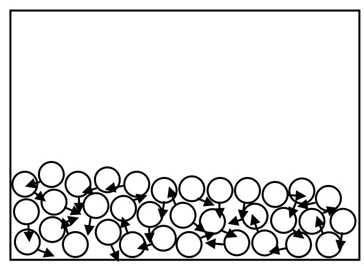
COMPETENCY 1.0. MATTER AND ENERGY

Skill 1.1 Organization of matter

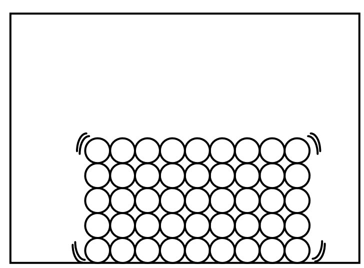
Molecules have **kinetic energy** (they move around), and they also have **intermolecular attractive forces** (they stick to each other). The relationship between these two determines whether a collection of molecules will be a gas, liquid, or solid.



A **gas** has an indefinite shape and an indefinite volume. The kinetic model for a gas is a collection of widely separated molecules, each moving in a random and free fashion, with negligible attractive or repulsive forces between them. Gases will expand to occupy a larger container so there is more space between the molecules. Gases can also be compressed to fit into a small container so the molecules are less separated. **Diffusion** occurs when one material spreads into or through another. Gases diffuse rapidly and move from one place to another.



A **liquid** assumes the shape of the portion of any container that it occupies and has a specific volume. The kinetic model for a liquid is a collection of molecules attracted to each other with sufficient strength to keep them close to each other but with insufficient strength to prevent them from moving around randomly. Liquids have a higher density and are much less compressible than gases because the molecules in a liquid are closer together. Diffusion occurs more slowly in liquids than in gases because the molecules in a liquid stick to each other and are not completely free to move.



A **solid** has a definite volume and definite shape. The kinetic model for a solid is a collection of molecules attracted to each other with sufficient strength to essentially lock them in place. Each molecule may vibrate, but it has an average position relative to its neighbors. If these positions form an ordered pattern, the solid is called **crystalline**. Otherwise, it is called **amorphous**. Solids have a high density and are almost incompressible because the molecules are close together. Diffusion occurs extremely slowly because the molecules almost never alter their position.

Skill 1.2 Physical and chemical properties and changes of matter

All matter has physical properties and chemical properties. Physical properties and chemical properties of matter describe the appearance or behavior of a substance. A **physical property can be observed without changing the identity of a substance.** For instance, you can describe the color, mass, shape, and volume of a book. Physical properties include color, size, luster, smell, freezing point, boiling point, melting point, mass, and density.

<u>Physical Properties:</u>

Matter takes up space and it has mass. **Mass** is a measure of the amount of matter in an object. Two objects of equal mass will balance each other on a simple balance scale no matter where the scale is located. For instance, two rocks with the same amount of mass that are in balance on earth will also be in balance on the moon. They will feel heavier on earth than on the moon because of the gravitational pull of the earth. So, although the two rocks have the same mass, they will have different **weights.**

Weight is the measure of the earth's pull of gravity on an object. It can also be defined as the pull of gravity between other bodies. The units of weight measurement commonly used are the pound (English measure) and the kilogram **(**metric measure).

In addition to mass, matter also has the property of volume. **Volume** is the amount of cubic space that an object occupies. Volume and mass together give a more exact description of the object. Two objects may have the same volume, but different mass, or the same mass but different volumes, etc. For instance, consider two cubes that are each one cubic centimeter, one made from plastic, one from lead. They have the same volume, but the lead cube has more mass. The measure that we use to describe the cubes takes into consideration both the mass and the volume. **Density** is the mass of a substance contained per unit of volume. If the density of an object is less than the density of a liquid, the object will float in the liquid. If the object is denser than the liquid, then the object will sink.

Density is stated in grams per cubic centimeter (g/cm^3) where the gram is the standard unit of mass. To find an object's density, you must measure its mass and its volume. Then divide the mass by the volume ($D = m/V$).

To discover an object's density, first use a balance to find its mass. Then calculate its volume. If the object is a regular shape, you can find the volume by multiplying the length, width, and height together. However, if it is an irregular shape, you can find the volume by seeing how much water it displaces. Measure the water in the container before and after the object is submerged. The difference will be the volume of the object.

Specific gravity is the ratio of the density of a substance to the density of water. For instance, the specific density of one liter of turpentine is calculated by comparing its mass (0.81 kg) to the mass of one liter of water (1 kg):

$$\frac{\text{mass of 1 L alcohol}}{\text{mass of 1 L water}} = \frac{0.81\ \text{kg}}{1.00\ \text{kg}} = 0.81$$

Conductivity: Substances can have two variables of conductivity. A conductor is a material that transfers a substance easily. That substance may be thermal or electrical in nature. Metals are known for being good thermal and electrical conductors. Touch your hand to a hot piece of metal and you know it is a good conductor- the heat transfers to your hand and you may be burned. Materials through which electric charges can easily flow are called electrical **conductors**. Metals that are good electric conductors include silicon and boron. On the other hand, an **insulator** is a material through which electric charges do not move easily, if at all. Examples of electrical insulators would be the nonmetal elements of the periodic table.

Solubility is defined as the amount of substance (referred to as solute) that will dissolve into another substance, called the solvent. The amount that will dissolve can vary according to the conditions, most notably temperature. The process is called solvation.

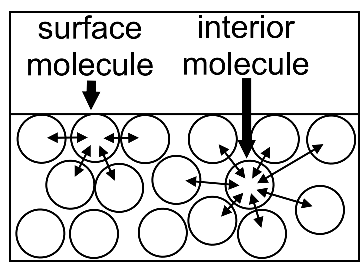
Melting point refers to the temperature at which a solid becomes a liquid. Melting takes place when there is sufficient energy available to break the intermolecular forces that hold molecules together in a solid.

Boiling point refers to the temperature at which a liquid becomes a gas. Boiling occurs when there is enough energy available to break the intermolecular forces holding molecules together as a liquid.

Boiling Point as a Function of Pressure: For a liquid in an open container, vapor pressure increases with temperature until it is equal to the external pressure, and the boiling point occurs at that temperature. Boiling is defined as the process of vapor bubbles forming and evolving from the liquid. Substances with stronger intermolecular attractive forces have a higher boiling point. An increase in the surrounding pressure forces molecules closer together and increases their intermolecular attractive forces. More kinetic energy is required to break these bonds, so the boiling point of a liquid increases with increasing pressure.

Viscosity measures the ability of a liquid to flow. Liquids with high viscosity flow less easily because they have strong intermolecular forces relative to kinetic energy. The viscosity of liquids decreases with temperature because it is easier for rapidly moving molecules to flow into the spaces between them. For most liquids (water is an exception), viscosity increases with pressure because the molecules are squeezed together, which forces a greater interaction, but this dependence is not as strong as the dependence on temperature.

Surface tension is the energy required to increase the surface area of a liquid by a unit amount. Because of surface tension, friction exists at the liquid-gas interface that makes it more difficult to move a solid object through the surface than to move it when it's completely submerged. It is as if there is a "film" at the interface that makes it more difficult for a solid object to "break through" the surface than to move around when it's already completely submerged.



The molecules on the surface of a liquid are affected by two type of intermolecular forces. One attraction is to the molecules that have evaporated and are in the air surrounding the liquid, and the other attraction is to other molecules in the liquid. The latter attraction is many times stronger than the first. So, there is a preference for the surface molecules to remain in the liquid phase. There is a net inwards pull away from the interface between liquid and gas, which has the effect of minimizing the liquid's surface area. This is not the case for molecules in the interior of the liquid because here the forces are balanced.

An increase in temperature decreases the surface tension because the kinetic energy acts in opposition to intermolecular attractive forces. Chemicals with strong intermolecular attractive forces have a high surface tension. Surface tension can also be altered by adding other substances. For example, NaOH added to water will raise its surface tension and soap added to water will lower its surface tension.

Hardness describes how difficult it is to scratch or indent a substance. The hardest natural substance is diamond.

Chemical properties describe the ability of a substance to be changed into new substances. Chemical properties include such things as heat of combustion, reactivity with water, pH, and electromotive force. Baking powder goes through a chemical change as it changes into carbon dioxide gas during the baking process. Measuring physical properties does not change the matter, but measuring the chemical properties involves a chemical change to the matter.

Chemical Properties:

Heat of combustion is the heat of reaction that is evolved by the complete combustion of one mole of a substance.

Because hydrogen has the potential to ignite and explode, it has **explosiveness** or **flammability** as a chemical property.

Some elements such as sodium are highly **reactive with water**.

The **pH** is a measure of the **acidity** or **alkalinity** (basic-ness) of a solution.

Physical changes, many of which are phase changes, include condensation, melting, freezing, evaporation and sublimation. These concepts will be reviewed in Skill 2.4.

Chemical changes are more commonly known as chemical reactions. These include combining or re-combining to create compounds, burning, decomposition, and the reactions of redox chemistry and acid-base chemistry which will be reviewed in a variety of skills.

Skill 1.3 Forms and transformations of matter and energy

The forms of matter are discussed in Skill 1.1. It is important to recognize that **matter is conserved** (see Skill 1.4) and so while it may undergo phase (see Skill 2.4) and chemical changes and even nuclear decay, it will never be created nor destroyed.

The **forms of energy include chemical, electrical, thermal, and mechanical**. All types of energy are important for the study of chemistry and some are discussed elsewhere in this guide (thermal energy in Competency 2.0 and electric energy in Skill 7.5). Like matter, **energy is conserved and cannot be created or destroyed** (see Skill 1.4).

Energy can be converted from one type to another. For instance, living things convert the chemical energy stored in adenosine-tri-phosphate (ATP) to mechanical energy to perform a variety of tasks.

Further, **mass and energy are related to one another via special relativity**. The total energy (E) of particle or object is related to its mass (m) via the famous equation $E = mc^2$ (where c is a constant, the speed of light in a vacuum). Note that in this equation, mass is specifically *rest mass* or mass measured independent of the observer (i.e., rest mass does not change with a change in reference). Therefore, in modern physics, all forms of energy exhibit mass and all mass is a form of energy.

Skill 1.4 Laws of conservation of mass and energy

The law of conservation of mass states that the **mass of a closed system will remain constant, regardless of the processes acting inside the system**. This means that matter can change form, but it cannot be created or destroyed. This implies that for any chemical process in a closed system, the mass of the reactants must equal the mass of the products**.**

Likewise, the law of conservation of energy states that **the total amount of energy in an isolated system remains constant.** The energy may be converted from one form to another, but will not be created or destroyed. Note that the conservation of energy is also the first law of thermodynamics (Skill 2.5).

COMPETENCY 2.0 HEAT AND THERMODYNAMICS

Skill 2.1 Heat and temperature; concepts; measurements and units

Heat and Temperature

The temperature exhibited by an object is proportional to the average kinetic energy of the particles in the substance. If the temperature of a substance is increased, its particles move faster so their average kinetic energies increase as well. But temperature is NOT energy; therefore, it is not conserved.

Heat is energy that is transferred between objects caused by differences in their temperatures. Heat passes spontaneously from an object of higher temperature to one of lower temperature. This transfer continues until both objects reach the same temperature.

Energy

Energy is the **driving force for change**. Energy has units of joules (J). Temperature remains constant during phase changes, so the **speed** of molecules and their **translational kinetic energy do not change** during a change in phase.

The **internal energy** of a material is the **sum of the total kinetic energy** of its molecules and the **potential energy** of interactions between those molecules. Total kinetic energy includes the contributions from translational motion and other components of motion such as rotation. The potential energy includes **energy stored in the form of resisting intermolecular attractions** between molecules.

The **enthalpy** (*H*) of a material is the **sum of its internal energy and the mechanical work** it can do by driving a piston. We usually don't deal with mechanical work in high school chemistry, so the differences between internal energy and enthalpy are not important. The key concept is that a change in the **enthalpy** of a substance is the total **energy** change caused by **adding or removing heat** at constant pressure.

When a material is heated and experiences a phase change, **thermal energy is used to break the intermolecular bonds** holding the material together. Similarly, bonds are formed with the release of thermal energy when a material changes its phase during cooling. Therefore, **the energy of a material increases during a phase change that requires heat and decreases during a phase change that releases heat**. For example, the energy of H_2O increases when ice melts and decreases when water freezes.

Entropy

Entropy may be thought of as **the disorder in a system** or as a measure of the **number of states a system may occupy**. Changes due to entropy occur in one direction with no driving force. For example, a small volume of gas released into a large container will expand to fill it, but the gas in a large container never spontaneously collects itself into a small volume. This occurs because a large volume of gas has more disorder and has more places for gas molecules to be. This change occurs because **processes increase in entropy** when given the opportunity to do so.

A brief definition will not help you master these concepts. But it is important that you can utilize them sufficiently to apply them to phase changes and to chemical reactions. Entropy has units of Joules/Kelvin.

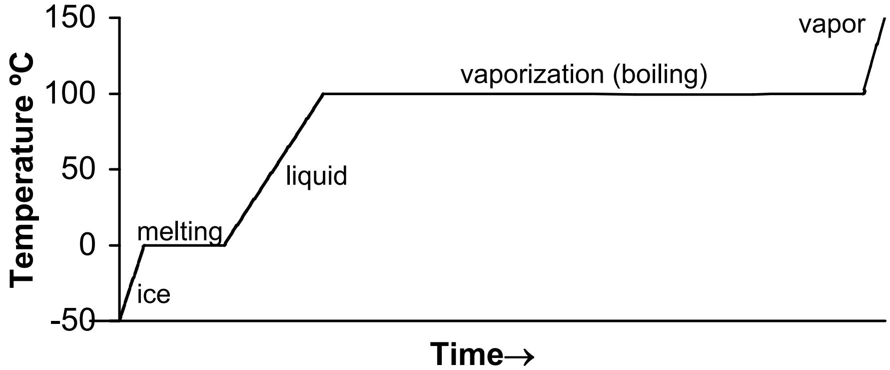
See skills 2.5 and 2.6 for a complete discussion of enthalpy and entropy.

Also see Skill 14.1 for more information on units and temperature scales.

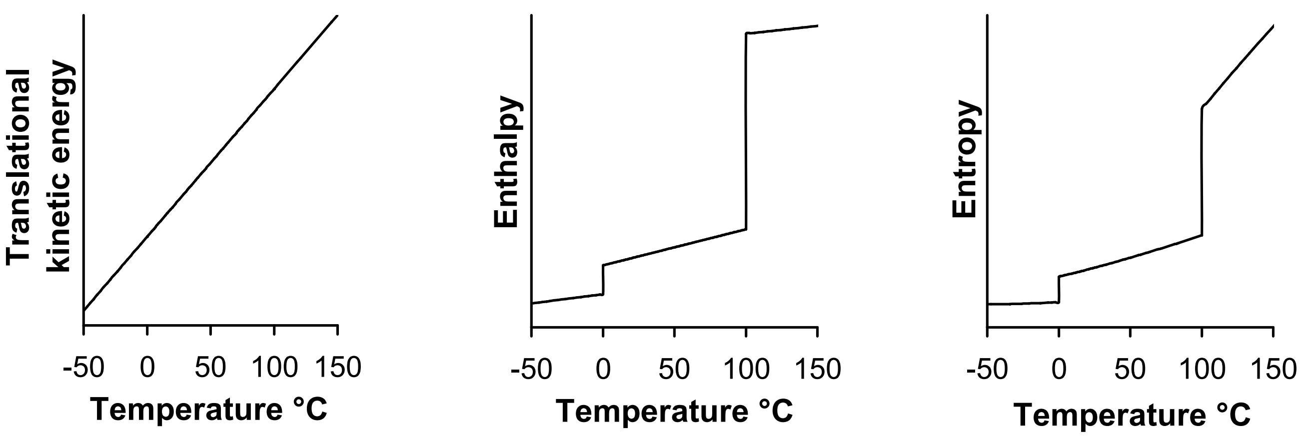
Skill 2.2 Measurement and transfer of thermal energy and its effects on matter

In the solid phase, each molecule may vibrate a little, but it is otherwise locked in place in an ordered position and may only be in a relatively small number of locations. In the gas phase, however, each molecule could be almost anywhere and there is greater disorder. Therefore, **the entropy of a material increases during a phase change that raises the freedom of molecular motion and decreases during a phase change that prevents molecular motion.** Entropy also increases with temperature because molecules experience more disorder when they have a wider range of energy states to occupy.

Raw phase change data is often charted by recording the temperature over time when heat is added at a constant rate. A diagram for water at 1 atm from –50°C to 150°C is shown below. Note that temperature does not change during melting and boiling. Also note the difference in the length of time required for melting compared to boiling. This is a result of greater energy requirements to boil a substance than to melt it.



The relationship of the translational kinetic energy, enthalpy, and entropy of water to temperature is charted below under the same conditions.



Skill 2.3 Kinetic molecular theory and gas laws

In a solid, the energy of intermolecular attractive forces is much stronger than the kinetic energy of the molecules. As temperature increases in a solid, the vibrations of individual molecules grow more intense and the molecules spread slightly further apart, decreasing the density of the solid.

The type of attractive forces within solids depends on the identity of the unit particle and the chemical bonds it can form. The forces between atoms in a covalent network solid (such as carbon in diamond) are **covalent bonds**. These bonds result when at least one pair of electrons is shared by two atoms. The forces between atoms within metallic elements (such as iron) are **metallic bonds**. Electrostatic attractions—also called **ionic bonds**—are the forces between ions, atoms which have lost one or more electrons to become positively charged ions or which have gained one or more electrons to become negatively charged ions (such as those found in NaCl). Ionic compounds are often known as salts. Covalent, metallic, and ionic bonds are strong chemical bonds.

The intermolecular forces between polar molecules are known as **dipole-dipole interactions**. The partial positive charge of one molecule is attracted to the partial negative charge of its neighbor. Polar molecules (such as CH_3Cl) form molecular solids with dipole-dipole bonds between units. Polar molecules with H on one molecule attracted to O, N, or F on an adjacent molecule (like H_2O) form relatively strong dipole-dipole bonds known as **hydrogen bonds** between molecules.

When a nonpolar molecule (or a noble gas atom) encounters an ion, its electron density is temporarily distorted resulting in an **induced dipole** that will be attracted to the ion. Intermolecular attractions due to induced dipoles in a nonpolar molecule are known as **London forces** or **Van der Waals interactions**. London dispersion forces are the only attractions between the units of non-polar molecules (like saturated hydrocarbons and N_2) and the noble gases when they form solids at low temperatures. London dispersion forces are the weakest intermolecular attractions, but these attractions grow stronger for larger molecules because a larger electron cloud is more easily polarized. The strength of London dispersion forces also **increases for molecules with a larger surface area** because there is greater opportunity for electrons to influence neighboring molecules if there is more potential contact between the molecules. Paraffin in candles is an example of a solid held together by weak London forces between large molecules. These materials are soft.

In a liquid, the energy of intermolecular attractive forces is about as strong as the kinetic energy of the molecules and both play a role in the properties of liquids.