CHEMICAL REACTIONS AND PROPERTIES OF MATTER

In simple terms, chemistry is the study of particle collisions in which electrons are agitated by energy differences and subjected to dislocation. In chemical reactions, the mass of the matter before and after the reaction remains the same, as does the number of atoms of each type that are involved in the reaction. Students will explore to what extent solute particles interact with a solvent and any new properties that may occur, such as changes in the concentration of hydrogen ions (H^+) or hydroxide ions (OH^-).

CORE IDEAS

- For gaseous substances, pressure, volume, and temperature are interdependent. (SPS5b)
- Temperature is a measure of the internal energy of a system. (SPS5b)
- The greater the molecular or particle motion, the higher the internal energy of a system. (SPS5a)
- The phases of matter are states of a system that have relatively the same physical properties. (SPS5a)
- Matter cannot be destroyed nor created in a chemical reaction. (SPS3a, b)
- Solutions are mixtures in which the relative proportion of solute and solvent varies. (SPS6b)
- The degree to which a solute dissolves is affected by physical conditions of the system. (SPS6b)
- The properties of a solution, such as conductivity and acidity, are related to whether the solute is ionic or covalent. (SPS6d, e)
- Acidic solutions have excess hydrogen ions, and basic solutions contain excess hydroxide ions. (SPS6d)

KEY CONCEPTS

Conservation of Matter in Chemical Reactions

Matter, like energy, is neither created nor destroyed. In a chemical reaction, the same number and types of atoms occur in the products as in the original reactants. As a result, the mass of the **products** always equals the mass of the **reactants**. This statement summarizes the **law of conservation of mass**. One example of this law in action involves the burning of firewood. At first glance, it appears that the law of conservation of mass is violated because the mass of the ashes left over is much less than the mass of the original wood. In fact, if one could measure the mass of the smoke, water vapor, and carbon dioxide given off in addition to the ash, the mass would exactly equal that of the unburned firewood.

The law of conservation of matter/mass can be used to balance **chemical equations**, which are used to show what happens in a chemical reaction. In chemical equations, the coefficients in front of the chemical formulas represent the number of molecules of reactants or products. For example, the reaction of hydrogen and oxygen to form water is shown below.

$$2H_2 + O_2 \rightarrow 2H_2O$$

Two molecules of hydrogen plus one molecule of oxygen combines to form, or yields, two molecules of water. Notice that the number of hydrogen atoms ($2 \times 2 = 4$) and oxygen atoms ($1 \times 2 = 2$) on the reactants side (left side of the arrow) of the equation equals the number of hydrogen and oxygen atoms on the products side (right side of the arrow) of the equation. The equation is balanced because the numbers of atoms of each element (H, O) are the same on both sides of the arrow.

In a **synthesis** reaction, two or more substances combine to form a compound. A synthesis reaction is represented by the general equation ***A* + *B* → *AB***. When balancing an equation for a synthesis reaction, the coefficients should be used to make the number of atoms of each element the same on each side of the equation. The following "bookkeeping" method was used to obtain the above balanced equation. The equation was first written without coefficients. Understand that even though no coefficients are written in the original equation, coefficients of one are understood. The steps are shown below.

In Step 1, two hydrogen atoms appeared on both sides of the equation. No change was needed.

$$H_2 + O_2 \rightarrow H_2O$$

Step 1

Element	No. of Atoms in Reactants	No. of Atoms in Product(s)
H	2	2
O	2	1

The reactants side contained two oxygen atoms, while the product(s) side contained only one oxygen atom. In Step 2, the number of water molecules was multiplied by two to balance the oxygen atoms. A two coefficient was placed before the H_2O.

$$H_2 + O_2 \rightarrow 2\ H_2O$$

Step 2

Element	No. of Atoms in Reactants	No. of Atoms in Product(s)
H	2	4
O	2	1 x 2

Finally, in Step 3, the reactants side still contained two hydrogen atoms, while the product(s) side contained four hydrogen atoms. The hydrogen molecule (H_2) was multiplied by two to balance the hydrogen atoms. The equation is balanced when a two coefficient is placed before the H_2.

$$2H_2 + O_2 \rightarrow 2\ H_2O$$

Step 3

Element	No. of Atoms in Reactants	No. of Atoms in Product(s)
H	2 x 2	4
O	2	1 x 2

Similar bookkeeping can be used to balance other types of simple equations.

A **decomposition** reaction is the opposite of a synthesis reaction. In a decomposition reaction, a compound breaks down into more simple substances. It is represented by the general equation ***AB* → *A* + *B***. An example of this reaction is the decomposition of sodium chloride (NaCl).

$$2NaCl \rightarrow 2Na + Cl_2$$

Notice that the equation is balanced as written. Count the number of atoms of each element on each side of the equation (right and left of the arrow). On the reactants side of the equation are two atoms of sodium and two atoms of chlorine. On the products side of the equation are two atoms of sodium and two atoms of chlorine. The coefficient for chlorine is understood, though not written.

A **single replacement** reaction involves a single element replacing another element in a compound, forming a different compound. A single replacement reaction may be represented by the general equation ***A + BC →AC + B***. An example of this reaction is the replacement of iodine (I) by chlorine (Cl) in a potassium iodide (KI) solution.

$$2KI + Cl_2 \rightarrow 2KCl + I_2$$

In a **double replacement** reaction, two elements in two different compounds replace each other, forming two different compounds. A double replacement reaction has the general equation ***AB + CD → AD + CB***. The reaction of sodium sulfide (Na_2S) by hydrogen chloride (HCl) is a good example of this type of reaction.

$$Na_2S + 2HCl \rightarrow 2NaCl + H_2S$$

If you count the number of atoms of each element on the reactants side of the equation and the number of atoms of the same elements on the products side of the equation, you will find that they are equal. There are two sodium (Na) atoms on the left side (reactants) and right side (products) of the arrow; one sulfur (S) atom on each side, two chlorine (Cl) atoms on each side, and two hydrogen (H) atoms on each side. The equation is balanced.

Pressure (*P*), **volume (*V*)**, and **absolute temperature (*T*)** are usually used to describe the condition of a gas. Pressure is the force exerted on a surface per unit area. To understand how the above variables are related, consider air in a fixed volume container. When the temperature of a gas is increased, the atoms or molecules move faster since they have more energy. Since the volume remains the same, the force pushing on the walls of the container increases, resulting in a rise in pressure. Conversely, if a gas is cooled at a constant volume, the pressure decreases. Compressing a gas at a constant temperature into a smaller volume results in an increase in the amount of collisions between the gas molecules and the walls of the container due to the reduction of volume. This change results in an increase in pressure. When the converse is true, the pressure decreases. Chemists have summarized these relationships mathematically with the following laws, assuming the amount of gas is constant:

> ***PV*** = a constant when the temperature is constant.
>
> ***V*** is directly proportional to ***T*** when the pressure is constant.
>
> ***P*** is directly proportional to ***T*** when volume is constant.

These laws can prove very useful when trying to describe the properties of a gas under changing conditions.

Atoms and molecules are in constant motion. The type and degree of motion determine the phase or state of matter.

- In the **solid phase**, atoms or molecules are held in a rigid structure. They are free to vibrate but cannot move around. As a result, solids have a definite volume and shape.
- In the **liquid phase**, intermolecular forces hold these atoms or molecules loosely together but do not force them into a rigid structure. The molecules of a liquid are free to move around to a certain degree and have a definite volume. As a result, liquids conform to the shape of their container.
- In the **gas phase**, atoms and molecules experience their greatest freedom. The forces attracting gas molecules are almost nonexistent. As a result, gas molecules are much farther apart and can move around freely. Since gas does not possess a definite volume, and since the molecules move freely, a gas expands to fill the container it is in.
- **Plasmas** are gases that have been so energized that their atoms have been stripped of some or all electrons. Solar flares are great examples of plasmas. Solar flares eject extremely hot hydrogen ions (H^+) away from the sun toward Earth.

Matter, the substance that is seen all around us, consists of anything that has mass and volume. The **density**, *d*, of an object is defined as the ratio of the object's **mass**, *m*, to its **volume**, *V*.

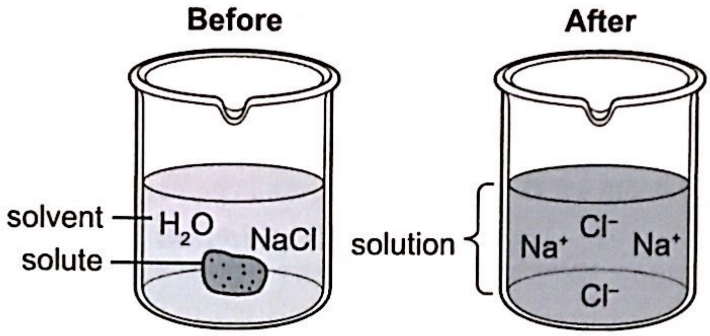
$$d = \frac{m}{V}$$

Density is a unique property of matter. Gases tend to have very low densities compared to liquids and solids. The large distances between atoms or molecules of a gas are responsible for the very low density.

Physical properties are any properties that are measurable and can be observed or measured without changing the identity of the substance. Color, hardness, area, length, strength, density, temperature, melting point, boiling point, solubility, electrical conductivity, and state of matter are examples of physical properties.

Chemical properties are any properties that can be measured only by chemically changing an object. Flammability, oxidation, toxicity, and heat of combustion are examples of chemical properties.

A **mixture** is a material that is made up of two or more different substances that has a uniform composition. A **solution** is a special type of mixture. It has a uniform composition throughout and is made up of two parts—a solute and a solvent. The **solute** is the substance that is being dissolved or broken down into smaller particles. The **solvent** is the substance doing the dissolving. Usually the solute is the substance that is in smaller quantity. For example, in a sodium chloride (NaCl) solution in water, the NaCl is the solute, while water is the solvent. What is chemically happening with the atoms of sodium chloride and water is shown in the diagram on the next page. **Solubility** is the ability of a substance to dissolve in a solvent, such as water. When the maximum amount of solute that can be dissolved is added to the solvent, the solution becomes **saturated**. Below this maximum amount, the solution is **unsaturated**.

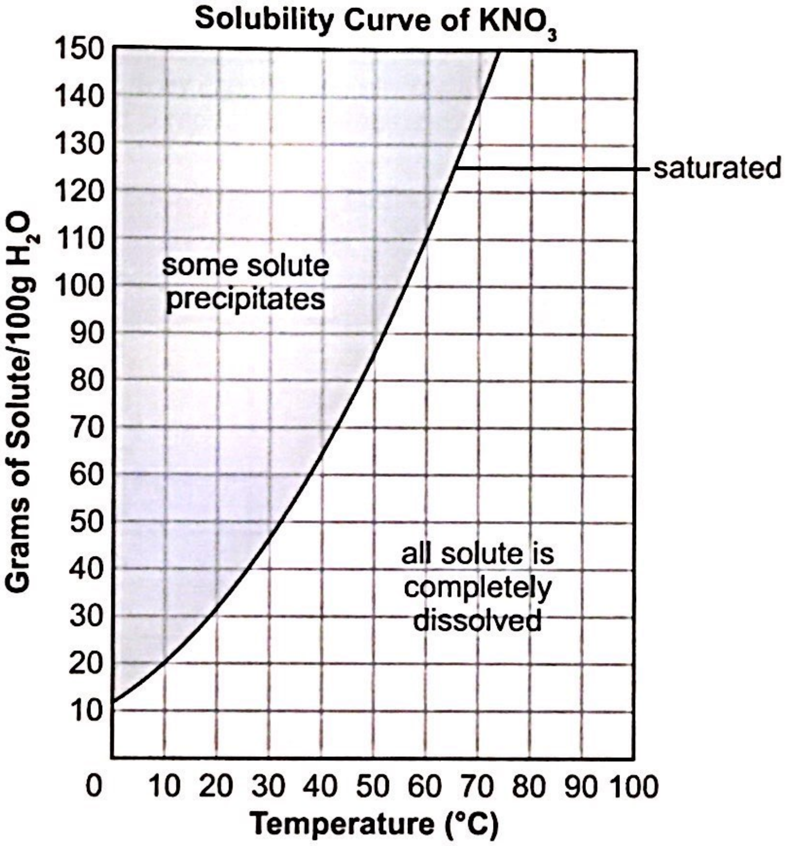


The **concentration** describes how much solute has been dissolved in solution. Almost all concentration units express some kind of ratio. For example, the mass percent of a solution is equal to the mass of the solute (in grams) divided by the mass of the solution (in grams) times 100%.

There are a number of factors that can affect the rate at which a solid solute dissolves in a liquid solvent:

- Stirring increases the amount of fresh solvent that comes in contact with a solute. When there is no stirring, the solvent around the solute becomes nearly saturated. Stirring keeps the solvent near the solute unsaturated, increasing the dissolving rate.
- When a solute is ground into smaller particles, the amount of surface area exposed to the solvent increases. This additional surface area allows the dissolving process to occur faster. The smaller the solute particles, the faster the rate of dissolving.
- Solvent molecules move faster when the temperature increases. These faster liquid solvent molecules come in contact with solid solute particles more often, increasing the dissolving rate. Also, at higher temperatures, the solubility usually increases. Higher temperatures, therefore, favor faster dissolving rates.
- In contrast, when a gas solute is dissolved in a liquid, the molecules of the gas are already energetic and have weak intermolecular attractive forces. As a result, gas solutes tend to escape from a solution by evaporation when the temperature increases, so solubility for gases in liquids tends to decrease at increasing temperatures.

A **solubility curve** shows how the amount of dissolved solute changes with temperature. The solubility curve shown below graphs the solubility of potassium nitrate (KNO_3) as a function of temperature. Under certain circumstances a solution can hold more of the solute than the usual limit. This is called **supersaturation** and is usually a temporary condition since the solution is unstable. Notice that the dimensions of solubility are grams of solute per 100 grams of solvent (water). The solubility of most salts, such as KNO_3, increases with higher temperatures, as can be seen in the graph below.



A solubility curve also shows the temperature at which a solute will begin to precipitate out of the solution. For example, if approximately 110 grams of KNO_3 are dissolved in 100 grams of water at 70°C, the salt completely dissolves. When the solution cools, though, the KNO_3 begins to precipitate out at 60°C because the solution has become saturated. As you can see above, as the solution cools further, more of the KNO_3 will precipitate out until, at 0°C, only 12 grams of KNO_3 will remain in solution. Can you determine from the graph how many grams of KNO_3 will be dissolved in solution at 50°C? If your answer is about 85 grams, you are correct.

Conductivity is the measure of a solution's ability to conduct electricity. Conductivity gives important clues as to the type of solute dissolved. In **aqueous** (water-based) solutions, dissolved ionic compounds yield solutions with high conductivity. Solutions with higher concentrations of ionic compounds tend to conduct electricity better than dilute solutions. Cations and anions easily carry electrical charges through the solution. Strong acids and bases also have a high conductivity for the same reason. All of these solutions are considered **strong electrolytes.**

Weak acids or bases ionize only partially, so they form solutions with low conductivity. These compounds are called **weak electrolytes.** Solutions made from covalent compounds have zero conductivity since they dissolve as molecules, not ions. They cannot carry electrical charges. These substances are known as **nonelectrolytes.** Some selected compounds and their electrical conductivity are shown in the chart below.

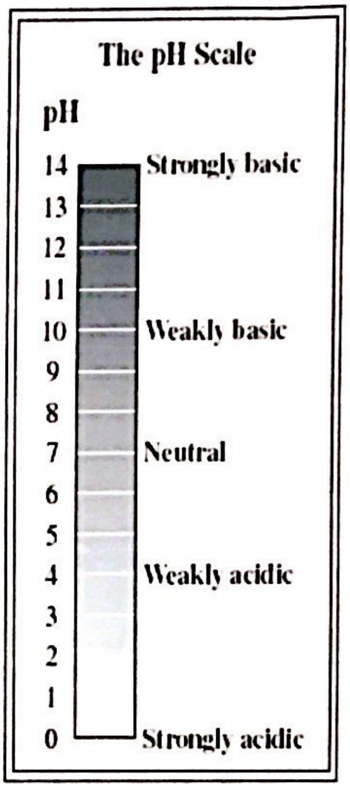
Conductivity of Some Aqueous Solutions		
High Conductivity/ Strong Electrolyte	**Low Conductivity/ Weak Electrolyte**	**Zero Conductivity/ Nonelectrolyte**
$AlCl_3$	CH_3CO_2H (acetic acid)	CH_3OH (methanol)
$CaCl_2$		
H_2SO_4	NH_3 (ammonia)	$C_{12}H_{22}O_{11}$ (table sugar)
HCl		
KCl	HF (hydrofluoric acid)	$C_6H_{12}O_6$ (glucose)
KOH		
$MgSO_4$		
NaCl		
NaOH		

As early as the 1600s, chemists recognized that some substances could be classified as either **acids** or **bases.** It took many more years to define and describe the behavior of these important compounds. Chemists today know that acids and bases have the properties shown in the following chart:

	Acid	Base
Taste	• Sour or tart	• Bitter
Touch	• Feels like water/may sting	• Feels smooth and slippery
Reactions with Metals	• Vigorously reacts with most metals to produce hydrogen gas, H_2	• Does not react with most metals
Electrical Conductivity	• Readily conducts electricity (less so for weak acids)	• Readily conducts electricity (less so for weak bases)
Litmus Paper* Test	• Turns blue litmus paper red	• Turns red litmus paper blue

*A type of paper containing a dye that changes color when exposed to acids or bases

The **pH scale** gives a measure of the acidity or basicity of a solution. The lower the pH of a solution, the more acidic it is. The higher the pH, the more basic it is. Any solution with a pH less than 7 is acidic. A solution with a pH greater than 7 is considered basic. Any solution with a pH of exactly 7 is neutral. See the pH scale on the right. Lemon juice has a pH between 2 and 3. It is acidic. Common household bleach is basic, with a pH between 12 and 13. Pure water has a pH of 7 and is neutral. All compounds that give off **hydrogen ions** (H^+) in solution are acids. Bases are any compounds that accept the hydrogen ions to form a salt. For example, hydrochloric acid (HCl) and sodium hydroxide ($NaOH$) react together in a **neutralization reaction.**



$$\underset{\text{acid}}{HCl} + \underset{\text{base}}{NaOH} \rightarrow \underset{\text{salt}}{NaCl} + \underset{\text{water}}{H_2O}$$

The hydroxide ion (OH^-) from the $NaOH$ accepted the hydrogen ion (H^+) from the HCl to form water. The salt ($NaCl$) was formed from the sodium ion (Na^+) and the chloride ion (Cl^-) left over.