Chapter 1
The Nature of Chemistry

The goal of this chapter is to introduce you to the world of **chemistry** from the perspective of a chemist. Although chemists think about chemistry using macroscale, nanoscale, and symbolic techniques, chemistry is often referred to as the molecular science. It is this molecular (nanoscale) interest that makes chemistry distinct from other scientific fields. This chapter introduces several macroscale (physical properties, types of mixtures, states of matter), nanoscale (structural formulas, ball-and-stick models, space-filling models, atomic theory, kinetic-molecular theory), and symbolic (balanced equations, density calculations, dimensional analysis, periodic table) representations commonly used by chemists and non-chemists alike. It also explains how chemists perform scientific experiments based on hypotheses, theories, and laws and introduces one of the most important tools used by chemists—mathematics and mathematical calculations.

The Power of Chemistry to Answer Intriguing Questions (1.1)

The properties of many chemicals are governed by their molecular structures. This is why scientists from other fields including biology, engineering, geology, physics, and medicine need to study chemistry and why they work with chemists in interdisciplinary teams. Chemical principles are also used to answer many important (and difficult) questions that arise in non-scientific fields like music, art, and history.

Using a Scientific Approach to Solve Problems (1.2 & 1.3)

Chemistry, like most other sciences, is *empirical* in nature. This means that the laws, theories, and hypotheses proposed in chemistry are largely based on data collected in the laboratory ('empirical' simply means 'based on observation and experiment', and is the opposite of 'theoretical' which means 'based on theory or speculation'). Ultimately, if there is a conflict between the empirical data and a scientific theory, the theory must be adapted to fit the data. The field of chemistry represents the work done by scientists to make sense of the world at the molecular (atomic) level.

Hypotheses, Theories, and Laws (1.3)

Hypotheses, theories, and laws are the result of the work done by scientists in their attempts to understand the world. In contrast to most students' view of the scientific method, hypotheses are not a scientists' first step. **Hypotheses** (which are usually described as 'educated guesses') are based on data collected by scientists and usually represent the scientists' first attempt to explain their observations. The results of a hypothesis that appear to work after several experiments can be referred to as a **theory**, a unifying principle used to explain many facts. Although theories can still be proven wrong based on new data, theories are usually pretty solid because they are based on large amounts of data. Theories that are of extremely broad significance, and have withstood the test of time and many experiments, can be 'upgraded' to laws. **Laws** are usually very well established and rarely change, although this happens from time to time.

Quantitative and Qualitative Observations (1.3)

Quantitative observations are based on numerical values that are often determined through experimental measurements. **Qualitative** observations, on the other hand, involve non-numerical information collected using the five senses: Color or luster (sight), odor (smell), pops or bangs (hearing), texture or temperature (touch), etc. You should never use the sense of taste in a chemistry laboratory.

Physical Properties of Matter and Physical Changes (1.4)

Physical properties are characteristics of a **substance** that describe the object. These properties are usually measured non-destructively (i.e., the object is the same before and after the physical property has been measured). **Melting point** (which is also called the **freezing point**), **boiling point**, density, color, and shape are all examples of physical properties. **Physical changes** are changes that occur in which the chemical composition of a substance has not changed. The most common physical changes seen in a chemistry laboratory are those involving changes in the state of matter (gas, liquid, solid, aqueous). A liquid boiling into a gas or a solid dissolving in water are common examples of physical changes.

Estimating Celsius Temperatures (1.4)

Although there is a formula for converting *Fahrenheit temperatures* to the **Celsius temperature scale** (which can be found in the back of the textbook), it is often useful to make quick qualitative comparisons of two or more **temperatures** (hotter/colder) without performing the mathematical conversion to get them in the same scale. In order to make these qualitative comparisons, you need to know the numerical values of certain temperatures in both scales. Some of the values include: –40°C = –40°F (the temperature where these two values are the same), 0°C = 32°F (melting/freezing point of water), 37°C = 98.6°F (normal human body temperature), and 100°C = 212°F (boiling point of water).

Density Calculations (1.4)

The definition of **density** as 'the mass per unit volume' of an object is a symbolic definition (based on the mathematical symbols for the mass and volume: $d = m/V$). The nanoscale definition of density is the "crowdedness" of **matter** (the more crowded the matter is in a given volume the higher the density, and vice versa). The density of most solids and liquids fall in the range of 0.5-20 g/mL, while most gases have densities that are much lower than that of solids and liquids.

When performing density calculations, density can be viewed as a mathematical ratio (**proportionality factor**) of two properties related by a mathematical formula ($d = m/V$) or as a **conversion factor** that converts a mass measurement into its equivalent volume or a volume measurement into its equivalent mass.

<u>Example</u>: What is the volume (in mL) of a sample of 514 g of liquid bromine (Br_2)? The density of bromine is 3.12 g/mL.

<u>Solution</u>: If you are more comfortable with using the density formula, you can solve for V (volume) and plug the numbers that were given into the equation:

$$d = \frac{m}{V},\ V = \frac{m}{d} = \frac{514\ \text{g}}{3.12\ \text{g/mL}} = 165\ \text{mL}$$

If you would prefer to think of density as a conversion factor that relates the mass and volume of bromine (i.e., 3.12 g = 1 mL), then you can start with the mass of Br_2 and convert it to volume of Br_2:

$$514\ \text{g} \times \frac{1\ \text{mL}}{3.12\ \text{g}} = 165\ \text{mL}$$

Both methods give you the same answer, and it is perfectly acceptable to use either method.

Chemical Properties of Matter and Chemical Changes (1.5)

Chemical properties are characteristics of a substance describing how it will react with other chemicals. A **chemical reaction** is considered a destructive process because once the **reactants** have been converted into the **products**, they are gone and cannot be recovered under normal conditions. The ability to bubble when placed in acid, to burst into flames when placed in water, and to turn cloudy when another substance is added are examples of chemical properties. **Chemical changes** are changes that occur in which the chemical composition of a substance is changed, and are often accompanied by changes in color, heat, etc.

Homogeneous and Heterogeneous Mixtures (1.6)

Most substances in the real world are *mixtures* (combinations of two or more chemicals). Mixtures can be classified as heterogeneous or homogeneous. **Heterogeneous mixtures** do not appear to be completely mixed and differences in the mixture can be seen by the unaided eye. **Homogeneous mixtures** (also called **solutions**), on the other hand, appear to be completely mixed so that every sample of the mixture contains the same substances and in the same ratios. An example of a heterogeneous mixture would be Raisin Bran cereal (where differences between the raisins and bran flakes can be seen); an example of a homogenous mixture would be Kool-Aid (where every sample of the liquid looks the same).

At the nanoscale, the different molecules in a homogeneous mixture can be seen but these molecules are completely and randomly mixed. In a heterogeneous mixture, the different molecules in the mixture are not randomly mixed and different types of molecules are clustered together in different regions.

Separation, Purification, and Analysis (1.6)

Separation and purification are methods that can be used to convert mixtures into pure substances. This is important because a substance must be pure if chemists are to measure and identify its physical and chemical properties. Analysis is used to determine the amount of any chemical present, and the quality of these techniques tends to improve over time. It is important to know the total amount of a substance present, because human toxicity greatly depends on amount.

Chemical Elements and Chemical Compounds (1.7 & 1.9)

In their attempts to understand matter, early chemists focused on separating mixtures into their individual components, and on separating these components into more and more components. When they identified a substance that could not be separated further, they classified this substance as a **chemical element**. Pure substances that could be separated further (but were still pure) were called **chemical compounds**. The difference between pure compounds and mixtures was that the properties of the pure compound were always the same while the properties of mixtures could be different if different relative amounts of the constituents were present (i.e., salt water can be very salty or only slightly salty, so it represents a mixture).

At the nanoscale, pure elements have only one kind of atom present. Pure compounds have more than one atom present, but they are always combined in the same way (i.e., pure water has H and O in it, but always as H_2O and never in any other form). At the nanoscale, mixtures have two or more different substances present—for example, sugar water would have H_2O (water) molecules and $C_{12}H_{22}O_{11}$ (sucrose) molecules.

Classifying Matter (1.7)

The chart in Figure 1.13 of the textbook (p. 17) describes how matter may be classified into heterogeneous mixtures, homogeneous mixtures, pure substances, pure compounds, and pure elements. Separating mixtures can often be done using physical processes, although chemical processes can be used as well. Separating pure compounds into pure elements, on the other hand, requires the use of chemical methods.

Properties of Gases, Liquids, and Solids (1.8)

One of the most important physical properties of an object is its *state of matter* (gas, liquid, or solid). At the macroscale, **gases** expand to fill the entire volume of any container they are placed in, and they can also be compressed into smaller volumes. Unless the gas sample is colored, gases are also invisible. The macroscale properties of **liquids** are that they have fixed volumes but fluid shapes and motions. Liquids conform to the shape of the bottom of any container in which they are placed. **Solids** can be recognized by their rigid shape and fixed volume. Solid objects move as one object and there is no fluidity in the motion of a single solid—powdered solids like salt and sugar consist of many solid particles and while the powder may appear to have fluid motion, each particle in the solid moves as a single object.

Estimating Macroscale, Microscale, and Nanoscale Sizes (1.8)

When discussing macroscale, microscale, and nanoscale properties, it is useful to look at the origin of these words. The prefixes '*macro*-' means 'large', '*micro*-' means 'small or requiring magnification to be seen' (as in a microscope), and '*nano*-' means 'extremely small' and is about the size of atoms and molecules.

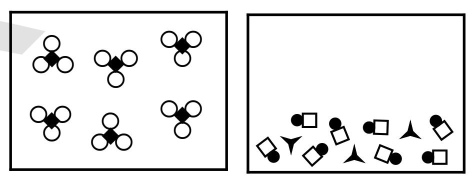
Scientists also use the prefixes '*micro-*' to mean 'one millionth' ($1/1{,}000{,}000 = 10^{-6}$) and '*nano-*' to mean 'one billionth' ($1/1{,}000{,}000{,}000 = 10^{-9}$). **Macroscale** observations are those that can be made using the human eye, and most everyday objects that you can see have sizes in the macroscale region. **Microscale** observations cannot be made by the unaided eye, and require the use of magnification devices like simple optical microscopes. Microscale objects are about 1 micrometer (μm) in size—the size of a single living cell. **Nanoscale** observations have only recently been made possible with the aid of powerful microscopes like the electron microscope and the scanning tunneling microscope. Nanoscale objects are about 1 nanometer (nm) in size—the size of single atoms or **molecules**.

Kinetic-Molecular Theory (1.8)

One of the most important nanoscale theories used in chemistry is the **kinetic-molecular theory**, which explains how atoms or molecules behave within gas, liquid, and solid samples. The kinetic-molecular theory will be described in more detail in the chapters on the properties of gases and the atmosphere (Chapter 10) and the properties of solids, liquids, and materials (Chapter 11).

At the nanoscale, gas molecules are very far apart from each other and there is a large amount of empty space between gas molecules. Gas molecules also have large amounts of **energy** and move very quickly in constant, random motions. Molecules in liquids and solids are close enough to touch each other. In a liquid, the molecules appear disorganized (no pattern) and have independent freedom of motion to move past each other. The molecules within a solid have an organized pattern and do not have the freedom to move from their positions. Solid molecules still have some motion, but it is usually in the form of simple vibrations around their fixed position in the solid.

Example: Consider the nanoscale pictures to the right.
(a) Do these pictures depict gases, liquids, or solids?
(b) Do these pictures depict pure substances, heterogeneous mixtures, or homogeneous mixtures?
(c) Do these pictures depict atoms, molecules, or both?
(d) Do these pictures depict elements, compounds, or both?



1 2

Solution:
(a) Picture 1 depicts a gas because the particles are occupying the entire container volume; Picture 2 depicts a liquid. These particles occupy the bottom of the container but do not show the ordered pattern that would be expected from a solid.
(b) Picture 1 depicts a pure substance; even though we can see two different atoms (circle and diamond), there is only one kind of chemical present (diamond with three circles). Picture 2 is a mixture because there are two different chemicals present (triangle and circle-square); this is a homogeneous mixture because the particles are randomly mixed and are not separated in different regions.
(c) Picture 1 depicts molecules made up of four atoms. Picture 2 contains atoms of triangle and molecules made up of circle and square atoms.
(d) Picture 1 depicts a compound made of two different kinds atoms. The atoms of triangle in Picture 2 represent an element. The circle-square molecules are compounds made of two different atoms.

Modern Atomic Theory (1.9)

Another important nanoscale theory used in chemistry is the **atomic theory**. Originally proposed by John Dalton in 1803, the atomic theory states that all matter is made of indivisible, indestructible particles called **atoms** (*atomos* means 'indivisible' in Greek). Chemical reactions are simply the rearrangements of atoms within the reactants to form new products. Each atom of the same element has very similar properties and reactivities, and atoms of different elements can have very different chemical and physical properties.

Dalton's atomic theory became popular because it could explain several puzzling yet reproducible observations made at the time. The **law of conservation of mass** could finally be explained because the atomic theory says that in chemical reactions, atoms are neither created nor destroyed, simply rearranged; if every atom that was present before the reaction is still present, then the total mass of the sample should not change. The atomic theory also explains the **law of constant composition**. The atomic theory says that each chemical is always made of the same number and kinds of atoms. Since each atom within the chemical has specific properties (masses) that don't change, then the ratio of masses of the atoms within this compound won't change either. The example below describes how the atomic theory explains the **law of multiple proportions**.

<u>Example</u>: When cuprous bromide is decomposed into its elements, it is found to be 55.7% bromine and 44.3% copper. When cupric bromide is decomposed into its elements, it is found to be 71.5% bromine and 28.5% copper. How do these compounds demonstrate the law of multiple proportions?

<u>Solution</u>: In order to test the law of multiple proportions, you need to determine the proportion of the mass of one element divided by the other in these two compounds. If you assume there is 100.0 g of each compound, you have 55.7 g of bromine and 44.3 g of copper in cuprous bromide, and 71.5 g of bromine and 28.5 g of copper in cupric bromide. The mass ratios of bromine to copper are calculated below.

$$\underline{\text{cuprous bromide}}: \quad \frac{mass\ Br}{mass\ Cu} = \frac{55.7\text{ g Br}}{44.3\text{ g Cu}} = 1.26$$

$$\underline{\text{cupric bromide}}: \quad \frac{mass\ Br}{mass\ Cu} = \frac{71.5\text{ g Br}}{28.5\text{ g Cu}} = 2.51$$

The ratios of the masses of bromine to copper are 1.26:1 in cuprous bromide and 2.51:1 in cupric bromide. Although these ratios do not tell you the **chemical formulas** of either compound, it does show that for the same amount of copper present, the total mass of bromine in cupric bromide must be exactly twice that present in cuprous bromide.

So, if the formula for cuprous bromide were Cu_xBr_y (where x and y are whole numbers), then the formula for cupric bromide would have to be Cu_xBr_{2y} (the actual formulas for cuprous bromide and cupric bromide are CuBr and $CuBr_2$, respectively).

Metals, Nonmetals, and Metalloids (1.10)

This chapter also introduced the single most important tool used by chemists—the periodic table. Atoms are arranged in the periodic table based on similarities in their physical and chemical properties. **Metals**, which are known to be good electrical conductors and have the ability to be deformed or reshaped without breaking (*ductile* and *malleable*), appear in the bottom left portion of the periodic table. Most atoms in the periodic table are metals.

Nonmetals have properties that are very different from the metals: They are generally poor electrical conductors, and while most metals are solids at room temperature, many of the nonmetals are gases or liquids at room temperature. Nonmetals appear in the top right portion of the periodic table.

Metalloids (also called *semimetals*) are elements that fall in between the metals and nonmetals on the periodic table, and their chemical and physical properties also fall somewhere between the properties of metals and nonmetals—many are lustrous like metals, and they conduct electricity but not as good as metals (this is why they are also referred to as *semiconductors*).

Molecular Elements and Allotropes (1.10)

Unlike metals and metalloids, most nonmetal elements are made of small molecules. Exceptions to this rule are the noble gases (column 8A in the periodic table), which exist as single atoms in the gas phase, and some solids like carbon (C) and selenium (Se). Most of the other nonmetals exist as simple **diatomic**

molecules—two atoms of the same element combined together. These diatomic molecules include hydrogen (H_2), nitrogen (N_2), oxygen (O_2), and the elements in column 7A (F_2, Cl_2, Br_2, and I_2).

Some elements can exist in two or more stable forms; these different forms are referred to as **allotropes** of each other. Classic examples of this are oxygen (O_2) and ozone (O_3), and graphite (solid C that is black and soft), diamond (solid C that is colorless and hard), and buckminsterfullerene (C_{60} molecules that look like soccer balls).

Macroscale, Nanoscale, and Symbolic Representations (1.11)

When chemists think about a chemical reaction, they commonly use three distinct but clearly related representations to describe the same chemical process—the macroscale, nanoscale, and symbolic representations. The *macroscale representation* is based on physical observations made using the five senses (color changes, odors, heat changes, changes in states of matter, etc.). The macroscale representation is most commonly used by students when performing experiments in the chemistry laboratory, or when an instructor performs chemical demonstrations in class.

The *symbolic representation* uses symbols to stand in the place of more abstract objects. Examples of symbolic representations are chemical symbols (H for hydrogen, O for oxygen), chemical formulas (H_2O for water), balanced chemical equations, units of measurement (like g for gram or L for liter), mathematical formulas, graphs, and tabulated data. The symbolic representation is used extensively in the chemistry classroom and laboratory in the form of balanced equations and mathematical formulas.

The *nanoscale representation* describes the chemical process in terms of the interactions of atoms and molecules. This representation often poses a problem for students because atoms and molecules are too small to be directly seen or touched. Some chemistry classes tend not to focus on the nanoscale representation—not because the instructor thinks that it's unimportant, but because it can be difficult to teach students about the interactions of particles that they cannot directly see or touch.

Chapter Review — Key Terms

The key terms that were introduced in this chapter are listed below, along with the section in which they were introduced. You should understand these terms and be able to apply them in appropriate situations.

allotrope (1.10)
atom (1.9)
atomic theory (1.9)
boiling point (1.4)
Celsius temperature scale (1.4)
chemical change (1.5)
chemical compound (1.7)
chemical element (1.7)
chemical formula (1.10)
chemical property (1.5)
chemical reaction (1.5)
chemistry (1.1)
conservation of mass, law of (1.9)
constant composition, law of (1.9)
conversion factor (1.4)
density (1.4)
diatomic molecule (1.10)
dimensional analysis (1.4)
energy (1.5)
freezing point (1.4)
gas (1.8)
heterogeneous mixture (1.6)
homogeneous mixture (1.6)
hypothesis (1.3)
kinetic-molecular theory (1.8)
law (1.3)
liquid (1.8)
macroscale (1.8)
matter (1.1)
melting point (1.4)
metal (1.10)
metalloid (1.10)
microscale (1.8)
model (1.3)
molecule (1.10)
multiple proportions, law of (1.9)
nanoscale (1.8)
nonmetal (1.10)
physical changes (1.4)
physical property (1.4)
product (1.5)
proportionality factor (1.4)
qualitative (1.3)
quantitative (1.3)
reactant (1.5)
solid (1.8)
solution (1.6)
substance (1.4)
temperature (1.4)
theory (1.3)

Practice Test

After you have finished studying the chapter and the homework problems, the following questions can serve as a test to determine how well you have learned the chapter objectives.

1. A scientist collects data to test an established theory, but the collected data contradicts the theory.
   (a) What is the first step the scientist should take? Why?
   (b) If the data and the theory are found to be incompatible, should the data discarded or should the theory be changed?

2. Classify each statement below as qualitative or quantitative.
   (a) A sample of ice has two hydrogen atoms for every oxygen atom.
   (b) A sample of ice is cold to the touch.
   (c) A sample of ice weighs 35 grams.

3. Classify the changes listed below as chemical or physical changes. Explain your answer.
   (a) Plants take in carbon dioxide and release oxygen.
   (b) Liquid gasoline evaporates after being spilled on the pavement.
   (c) When placed on an icy road, salt melts the ice.

4. Which temperature is higher? Explain your answer.
   (a) 80°C or 240°F
   (b) 37°C or 73°F
   (c) 20°C or 20°F
   (d) –40°C or –40°F

5. What weighs more—a pound of lead or a pound of feathers? Explain your answer and relate it to the concept of density.

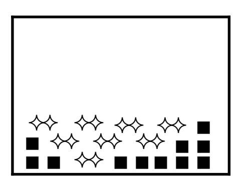
6. Which weighs more 313 mL of ethanol or 286 mL of benzene?

7. Classify each of these samples as an element, a compound, a heterogeneous mixture, or a homogeneous mixture. Explain your answer.
   (a) Cheerios cereal
   (b) Froot Loops cereal
   (c) milk
   (d) sugar

8. Benzene was first isolated from coal tar (a by-product of the distillation of coal) in the late 1800s. While studying the properties of benzene, von Baeyer noticed that a sample of benzene turned blue when treated with isatin and sulfuric acid (called the *indophenine test*). Later, Meyer used this test on a sample of benzene isolated in a different way (from calcium benzoate instead of coal tar), but the sample did not turn blue.
   (a) How does this story demonstrate how science is done?
   (b) Can you explain why the second sample of benzene did not turn blue?

9. Use the kinetic-molecular theory to explain these nanoscale properties of gases, liquids, and solids.
   (a) Colorless gases are invisible, but we can see colorless liquids.
   (b) Liquids and solids cannot be easily compressed into smaller volumes, but gases can be.
   (c) When liquid food coloring is added to liquid water, they slowly mix but when solid salt is poured onto a sample of solid sand, the samples do not mix.

10. Consider the nanoscale picture on the right.
   (a) Does this picture depict a gas, liquid, or solid? Explain your answer.
   (b) Does this picture depict a pure substance, a heterogeneous mixture, or a homogeneous mixture? Explain your answer.
   (c) Does this picture depict atoms, molecules, or both? Explain your answer.
   (d) Does this picture depict elements, compounds, or both? Explain your answer.



11. Use the atomic theory to explain why elements cannot be decomposed into two or more other substances.

12. A chemist has performed four experiments to analyze different samples of chemicals known to contain only nitrogen and oxygen. Can any of these compounds be the same chemicals? Explain your answer.
    (a) Compound A contained 18.4 g of nitrogen and 42.0 g of oxygen.
    (b) Compound B contained 23.8 g of nitrogen and 40.8 g of oxygen.
    (c) Compound C contained 42.6 g of nitrogen and 97.3 g of oxygen.
    (d) Compound D contained 52.5 g of nitrogen and 60.0 g of oxygen.

13. Do the following statements describe metals, nonmetals, metalloids, or a combination of the three?
    (a) The sample is a gas at room temperature.
    (b) The sample conducts electricity very well.
    (c) The sample has a shiny, lustrous appearance.

14. Classify the following atoms as metals, nonmetal, or metalloids based on their positions in the periodic table.
    (a) silicon, Si
    (b) silver, Ag
    (c) sodium, Na
    (d) sulfur, S

15. Classify the following statements as macroscale, nanoscale, or symbolic. Explain your answers.
    (a) A sample of water contains two hydrogen atoms for every one oxygen atom.
    (b) A sample of water is colorless and has no odor or taste.
    (c) The molecular formula for water is H_2O.