2.1 The Atomic Theory of Matter

- Greek philosophers: Can matter be subdivided into fundamental particles?
- Democritus (460 – 370 BC): All matter can be divided into indivisible *atomos.*
- Dalton: Proposed atomic theory with the following postulates:
    - Elements are composed of atoms.
    - All atoms of an element are identical.
    - In chemical reactions atoms are not changed into different types of atoms. Atoms are neither created not destroyed.
    - Compounds are formed when atoms of elements combine.
- **Atoms** are the building blocks of matter.
- *Law of constant composition*: the relative kinds and numbers of atoms are constant for a given compound.
- *Law of conservation of mass*: during a chemical reaction, the total mass before reaction is equal to the total mass after reaction.
    - Conservation means something can neither be created nor destroyed. Here it applies to matter (mass). Later we will apply it to energy (Chapter 5).

- *Law of multiple proportions*: if two elements A and B combine to form more than one compound, then the mass of B that combines with the mass of A is a ratio of small whole numbers.
- Dalton's theory *predicted* the law of multiple proportions.

2.2 The Discovery of Atomic Structure

- By 1850 scientists knew that atoms were composed of charged particles.
- **Subatomic particles**: those particles that make up the atom,
- Recall the law of electrostatic attraction: like charges repel and opposite charges attract.

Cathode Rays and Electrons

- Cathode rays were first discovered in the mid- 1800s from studies of electrical discharge through partially evacuated tubes (cathode ray tubes or CRTs).
  - Computer terminals were once popularly referred to as CRTs (cathode ray tubes).
  - They are now commonly called VDTs (video display terminals)
- Cathode rays = radiation produced when high voltage is applied across the tube.
- The voltage causes negative particles to move from the negative electrode (cathode) to the positive electrode (anode).
- The path of the electrons can be altered by the presence of a magnetic field.
- Consider cathode rays leaving the positive electrode through a small hole.
  - If they interact with a magnetic field perpendicular to an applied electric field, then the cathode rays can be deflected by different amounts.
  - The amount of deflection also depends on the applied magnetic and electric fields.
  - The amount of deflection also depends on the charge-to-mass ratio of the electron.
  - In 1897 Thomson determined the charge-to-mass ratio of an electron.
    - Charge-to-mass ratio: 1.76×10^{8} C / g
    - C is a symbol for coulomb
      - SI unit of electric charge
- Millikan Oil-Drop Experiment
  - Goal: find the charge on the electron to determine its mass.
  - Oil drops were sprayed above a positively charged plate containing a small hole.
  - As the oil drops fall through the hole they acquire a negative charge.
  - Gravity forces the drops downward. The applied electric field forces the drops upward.
  - When a drop is perfectly balanced, then the weight of the drop is equal to the electrostatic force of attraction between the drop and the positive plate.
  - Millikan carried out the above experiment and determined the charges on the oil drops to be multiples of 1.60×10^{-19} C.
  - He concluded that the charge on the electron must be 1.60×10^{-19} C.
- Knowing the charge-to-mass ratio of the electron, we can calculate the mass of the electron:

$$Mass = \frac{1.60x10^{-19}C}{1.76x10^{8}\, C/g} = 9.10x10^{-28}g$$

Radioactivity

- **Radioactivity** is the spontaneous emission of radiation.
- Consider the following experiment:
    - A radioactive substance is placed in a lead shield containing a small hole so that a beam of radiation is emitted from the shield.
    - The radiation is passed between two electrically charged plates and detected.
    - Three spots are observed on the detector:
        - A spot deflected in the direction of the positive plate.
        - A spot that is not affected by the electric field.
        - A spot deflected in the direction of the negative plate.
    - A large deflection toward the positive plate corresponds to radiation that is negatively charged and of low mass. This is called β-radiation (consists of electrons).
    - No deflection corresponds to neutral radiation. This is called γ-radiation (similar to X-rays).
    - A small deflection toward the negatively charged plate corresponds to high mass, positively charged radiation. This is called α-radiation (positively charged core of a helium atom).
    - X-rays and γ radiation are true electromagnetic radiation, whereas α- and β-radiation are actually streams of particles – helium nuclei and electrons, respectively.

The Nuclear Atom

- The 'plum pudding' model: an early picture of the atom.
- The Thomson model pictures the atom as a sphere with small electrons embedded in a positively charged mass.
- Rutherford carried out the following experiment:
    - A source of α-particles was placed at the mouth of a circular detector.
        - The α-particles were shot through a piece of gold foil.
        - Both the gold nucleus and the a-particle are positively charged, so they repel each other.
        - Most of the α-particles went straight through the foil without deflection.
        - If the Thomson model of the atom was correct, then Rutherford's results was impossible.
- Rutherford modified Thomson's model as follows:
    - Assume that the atom is spherical, but the positive charge must be located at the center.
    - In order for the majority of α-particles shot through a piece of foil to be undeflected, the majority of the atom must consist of empty space where the electrons can be found.
    - To account for the small number of large deflections of the α-particles, the center or **nucleus** of the atom must consist of a dense positive charge.

2.3 The Modern View of Atomic Structure

- The atom consists of positive, negative, and neutral entities (**protons, electrons**, and **neutrons**).
- Protons and neutrons are located in the nucleus of the atom, which is small. Most of the mass of the atom is due to the nucleus.
- Electrons are located outside of the nucleus. Most of the volume of the atom is the space where electrons are found.
- The quantity 1.602×10^{-19} C is called **electronic charge**. The charge on an electron is -1.602×10^{-19} C; the charge on a proton is $+1.602 \times 10^{-19}$ C.
- Masses are so small that we define the **atomic mass unit**, amu.
  - 1 amu = 1.66054×10^{-24} g
  - The mass of a proton is 1.0073 amu, a neutron is 1.0087 amu, and an electron is 5.486×10^{-4} amu.
  - The **angstrom** is a convenient non-SI unit of length used to denote atomic dimensions.
    - Since most atoms have radii around 1×10^{-10} m, we define 1 A = 1×10^{-10} m.

Isotopes, Atomic Numbers, and Mass Numbers

- **Atomic number** (Z) = number of protons in the nucleus
- **Mass number** (A) = total number of nucleons in the nucleus (i.e., protons and neutrons).
- By convention, for element **X**, we write ${}^{A}_{Z}X$
- **Isotopes** have the same Z but different A.
  - There can be a variable number of neutrons for the same number of protons. Isotopes have the same number of protons but different numbers of neutrons.
  - An atom of a specific isotope is called a **nuclide**.
  - Examples: Nuclides of hydrogen include:
    - H-1 (protium); H-2 (deuterium); H-3 (tritium): tritium is radioactive

2.4 The Periodic Table

- **The Periodic Table** is used to organize the elements in a meaningful way.
- As a consequence of this organization, there are periodic properties associated with the periodic table.
- Columns in the periodic table are called **groups**.
  - Several numbering conventions are used (i.e. groups may be numbered from 1 to 18, or from 1A to 8A, and from 1B to 8B).
- Rows in the periodic table are called **periods.**
- Some of the groups in the periodic table are given special names.
  - These names indicate the similarities among group members.
  - Examples:
    - Group 1 or (1A): alkali metals
    - Group 17 or (7A): halogens
- **Metallic elements** are located on the left hand-side of the periodic table (most of the elements are metals).
- **Nonmetallic elements** are located in the top right-hand side of the periodic table.
- Elements with properties similar to both metals and nonmetals are called **metalloids** and are located at the interface between the metals and nonmetals.
  - These include the elements B, Si, Ge, As, Sb, and Te.
- Metals tend to be malleable, ductile, and lustrous and are good thermal and electrical conductors. Nonmetals generally lack these properties; they tend to be brittle solids, dull in appearance, and do not conduct heat of electricity well.

2.5 Molecules and Molecular Compounds

- A **molecule** consists of two or more atoms bound together.
- Each molecule has a **chemical formula**.
- The chemical formula indicates
  1. Which atoms are found in the molecule, and
  2. In what proportion they are found
- Compounds composed of molecules are **molecular compounds**
  - These contain at least two types of atoms.
- Different forms of an element have different chemical formulas are known as *allotropes*. Allotropes differ in their chemical and physical properties. (Chapter 7 will give more information on allotropes of common elements)

Molecular and Empirical Formulas

- **Molecular formulas**
  - Give the actual numbers and types of atoms in a molecule.
  - Examples: H_2O, CO_2, CO, CH_4, H_2O_2, O_2, O_3, and C_2H_4
- **Empirical** formulas
  - Give the relative numbers and types of atoms in a molecule (they give the lowest whole-number ratio of atoms in a molecule).
  - Examples: H_2O, CO_2, CO, CH_4, HO, CH_2

Picturing Molecules

- Molecules occupy three-dimensional space.
- However, we often represent them in two dimensions.
- The **structural formula** gives the connectivity between individual atoms in the molecule.
- The structural formula may or may not show the three-dimensional shape of the molecule.
- If the structural formula does not show the shape of the molecule, then either a perspective drawing, ball-and-stick model, or space-filling model is used.
  - Perspective drawings use dashed lines and wedges to represent bonds receding and emerging from the plane of the paper.
  - Ball-and-stick models show atoms as contracted spheres and the bonds as sticks. The angles in the ball-and-stick model are accurate.
  - Space-filling models give an accurate representation of the relative sizes of the atoms and the 3D shape of the molecule.

2.6 Ions and Ionic Compounds

- If electrons are added or removed from a neutral atom, an **ion** is formed.
- When an atom or molecule loses electrons, it becomes positively charged.
  - Positively charged ions are called **cations**.
- When an atom or molecule gains electrons, it becomes negatively charged.
  - Negatively charged ions are called **anions**.
- In general, metal atoms tend to lose electrons, and nonmetal atoms gain electrons.
- When molecules lose electrons, **polyatomic ions** are formed (e.g. SO_4^{2-}, NO_3^{1-})

Predicting Ionic Charges

- An atom or molecule can lose more than one electron.
- Many atoms gain or lose enough electrons to have the same number of electrons as the nearest noble gas (group 18 or 8A).
- The number of electrons an atom loses is related to its position on the periodic table.

Ionic Compounds

- A great deal of chemistry involves the transfer of electrons between species.
- Example:
  - To form NaCl. the neutral sodium atom, Na, must lose an electron to become a cation: Na1+.
  - The electron cannot be lost entirely, so it is transferred to a chlorine atom, Cl, which then becomes an anion: Cl^{1-}.
  - The Na^{1+} and Cl^{1-} ions are attracted to form an ionic NaCl lattice, which crystallizes.
- NaCl is an example of an **ionic compound** – consisting of positively charged cations and negatively charged anions.
  - Important: note that there are no easily identified NaCl molecules in the ionic lattice. Therefore we cannot use molecular formulas to describe ionic substances.
- In general, ionic compounds are usually combinations of metals and nonmetals, whereas molecular compounds are generally composed of nonmetals only.
- Writing empirical formulas for ionic compounds:
  - You need to know the ions of which it is composed.
  - The formula must reflect the electrical neutrality of the compound.
  - You must combine cations and anions in a ratio so that the total positive charge is equal to the total negative charge.
  - Example: consider the formation of Mg_3N_2:
    - Mg loses two electrons to become Mg^{2+}
    - Nitrogen gains three electrons to become N^{3-}
    - For a neutral species, the number of electrons lost and gained must be equal.
    - However, Mg can lose electrons only in twos, and N can accept electrons only in threes.
    - Therefore, Mg needs to form 3 Mg^{2+} ions (total 3 x 2 positive charges) and 2 N atoms need to form 2 N^{3-} ions (total 2 x 3 negative charges)
    - Therefore, the formula is Mg_3N_2
    -

Chemistry and Life: Elements Required by Living Organisms

- Of the 112 elements known, only about 26 are required for life.
- Water accounts for more than 70 percent of the mass of the cell.
- Carbon is the most common solid constituent of cells.
- The most important elements for life are H, C, N, O, P, and S (red).
- The next most important ions are Na^{1+}, Mg^{2+}, K^{1+}, Ca^{2+}, and Cl^{1-} (blue)
- The other 15 elements are needed only in trace amounts (green).

2.7 Naming Inorganic Compounds

Names and Formulas of Ionic Compounds

- Chemical nomenclature – naming of substances.
- Divided into organic compounds (those containing C, usually in combination with H, O, N, or S) and inorganic compounds (all other compounds)

1. **Positive Ions (Cations)**
   - Cations formed from a metal have the same name as the metal
     - Example: Na^{1+} = sodium ion
   - If the metal can form more than one cation, then the charge is indicated in parentheses in the name.
     - Examples: Cu^{1+} = copper (I); Cu^{2+} = copper (II) [Stock system]
   - Cations formed from nonmetals end in **–ium**.
     - Example: NH_4^{1+} ammon**ium** ion

2. **Negative Ions (anions)**
   - Monatomic anions (with only one atom) use the ending **–ide**.
     Example: Cl^{1-} is chlor**ide** ion

   - Some simple polyatomic anions also have the ending **-ide**; hydroxide, cyanide, and peroxide ions.
   - Polyatomic ions (with many atoms) containing oxygen are called **oxyanions**.
     - These end in **–ate** or **–ite**. (The one with more oxygen uses **–ate**.)
     - Examples: NO_3^{1-} is nitr**ate**, NO_2^{1-} is nitr**ite**.

   - Polyatomic anions containing oxygen with additional hydrogens are named by adding hydrogen or bi (one H), dihydrogen (two H), etc. to the name, as follows:
     - CO_3^{2-} is the carbon**ate** anion
     - HCO_3 is the hydrogen carbonate (or **bi**carbonate) anion
     - H_2PO_4 is the **dihydrogen** phosphate anion

3. **Ionic Compounds**
   - These are named cation and anion
     - Example: $BaBr_2$ = barium brom**ide**

Names and Formulas of Acids

- The names of acids are related to the names of **anions**:
  - **-ide** becomes **hydro**- ...**-ic** acid; Examples: HCl **hydro**chlor**ic** acid
  - -**ate** becomes **–ic** acid; $HClO_4$ perchlor**ic** acid
  - **-ite** becomes –**ous acid.** HClO hypochlor**ous** acid

Names and Formulas for binary Molecular Compounds

- Binary molecular compounds contain two elements.
- The most metallic element (i.e., the one farthest to the left on the periodic table) is usually written first. Exception: NH_3 (ammonia)
- If both elements are in the same group, the lower one is written first.
- Greek prefixes are used to indicate the number of atoms (e.g. mono, di, tri).
  - The prefix mono is never used with the first element (i.e., carbon monoxide, CO).
  - Examples:
    - Cl_2O **di**chlorine *mon*oxide
    - N_2O_4 **di**nitrogen *tetr*oxide
    - NF_3 nitrogen *tri*fluoride
    - P_4S_{10} **tetra**phosphorus *deca*sulfide