Chapter 2

Formation of Chemical Compounds
Law of Conservation of Mass

Antoine Lavoisier
1743-1794

In a chemical reaction, matter is neither created nor destroyed. The total mass of the materials you have before the reaction must equal the total mass of the materials you have at the end.

\[ \text{total mass of reactants} = \text{total mass of products} \]
Law of Conservation of Mass

\[ 7.7 \text{ g Na} + 11.9 \text{ g Cl}_2 \rightarrow 19.6 \text{ g NaCl} \]
Law of Definite Proportions

Joseph Proust
1754-1826

All samples of a given compound, regardless of their source or how they were prepared, have the same proportions of their constituent elements.
A 100.0 g sample of sodium chloride contains 39.3 g of sodium and 60.7 g of chlorine.

\[
\frac{\text{mass of Cl}}{\text{mass of Na}} = \frac{60.7 \text{ g}}{39.3 \text{ g}} = 1.54
\]

A 200.0 g sample of sodium chloride contains 78.6 g of sodium and 121.4 g of chlorine.

\[
\frac{\text{mass of Cl}}{\text{mass of Na}} = \frac{121.4 \text{ g}}{78.6 \text{ g}} = 1.54
\]

A 58.44 g sample of sodium chloride contains 22.99 g of sodium and 35.44 g of chlorine.

\[
\frac{\text{mass of Cl}}{\text{mass of Na}} = \frac{35.44 \text{ g}}{22.99 \text{ g}} = 1.541
\]
Law of Multiple Proportions

John Dalton
1766-1844

When two elements (call them A and B) form two different compounds, the masses of B that combine with 1 g of A can be expressed as a ratio of small, whole numbers.
Carbon monoxide contains 1.33 g of oxygen for every 1.00 g of carbon.

\[ \frac{1.33}{1.00} = \frac{4}{3} \]

Carbon dioxide contains 2.67 g of oxygen for every 1.00 g of carbon.

\[ \frac{2.67}{1.00} = \frac{8}{3} \]
Elements of Dalton’s Atomic Theory

All matter is made up of tiny particles called **atoms**.

The **atoms of a given element are identical**; the atoms of **different elements are different** in some fundamental way.

**Chemical compounds are formed when atoms** combine with each other. **A given compound always has the same relative numbers and types of atoms.**

**Chemical reactions involve reorganization of the atoms** -- changes in the way they are bound together. **The atoms themselves are not changed in a chemical reaction.**
Matter is conserved in a chemical reaction because the reaction consists simply of atoms either hooking together or unhooking.
Ions - Charged Atoms
**Ions**

Ions are atoms which have acquired a charge through loss or gain of electrons.

When atoms gain electrons, they become negatively charged ions, called **anions**.

When atoms lose electrons, they become positively charged ions, called **cations**.
Nonmetals form anions.

Anions named by changing the ending of the name to \textit{-ide}.

\begin{align*}
F + 1e^- & \rightarrow F^- \\
\text{fluorine atom} & \rightarrow \text{fluoride ion} \\
F^- & \\
O + 2e^- & \rightarrow O^{2-} \\
\text{oxygen atom} & \rightarrow \text{oxide ion} \\
O^{2-} &
\end{align*}
Metals form cations.

Cations are named the same as the metal.

\[ \text{Na} \rightarrow \text{Na}^+ + 1\text{e}^- \]

sodium \quad \text{atom} \quad \text{sodium} \quad \text{ion}

\[ \text{Ca} \rightarrow \text{Ca}^{2+} + 2\text{e}^- \]

calcium \quad \text{atom} \quad \text{calcium} \quad \text{ion}
Complete the table

<table>
<thead>
<tr>
<th>Atomic Number</th>
<th>Protons</th>
<th>Electrons</th>
<th>Ion Charge</th>
<th>Ion Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>16</td>
<td>18</td>
<td>2-</td>
<td>S^{2-}</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>10</td>
<td>2+</td>
<td>Mg^{2+}</td>
</tr>
<tr>
<td>13</td>
<td>13</td>
<td>10</td>
<td>3+</td>
<td>Al^{3+}</td>
</tr>
<tr>
<td>35</td>
<td>35</td>
<td>36</td>
<td>1-</td>
<td>Br^{-}</td>
</tr>
</tbody>
</table>
The charge on an ion can often be determined from an element’s position on the Periodic Table.

### Ion Charge and the Periodic Table

- **Main-group elements**
  - 1A (1+)
  - 2A (2+)
  - 3A (3+)
  - 4A
  - 5A
  - 6A
  - 7A
  - 8A

- **Transition elements**
  - 1B
  - 2B

- **Main-group elements**
  - 13 (1+)
  - 14 (2+)
  - 15 (3+)
  - 16 (4+)
  - 17 (5+)

**Periods**

1. 1H
2. 2Li
3. 3Na
4. 4K
5. 5Rb
6. 6Cs
7. 7Fr

**Group Numbers**

1. 1
2. 2
3. 3
4. 4
5. 5
6. 6
7. 7
8. 8

**Charges**

- 1+, 2+
- 3+, ..., 3-, 2-, 1-
Main-group ions and the noble gas configurations.

Nonmetals

Metals
Chapter 2

Molecules and Compounds
Elements and Compounds

Elements combine together to make an almost limitless number of compounds.

The properties of the compound are totally different from the constituent elements.

Compounds ≠ Mixtures
Hydrogen gas  
*b.p.* -253º

Oxygen gas  
*b.p.* -183º

Hydrogen and Oxygen gases can mix in any ratio.

Water  
*b.p.* 100º

Hydrogen and Oxygen atoms present in fixed ratios

Hydrogen peroxide  
*b.p.* 150º
Chemical Bonds

Compounds are made of atoms held together by bonds. *Chemical bonds* are forces of attraction between atoms. The bonding attraction comes from attractions between protons and electrons.
Bond Types

Two general types of bonding between atoms found in compounds, **ionic** and **covalent**.

*Ionic bonds* result when electrons have been transferred between atoms, resulting in oppositely charged ions that attract each other.

Generally found when metal atoms bond to nonmetal atoms

*Covalent bonds* result when two atoms share some of their electrons.

Generally found when nonmetal atoms bond together
Formation of an Ionic Compound

Neutral Atoms Undergo Electron Transfer

Charged Ions

An Orderly Aggregate Called an Ionic Crystal
Formation of an Covalent Compound Involves Competing Forces
The total energy of two atoms is a combination of the attractive and repulsive forces.

For two hydrogen atoms, the internuclear distance is 74 pm.
Chemical Formulas Describe Compounds

A **compound** is a distinct substance that is composed of atoms of two or more elements.

We **describe a compound** by describing the number and type of each atom in the simplest unit of the compound.

**Each element is represented** by its letter symbol.

The **number of atoms of each element** is written to the right of the element as a subscript.

**Polyatomic ions** are placed in parentheses.

(if more than one is present)
An **empirical formula** gives the relative number of atoms of each element in a compound.

*It does not describe how many atoms, the order of attachment, or the shape.*

**For example:**

1) The empirical formula for the ionic compound fluorspar is **CaCl$_2$**. This means that there is 1 Ca$^{2+}$ ion for every 2 Cl$^-$ ions in the compound.

2) The empirical formula for the molecular compound oxalic acid is **CHO$_2$**. This means that there is 1 C atom and 1 H atom for every 2 O atoms in the molecule.
Types of Formulas: Molecular Formula

A *molecular formula* gives the *actual number of atoms of each element* in a molecule of a compound.

*It does not describe the order of attachment, or the shape.*

The empirical formula for the molecular compound oxalic acid is \( \text{CHO}_2 \).

*The actual molecular formula is* \( \text{C}_2\text{H}_2\text{O}_4 \).
Types of Formulas: Structural Formula

A structural formula uses lines to represent covalent bonds and shows how atoms in a molecule are connected or bonded to each other.

Structural Formulas of Oxalic Acid
Molecular Models for CH\textsubscript{4}

Structural formula

Ball-and-stick model

Space-filling model
3. Practice — Find the empirical formula for each of the following

The ionic compound that has *two aluminum ions for every three oxide ions* 

<table>
<thead>
<tr>
<th>Compound</th>
<th>Molecular Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃</td>
<td></td>
</tr>
<tr>
<td>Ribose, C₅H₁₀O₅</td>
<td>CH₂O</td>
</tr>
<tr>
<td>Pyrimidine</td>
<td>C₄H₄N₂</td>
</tr>
<tr>
<td>Ethylene glycol</td>
<td>C₂H₆O₂</td>
</tr>
</tbody>
</table>
**Elements**

**MOST ELEMENTS**

*Single atoms* are the constituent particles. The atoms may be physically attracted to each other, but are not chemically bonded together.

**A FEW ELEMENTS**

*Molecules* are the constituent particles. The molecules are made of two or more atoms chemically bonded together by covalent bonds.
Atomic Elements
Molecular Elements

N₂  O₂  F₂  Cl₂  Br₂  I₂
Molecular Elements

$S_8$

$P_4$
Compounds

SOME COMPOUNDS
Composed of ions arranged in a 3-dimensional pattern
These are called ionic compounds.

OTHER COMPOUNDS
Composed of individual molecule units
Each molecule contains atoms of different elements
chemically attached by covalent bonds
These are called molecular compounds.
**Ionic vs. Molecular Compounds**

- **Table salt** – contains an array of Na$^+$ ions and Cl$^-$ ions
- **Propane** – contains individual C$_3$H$_8$ molecules
**Ionic vs. Molecular Compounds**

Table salt – contains an array of Na\(^+\) ions and Cl\(^-\) ions

Propane – contains individual C\(_3\)H\(_8\) molecules
Classify Each of the Following as Either an **Atomic Element**, **Molecular Element**, **Molecular Compound**, or **Ionic Compound**

Aluminum, Al — **atomic element**
Aluminum chloride, AlCl₃ — **ionic compound**
Chlorine, Cl₂ — **molecular element**
Acetone, C₃H₆O — **molecular compound**
Carbon monoxide, CO — **molecular compound**
Cobalt, Co — **atomic element**
A compound must have no total charge, therefore we must balance the numbers of cations and anions in a compound to get $\phi$ charge.

**Practice — What are the formulas for compounds made from the following ions?**

Potassium ion with a nitride ion  
$K^+ \text{ with } N^{3-} \quad K_3N$

Calcium ion with a bromide ion  
$Ca^{2+} \text{ with } Br^- \quad CaBr_2$

Aluminum ion with a sulfide ion  
$Al^{3+} \text{ with } S^{2-} \quad Al_2S_3$
Chapter 2

Formation of Ionic Compounds
Table of Representative Elements
### Periodic Table - Main Groups Only

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IA</strong></td>
<td><strong>IIA</strong></td>
<td><strong>IIIA</strong></td>
<td><strong>IVA</strong></td>
<td><strong>VA</strong></td>
</tr>
<tr>
<td><strong>K</strong></td>
<td><strong>Ca</strong></td>
<td><strong>(14)</strong> Ga</td>
<td><strong>(15)</strong> Ge</td>
<td><strong>(16)</strong> As</td>
</tr>
<tr>
<td><strong>Rb</strong></td>
<td><strong>Sr</strong></td>
<td><strong>In</strong></td>
<td><strong>Sn</strong></td>
<td><strong>Sb</strong></td>
</tr>
<tr>
<td></td>
<td>(1) IA</td>
<td>(2) IIA</td>
<td>(3) IIIA</td>
<td>(4) IVA</td>
</tr>
<tr>
<td>----</td>
<td>--------</td>
<td>---------</td>
<td>----------</td>
<td>---------</td>
</tr>
<tr>
<td>1</td>
<td>H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Li</td>
<td>Be</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>3</td>
<td>Na</td>
<td>Mg</td>
<td>Al</td>
<td>Si</td>
</tr>
<tr>
<td>4</td>
<td>K</td>
<td>Ca</td>
<td>Ga</td>
<td>Ge</td>
</tr>
<tr>
<td>5</td>
<td>Rb</td>
<td>Sr</td>
<td>In</td>
<td>Sn</td>
</tr>
</tbody>
</table>

**Lose electrons**: 1, 2, 3, 4, 5

**Gain electrons**: 13, 16, 17
<table>
<thead>
<tr>
<th>Period</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H⁺, H⁻</td>
</tr>
<tr>
<td>2</td>
<td>Li⁺, Be²⁺, B⁺, Na⁺, Mg²⁺, Al³⁺, Si⁴⁺, P⁵⁺, S⁶⁺, Cl⁻, Ar⁻, K⁺, Ca²⁺, Ga³⁺, Ge⁴⁺, As⁵⁺, Se⁶⁺, Br⁻, Kr⁻, Rb⁺, Sr²⁺, I⁻, Cs⁺, Ba²⁺</td>
</tr>
<tr>
<td>3</td>
<td>H⁺, H⁻</td>
</tr>
<tr>
<td>4</td>
<td>Li⁺, Be²⁺, B⁺, Na⁺, Mg²⁺, Al³⁺, Si⁴⁺, P⁵⁺, S⁶⁺, Cl⁻, Ar⁻, K⁺, Ca²⁺, Ga³⁺, Ge⁴⁺, As⁵⁺, Se⁶⁺, Br⁻, Kr⁻, Rb⁺, Sr²⁺, I⁻, Cs⁺, Ba²⁺</td>
</tr>
<tr>
<td>5</td>
<td>H⁺, H⁻</td>
</tr>
<tr>
<td>6</td>
<td>Li⁺, Be²⁺, B⁺, Na⁺, Mg²⁺, Al³⁺, Si⁴⁺, P⁵⁺, S⁶⁺, Cl⁻, Ar⁻, K⁺, Ca²⁺, Ga³⁺, Ge⁴⁺, As⁵⁺, Se⁶⁺, Br⁻, Kr⁻, Rb⁺, Sr²⁺, I⁻, Cs⁺, Ba²⁺</td>
</tr>
</tbody>
</table>

**Groups:**
- VA: N³⁻, O²⁻, F⁻, Ne, Ar
- VIA: Na⁺, Mg²⁺, Al³⁺, Kr
- VIIA: Cl⁻, Ar, Rb⁺, Br⁻, Xe
- VIIIA: F⁻, Ne, Ar, Xe
- IIA: Be²⁺, Mg²⁺, Ca²⁺, Sr²⁺, Ba²⁺
Writing Formulas for Ionic Compounds

A compound must have no total charge. Therefore we must balance the numbers of cations and anions in a compound to get zero charge.

Remember !!!!

Metal atoms lose electrons to form cations.

Nonmetal atoms gain electrons to form anions.

The number of electrons lost or gained can be predicted from the elements position on the Periodic Table.
Why is a particular number of electrons lost or gained? 

Na → Na⁺ 

Cl → Cl⁻ 

nucleus  
core electrons  
valence electrons
Lewis Dot Structures of Atoms

The column number on the Periodic Table will tell you how many *valence electrons* a main group atom has. We represent the valence electrons of main-group elements as dots surrounding the symbol for the element.

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>IIA</td>
<td>IIA</td>
<td>IIIA</td>
<td>IVA</td>
<td>VA</td>
<td>VIA</td>
<td>VIIA</td>
<td>V</td>
</tr>
<tr>
<td>IA</td>
<td>IA</td>
<td>IA</td>
<td>IA</td>
<td>IA</td>
<td>IA</td>
<td>IA</td>
<td>IA</td>
</tr>
<tr>
<td>H</td>
<td>Be</td>
<td>B</td>
<td>C</td>
<td>N</td>
<td>O</td>
<td>F</td>
<td>Ne</td>
</tr>
<tr>
<td>Li</td>
<td>Mg</td>
<td>Al</td>
<td>Si</td>
<td>P</td>
<td>S</td>
<td>Cl</td>
<td>Ar</td>
</tr>
<tr>
<td>Na</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Practice – Write the Lewis structure for Arsenic

A lithium ion \( \rightarrow \) Li\(^{+1} \)

A fluoride ion

\[ \begin{array}{c}
\cdot \quad \cdot \\
\cdot \\
\cdot \\
\cdot \quad \cdot \\
\cdot \\
\end{array} \]
Formation of Calcium Chloride

Ca\(^{2+}\) + 2Cl\(^{-}\) → CaCl\(_2\)
**Stable Electron Arrangements and Ion Charge**

*Metals form cations by losing electrons* to get the same number of valence as the previous noble gas.

*Nonmetals form anions by gaining electrons* to get the same number of valence electrons as the next noble gas.

A *noble gas electron configuration* with eight valence electrons appears to be particularly stable.
Octet Rule

When atoms bond, they tend to gain, lose, or share electrons to result in eight valence electrons.

Exceptions

H, Li, Be, B attain an electron configuration like He

- **He** = two valence electrons (a duet)
- **Li** loses its one valence electron
- **H** may share or gain one electron
  - It commonly loses its one electron to become H$^+$
- **Be** loses two electrons to become Be$^{2+}$
  - It commonly shares its two electrons in covalent bonds, resulting in four valence electrons
- **B** loses three electrons to become B$^{3+}$
  - It commonly shares its three electrons in covalent bonds, resulting in six valence electrons

Expanded octets for elements in Period 3 or below
Dot structures can illustrate the process.

- **Sodium Chloride**
  - Formula: NaCl
  - Dot structure: Na⁺ + Cl⁻ → NaCl

- **Calcium Chloride**
  - Formula: CaCl₂
  - Dot structure: Ca²⁺ + 2Cl⁻ → CaCl₂

- **Sodium Oxide**
  - Formula: Na₂O
  - Dot structure: 2Na⁺ + O²⁻ → Na₂O
Write a formula for the ionic compound that forms from aluminum and oxygen.

\[ \text{Al}^{3+} \quad \text{O}^{2-} \]

\[ \text{Al}_2\text{O}_3 \]
Write a formula for the ionic compound that forms from magnesium and oxygen.

\[ \text{Mg}^{2+} \text{O}^{2-} \rightarrow \text{Mg}_2\text{O}_2 \rightarrow \text{MgO} \]