Chapter 4
Molecules, Compounds, and Chemical Reactions
Molecular Changes

- **Compounds and Molecules cause the behavior of matter.**
  - Human body
  - Cooking
  - Cars
  - Fire
  - Weather
Molecular Reasons

• Chemistry is a microscopic (nanoscopic) world
• Chemists examine the molecular reasons.

• Sugar and Salt
  – Composition
    • $\text{C}_{12}\text{H}_{22}\text{O}_{11}$
    • NaCl
  – Chemistry
    • Molecular/covalent
    • Ionic
  – Conductivity
    • Not conductive
    • Conductive
• Water
  – $\text{H}_2\text{O}$
  – 2 Hydrogens
  – 1 Oxygen
  – Mass ratio always 8:1 for Oxygen to hydrogen

  – Why not 2:1 hydrogen to oxygen?

• Hydrogen peroxide
  – $\text{H}_2\text{O}_2$
  – 2 Hydrogens
  – 2 Oxygens
  – Mass ratio always 16:1 for Oxygen to hydrogen

  – Why not 1:1 hydrogen to oxygen?
Concept Check 4.1

• Determine the number of each type of atom in glucose, which has the molecular formula $C_6H_{12}O_6$. 
Ionic and Molecular Compounds

- Elements with unstable electron configurations form compounds with other elements to gain stability.
- This can be accomplished by the transfer of electrons (ionic compounds) or by the sharing of electrons (molecular compounds).

$$2 \text{Na} \ (s) + \text{Cl}_2 \ (g) \rightarrow 2 \text{NaCl} \ (s)$$

\[
\begin{align*}
\text{Na} & \rightarrow \text{Na}^+ + e^- \quad (0 \text{ valence electrons}) \\
\text{Cl} + e^- & \rightarrow \text{Cl}^- \quad (8 \text{ valence electrons}) \\
\text{Na}^+ + \text{Cl}^- & \rightarrow \text{NaCl}
\end{align*}
\]
Ionic Compounds

- Contain a metal and one or more nonmetals
- Metals and nonmetals are a good chemical match.
  - Metals lose electrons.
  - Nonmetals gain electrons.
- The result is an ionic bond.
- Subscripts represent the ratio of elements in the crystal lattice of the compound.
Sodium Chloride

$$2 \text{Na} (s) + \text{Cl}_2 (g) \rightarrow 2 \text{NaCl} (s)$$

Na $\rightarrow$ Na$^+$ + e$^-$ (0 valence electrons)

Cl + e$^-$ $\rightarrow$ Cl$^-$ (8 valence electrons)

Na$^+$ + Cl$^-$ $\rightarrow$ NaCl
Sodium Chloride

- Soluble ionic compounds dissociate in water to form electrolyte solutions.

- Such solutions conduct electricity.
Hydrogen is a metalloid. Hydrogen can form $H^+$ (0 electrons) or $H^-$ (2 electrons). 

*Most of the time it forms $H^+*. Its electronegativity is between that of Boron and Carbon.
Molecular Compounds

- Contain only nonmetals
- Electrons in a bond are shared but not always equally.
- The resulting bond is covalent.
- Subscripts represent the actual number(s) of each kind of atom in the molecule.
- Molecules can be very small or VERY large and VERY complex, such as in protein molecules.

hemoglobin molecule
Molecular Compounds

Covalent bonds are made by sharing electrons. Sharing lets each atom fill its shell with fewer electrons than would be needed otherwise.

2 H → H₂
H has 1 valence electron
If 1 e- is shared, each H has 2 e-

2 Cl → Cl₂
Cl has 7 valence electrons
If 1 e- is shared, each Cl has 8 e-

2 O → O₂
O has 6 valence electrons
If 2 e- are shared, each O has 8 e-
This is called a double bond
Properties of Molecular Compounds

• The bulk properties of molecular compounds depend on the molecules that compose them.

• The composition of molecules is responsible for what we observe and experience.
  – Atoms, shape, structure, and bonds

• Small changes in a molecule can dramatically change the properties of the substance.
Which of these is ionic?

1. MgF₂
2. CH₄
3. Neither
Which of these is molecular?

1. NaBr
2. CO₂
3. Neither
Concept Check 4.2 Solution

Compounds formed between a metal and at least one nonmetal are **ionic**. Compounds formed between nonmetals are **molecular**.

a) NaBr: ionic
   Na (metal) and Br (nonmetal)

b) SO$_2$: molecular
   S and O (nonmetals)

c) MgF$_2$
   Mg (metal) and F (nonmetal)

d) CH$_4$
   C and H (nonmetals)
Naming Compounds

Ionic

- Name begins with the cation (metal)
- Followed by the base name of the anion (nonmetal) + *ide*
- NaBr is sodium bromide.
- MgBr$_2$ is magnesium bromide.
- Names for ionic compounds DO NOT contain prefixes to indicate the number of each type of atom.
### TABLE 4-1

**Some Common Anions**

<table>
<thead>
<tr>
<th>Nonmetal</th>
<th>Symbol for Ion</th>
<th>Base Name</th>
<th>Anion Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorine</td>
<td>F(^-)</td>
<td>Fluor</td>
<td>Fluoride</td>
</tr>
<tr>
<td>Chlorine</td>
<td>Cl(^-)</td>
<td>Chlor</td>
<td>Chloride</td>
</tr>
<tr>
<td>Bromine</td>
<td>Br(^-)</td>
<td>Brom</td>
<td>Bromide</td>
</tr>
<tr>
<td>Iodine</td>
<td>I(^-)</td>
<td>Iod</td>
<td>Iodide</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O(^{2-})</td>
<td>Ox</td>
<td>Oxide</td>
</tr>
<tr>
<td>Sulfur</td>
<td>S(^{2-})</td>
<td>Sulf</td>
<td>Sulfide</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N(^{3-})</td>
<td>Nitr</td>
<td>Nitride</td>
</tr>
</tbody>
</table>
1. Lithium oxygen
2. Lithium oxide
3. Lanthanum oxygen
4. Lanthanum oxide
5. None of the above
What is calcium bromide

1. CBr
2. CBr$_4$
3. CaBr
4. CaBr$_2$
5. C$_2$Br
a) Li$_2$O: lithium + ox(ide) = **lithium oxide**  
[Note that prefix “di” is not used in front of lithium]

b) CaBr$_2$: calcium + brom(ide) = **calcium bromide**  
[Note that prefix “di” is not used in front of bromide]

c) KI: potassium + iod(ide) = **potassium iodide**
Polyatomic ions are ions that are composed of two or more atoms covalently bonded that behave as a single ionic unit.

**TABLE 4-2**

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonate</td>
<td>CO$_3^{2-}$</td>
</tr>
<tr>
<td>Bicarbonate</td>
<td>HCO$_3^-$</td>
</tr>
<tr>
<td>Hydroxide</td>
<td>OH$^-$</td>
</tr>
<tr>
<td>Nitrate</td>
<td>NO$_3^-$</td>
</tr>
<tr>
<td>Phosphate</td>
<td>PO$_4^{3-}$</td>
</tr>
<tr>
<td>Sulfate</td>
<td>SO$_4^{2-}$</td>
</tr>
</tbody>
</table>
1. Magnesium oxygen hydrogen
2. Magnesium oxide hydride
3. Magnesium hydrate
4. Magnesium hydroxide
5. None of the above
What is Sodium Sulfate

1. NaS
2. Na$_2$S
3. Na$_2$SO$_3$
4. Na$_2$SO$_4$
5. None of the above
Find the name of polyatomic ions on Table 4.2. For naming purposes, the metal atom is treated as it is in other ionic compounds.

1) Mg(OH)$_2$: magnesium + hydroxide = magnesium hydroxide

2) Na$_2$SO$_4$: sodium + sulfate = sodium sulfate
Naming Compounds

• Molecular
  – The more metallic element is listed first and is followed by the less metallic element.
  – Prefixes are used to show the number of atoms of the element that are present.
  – The mono- prefix is not used on the first element.
  – Examples:
    • CO – carbon monoxide
    • CO₂ – carbon dioxide
    • P₂O₅ - diphosphorus pentoxide
1. Nitrogen oxygen
2. Nitrogen oxide
3. Nitrogen trioxide
4. Dinitrogen trioxide
5. Nitrate
What is Sulfur Trioxide

1. SO
2. SO₃
3. SO₃²⁻
4. (SO)₃
5. None of the above
Name the following molecular compounds

1) \( \text{N}_2\text{O}_3 \): dinitrogen pentoxide
   • Note: use the “di” prefix to indicate two nitrogens and the “pent” suffix to indicate five oxygens.

2) \( \text{SO}_3 \): sulfur trioxide
   • Note: no prefix for one sulfur and use the “tri” suffix to indicate three oxygens.
Formula Mass

- Formula mass of a compound is analogous to the atomic mass of an element.
- It is computed by summing the atomic masses of all the atoms in its formula.
- Calculating the formula mass of NaCl:
  
  Sodium  \[ 22.99 \text{ amu} \times 1 = 22.99 \text{ amu} \]
  
  Chloride  \[ 35.45 \text{ amu} \times 1 = 35.45 \text{ amu} \]
  
  \[ 58.44 \text{ amu} \]
Molar Mass

- The formula mass of a compound in amu is **numerically equivalent** to its molar mass in grams per mole (g/mol).
- The molar mass of an element is the conversion factor between grams and moles of the element.
- Likewise, the molar mass of a compound is the conversion factor between grams and moles of that compound.

  - Calcium carbonate, CaCO₃

    Calcium  \(40.08 \text{ g/mol} \times 1 \text{ mole} = 40.08 \text{ grams}\)
    Carbon  \(12.01 \text{ g/mol} \times 1 \text{ mole} = 12.01 \text{ grams}\)
    Oxygen  \(16.00 \text{ g/mol} \times 3 \text{ moles} = 48.00 \text{ grams}\)

  - 100.09 grams

- So the molar mass of CaCO₃ is 100.09 g/mol.
What is the molar mass of the highly toxic gas hydrogen sulfide, H$_2$S?

1. 34 amu
2. 34.08 amu
3. 34 g/mol
4. 34.08 g/mol
5. None of the above
How many moles of H$_2$S are in a 10.0g sample?

1. 0.3 mol
2. 0.293 mol
3. 340.8 mol
4. 341 mol
5. None of the above
How many moles of hydrogen are in 10.0g of H$_2$S?

1. 0.147 mol
2. 0.293 mol
3. 0.587 mol
4. None of the above
Molar mass of $\text{H}_2\text{S}$ = 
$(2 \times 1.0079 \text{ g/mol}) + 32.066 \text{ g/mol} = 34.08 \text{ g/mol}$
(to 2 digits past the decimal)

Moles in 10.0 g $\text{H}_2\text{S}$ =
$10.0 \text{ g} \text{H}_2\text{S} \times \frac{1 \text{ mol} \text{H}_2\text{S}}{32.08 \text{ g} \text{H}_2\text{S}} = 0.293 \text{ mol} \text{H}_2\text{S}$

32.08 g $\text{H}_2\text{S}$ (3 significant figures)

Moles H in 10.0 g $\text{H}_2\text{S}$ =
$0.293 \text{ mol} \text{H}_2\text{S} \times \frac{2 \text{ mol} \text{H}}{1 \text{ mol} \text{H}_2\text{S}} = 0.587 \text{ mol} \text{H}$

1 mol $\text{H}_2\text{S}$ (3 significant figures)
Chemical Formulas as Conversion Factors

• Scientists, manufacturers, farmers, and many others may want to know how much of a particular element is in a certain substance.
  – How much iron is present in a shipment of iron oxide?

• A chemical formula gives us *equivalences* between the elements in a particular compound and the compound itself.

  4 tires \( \equiv \) 1 car

  NO, 4 tires are in 1 car

  2 H atoms \( \equiv \) 1 \( \text{H}_2\text{O} \) molecule

  NO, 2 H are in 1 \( \text{H}_2\text{O} \)
Chemical Reactions

• Compounds exist as the result of chemical reactions.

• Existing compounds can be transformed by further chemical reactions.

• These chemical reactions are represented by chemical equations.
Chemical Reactions

\[ \text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \]

- **Reactants**, the substances present prior to the reaction, are written on the left side of the equation.

- **Products**, the substances formed by the reaction, are written on the right side of the equation.

- The **number and types of atoms in chemical equations must be the same on both sides (balanced)**.
Chemical Reactions

- $\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$
Balancing Guidelines

- If an element occurs in only one compound, balance that element first.

- If an element occurs as a free element, balance that element last.

- Change only coefficients, never subscripts.
  - Subscripts tell you how many atoms are in your molecule
  - Coefficients tell you how many molecules you have

- Eliminate fractions; use the lowest whole number ratio of coefficients.
Propane, C\textsubscript{3}H\textsubscript{8}, is often used in place of methane, CH\textsubscript{4}, as a fuel for home heating and cooking. Much like methane, it burns in (reacts with) oxygen to produce carbon dioxide (CO\textsubscript{2}) and water (H\textsubscript{2}O). Balance the reaction for the burning of propane in oxygen.
Concept Check 4.9 Solution

• The unbalanced equation:

\[ C_3H_8 + O_2 \rightarrow CO_2 + H_2O \]

• First, balance the elements present in only one compound on each side of the equation.

\[ C_3H_8 + O_2 \rightarrow 3CO_2 + H_2O \] 3 C’s on each side

\[ C_3H_8 + O_2 \rightarrow 3CO_2 + 4H_2O \] 8 H’s on each side

• Balance the element present as a free element last.

\[ C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O \] 10 O’s on each side

• Final balanced equation:

\[ C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O \]

Note: The absence of coefficient in front of a reactant or product implies a “1”.
As was the case with the subscripts within a chemical formula, the coefficients of a chemical equation can be used as conversion factors in chemical calculations, which are mathematical expressions that can answer the question “How much?”
Reaction Stoichiometry: Chemical Equations as Conversion Factors

- Coefficients of a chemical equation can be used as conversion factors in chemical calculations.

- Campfires as chemical reactions
  - How much oxygen is needed?
  - What are the reactants?
  - What are the products?
How many moles of nitrogen gas (N₂) are required to convert 11.5 moles of hydrogen gas (H₂) to ammonia (NH₃) according to the following reaction?

\[ \text{N}_2 + 3\text{H}_2 \rightarrow 2\text{NH}_3 \]
The reaction equation tells us that $N_2$ reacts with $H_2$ in a 1:3 mole ratio which we use as the conversion factor:

\[
\frac{11.5 \text{ mol } H_2}{3 \text{ mol } H_2} \times \frac{1 \text{ mol } N_2}{3 \text{ mol } H_2} = 3.83 \text{ moles of } N_2
\]
Suppose the city in which you live burns $2.13 \times 10^8$ grams of methane per day (approximate usage for a city with 50,000 inhabitants). How many grams of $H_2O$ are produced? The balanced reaction for the combustion of methane is as follows:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
Concept Check 4.11 Solution

- $2.13 \times 10^8$ g of CH$_4$
- CH$_4$ + 2O$_2$ → CO$_2$ + 2H$_2$O

\[
2.13 \times 10^8 \text{ g CH}_4 \times \frac{1 \text{ mol CH}_4}{16.04 \text{ g CH}_4} \times \frac{2 \text{ mol H}_2\text{O}}{1 \text{ mol CH}_4} \times \frac{18.02 \text{ g H}_2\text{O}}{1 \text{ mol H}_2\text{O}} = 4.79 \times 10^8 \text{ g H}_2\text{O}
\]

conversion factor: grams of CH$_4$ to moles of CH$_4$
conversion factor: moles of CH$_4$ to moles of H$_2$O
conversion factor: moles of H$_2$O to grams of H$_2$O
Suppose the city in which you live burns $2.13 \times 10^8$ grams of methane per day (approximate usage for a city with 50,000 inhabitants). How many grams of $\text{CO}_2$ are produced? The balanced reaction for the combustion of methane is as follows:

$$\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$$

1. $2.13 \times 10^8$ g
2. $4.79 \times 10^8$ g
3. $4.26 \times 10^8$ g
4. $5.84 \times 10^8$ g
5. None of the above