Stoichiometry

Chapter 3
Chemical reactions

1 cup sugar
1 cup butter
2 cups flour
1 ½ cups oats

2K(s) + 2H₂O(ℓ) → H₂(g) + 2KOH(aq)
Chemical Equations

\[ C + H_2O \xrightarrow{\Delta} CO + H_2 \]

- Represent chemical reactions.
  - + reacts with
  - $\rightarrow$ produces
  - $\Delta$ addition of heat

- Number of atoms for each element must remain the same!

- So may need to balance the equation.
Balancing equations

• Atoms on LHS = Atoms on RHS.

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

(***Subscript means 2 oxygen atoms)

<table>
<thead>
<tr>
<th>Atoms</th>
<th>LHS</th>
<th>RHS</th>
</tr>
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<tbody>
<tr>
<td>Mg</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>O</td>
<td>2</td>
<td>1</td>
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• Need 2 atoms of O on RHS so multiply the MgO by 2

\[ 2 \times \text{MgO} = 2\text{MgO} \]
Mg + O₂ → 2MgO

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• Need to have 2Mg on the LHS:

2Mg + O₂ → 2MgO

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• Balanced Equation!
**NiCl\(_2\) + NaOH \rightarrow Ni(OH)\(_2\) + NaCl**

- **Ni(OH)\(_2\)** means 1 Ni atom, 2O atoms and 2 H atoms!

<table>
<thead>
<tr>
<th></th>
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<th>O</th>
<th>H</th>
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Need 2 Chlorides on RHS so 2 NaCl

\[
\text{NiCl}_2 + \text{NaOH} \rightarrow \text{Ni(OH)}_2 + 2\text{NaCl}
\]

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Need 2 Na on LHS so 2 NaOH

\[
\text{NiCl}_2 + 2\text{NaOH} \rightarrow \text{Ni(OH)}_2 + 2\text{NaCl}
\]

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Try

- \( \text{Cu} + \text{HNO}_3 \rightarrow \text{Cu(NO}_3\text{)}_2 + \text{NO} + \text{H}_2\text{O} \)
- \( \text{P}_4\text{O}_{10} + \text{H}_2\text{O} \rightarrow \text{H}_3\text{PO}_4 \)
- \( \text{UO}_2 + \text{HF} \rightarrow \text{UF}_4 + \text{H}_2\text{O} \)
- \( \text{ZnS} + \text{O}_2 \rightarrow \text{ZnO} + \text{SO}_2 \)
Some chemical reactions

- Combination reactions

- 2 or more substances react to form one product

\[ \text{N}_2 + 3\text{H}_2 \rightarrow 2\text{NH}_3 \]
\[ \text{HCl} + \text{NH}_3 \rightarrow \text{NH}_4\text{Cl} \]
\[ \text{Ni} + 4\text{CO} \rightarrow \text{Ni(CO)}_4 \]

- **Metal + non-metal \rightarrow ionic solid**
• Decomposition reactions
  – One substances undergoes a reaction to produce 2 products.

  
  \[ 6\text{NaHCO}_3 \rightarrow 3\text{Na}_2\text{CO}_3 + 3\text{H}_2\text{O} + 3\text{CO}_2 \]
  – \( 2\text{KClO}_3 \rightarrow 2\text{KCl} + 3\text{O}_2 \)
  – \( 2\text{CaO} \rightarrow 2\text{Ca} + \text{O}_2 \)
Combustion Reactions

• Reactions involving a flame and $O_2$
  – **Hydrocarbons (C,H,O) $\xrightarrow{\Delta}$ $CO_2 + H_2O$

$$2SO_2 + O_2 \xrightarrow{\Delta} 2SO_3$$
$$C_3H_8 + O_2 \xrightarrow{\Delta} CO_2 + H_2O$$
$$PbS + 3O_2 \xrightarrow{\Delta} 2PbO + 2SO_2$$
Units for Convenience

• Biscuits
  1 cup sugar
  1 cup butter
  2 cups flour
  1 ½ cups oats

• Not grains of sugar or flour! – Impractical!!!

• Measurement of amounts are reproducible and convenient
Basic Units in Chemistry - Mole

• Chemical reactions often take place at levels where using atoms/molecules/ions would be confusing.

• Unit used is the MOLE

• Abbreviate mol

• Baking Cup ↔ moles
Definition - Mole

• A mole is the quantity of anything that has the same number of particles found in 12.000 grams of $^{12}\text{C}$

• This number of particles is **Avogadro's Number** - $6.022 \times 10^{23}$

• 1 mol of anything contains $6.022 \times 10^{23}$ particles

• Mole is a unit just like grams, bytes and centimeters
Moles and Mass

• Mass of 1 mol is called the molar mass (M)

• Unit: g of substance per mol substance [g/mol]

• Molar mass is the SUM of the atomic weights of each atom in the molecule.

• Periodic table for atomic weight.
\[ C_6H_{12}O_6 = [(6 \times 12.011) + (12 \times 1.0079) + (6 \times 15.999)] = \]

\[ \text{Mg(NO}_3\text{)}_2 = \]

\[ \text{MgSO}_4 \cdot 7\text{H}_2\text{O} = \]
Try

• Calculate the molar mass of one gram of each of the following molecules:

  – Malachite: $\text{Cu}_2\text{CO}_3(\text{OH})_2$
  – Sulphuric acid: $\text{H}_2\text{SO}_4$
  – Sodium dichromate: $\text{Na}_2\text{Cr}_2\text{O}_7.2\text{H}_2\text{O}$
  – Saccharin: $\text{C}_7\text{H}_5\text{NSO}_3$
Moles and Mass

- So far we have looked at 1 mol of a substance.

- Molar mass gives the relationship between the mass, molar mass and the number of moles.
Calculate the number of moles in 15.00 g of Cu.

Calculate the number of moles in 16.5 g of NH₃.
Example

A sample of metal contains $2.516 \times 10^{23}$ atoms and has a mass of 46.96 g. Determine the molar mass and identify the element.
1. Calculate the mass of 1.42 mol of chromium (III) sulfate decahydrate.

2. Calculate the mass in kg of $3.8 \times 10^{22}$ molecules of NO$_2$.

3. Calculate the number of moles of 0.0263 L of chloroform (CHCl$_3$). The density of chloroform is 1.483 g/cm$^3$.
Percentage composition

• To determine the % by mass contribution of each element in a substance.
• To determine purity.
Percent composition

1. Determine the molar mass of the compound

2. Determine the contribution of each element

\[
\text{Mass \% element} = \left( \frac{\text{no. of atoms of element}}{\text{molar mass of compound}} \right) \times \left( \frac{\text{molar mass of element}}{} \right) \times 100\%
\]

3. Percentages total 100
Example

Calculate the percent composition of HNO$_3$
Empirical and Molecular Formulas

- To determine the ratio of the number of moles of each element in a compound.
Formula from % composition

1. Assume mass of 100 g (easier calculation)

2. Calculate the number of moles

3. Divide by the smallest number

4. Write of the ratio of atoms

5. Molecular formula
Example

Elemental analysis of a sample showed 18.8% Na, 29.0 % Cl and 52.2% O. What is the empirical formula of the compound.
Analysis of a compound showed its components to be: 13.73 g Zn, 4.336 g P and 8.959 g O. Determine the empirical formula.
Glucose has a molar mass of 180 amu. Determine the empirical and molecular formula:

- C = 39.99%
- H = 6.72%
- O = 53.2%
Try:
An alcohol is 64.81% C, 13.60% H and 21.59% O by mass. Another experiment shows that its molecular weight is approximately 74 amu. What is the molecular formula of the alcohol?
Combustion Analysis

Another way to determine empirical formula.

1. Calculate the mass fraction contributed by individual atoms **Choose wisely!**
2. Calculate the % contributed by each element as a fraction of the total mass.
3. Then follow the steps to determine empirical formula.
\[ \text{C}_6\text{H}_{12}\text{O}_6 \xrightarrow{\Delta} \text{CO}_2 + \text{H}_2\text{O} \]

\begin{align*}
0.1014 \text{ g} & \quad 0.1486 \text{ g} & \quad 0.06090 \text{ g} \\
\text{Determine the masses and mass percentages of C, H, O} \\
\end{align*}

\[
g \text{C} = 0.1486 \text{ g} \text{ CO}_2 \times \frac{12.01 \text{ g C}}{44.01 \text{ g CO}_2} = 0.04055 \text{ g C}
\]

\[
g \text{H} = 0.0609 \text{ g} \text{ H}_2\text{O} \times \frac{0.0609 \text{ g H}}{18.02 \text{ g H}_2\text{O}} = 0.00681 \text{ g H}
\]

\[
g \text{O} = 0.1014 \text{ g sample} - [0.04055 \text{ g} + 0.00681 \text{ g}] = 0.0540 \text{ g O}
\]

\[
\% \text{ C} = \frac{0.04055 \text{ g C}}{0.1014 \text{ g}} \times 100\% = 39.99\% 
\]

\[
\text{C} = 39.99\% \quad \text{H} = 6.720\% \quad \text{O} = 53.20\%
\]
Try...

1. The combustion of 1.01 g Vitamin C (M = 176.12 g/mol) produces 1.50 g of CO$_2$ and 0.41 g of H$_2$O. What is the molecular formula of Vitamin C.

2. A solvent (0.250g, M = 146.99 g/mol) containing C, H and Cl underwent combustion to produce 0.451 g of CO$_2$ and 0.0617 g of H$_2$O. Determine the molecular formula.

1. Vitamin C = C$_6$H$_8$O$_6$
2. C$_6$H$_4$Cl$_2$
Quantitative Analysis of Chemical Equations

- What information can I get from

\[
2K(s) + 2H_2O(l) \rightarrow _\text{?}H_2(g) + 2KOH(aq)
\]

<table>
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<tr>
<th>2 molecules</th>
<th>2 molecules</th>
<th>1 molecule</th>
<th>2 molecules</th>
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*Use Avagadro....*

| 2 moles | 2 moles | 1 mole   | 2 moles   |

- Use the ratio of moles (indicated by the numbers **BEFORE** the compounds) to carry out quantitative analysis.
Steps to follow for a BALANCED equation

Step 1
• Amount of substance A (may need to use density, concentration etc.)
• (use the molar mass)

Step 2
• Moles of substance A
• Use coefficients from balanced equation

Step 3
• Moles of substance B
• (use molar mass of B)

Step 4
• Grams of Substance B
\[ \text{N}_2 + \text{H}_2 \rightarrow 2\text{NH}_3 \]

How many g of NH\(_3\) is produced if 2.65g of N\(_2\) is reacted with H\(_2\).
Limiting Reagents

6 strawberries + excess chocolate → 6 choc-strawberries
AgNO₃ (aq) + HCl (aq) → AgCl (s) + HNO₃ (aq)

• If 2 mole of silver nitrate reacts with 1 mole of HCl, how many moles of HNO₃ are produced?
• If 0.6 mole of silver nitrate reacts with 1 mole of HCl, how many moles of HNO₃ are produced?

Ba(NO₃)₂ (aq) + 2HCl (aq) → BaCl₂ (s) + 2HNO₃ (aq)

• If 1 mol of Ba(NO₃)₂ reacts with 1.2 mol of HCl, how many moles of BaCl₂ are produced?
• How many moles of HNO₃ are produced?
Limiting Reagents

1. Balance equation

2. Determine the molar masses

3. Calculate the number of moles for each reactant

4. Identify the limiting reagent

5. Use the limiting reagent for calculation of mass
\[ \text{N}_2 + \text{H}_2 \rightarrow \text{NH}_3 \]

85.5g  17.3g  ?
Try

1. 7.62 g of iron are allowed to react with 8.67 g of sulphur.
   a) Calculate the mass of FeS formed.
   b) How much of the excess reagent is left over?

2. Consider the unbalanced reaction:
   \[
   \text{MnO}_2 + \text{HCl} \rightarrow \text{MnCl}_2 + \text{Cl}_2 + \text{H}_2\text{O}
   \]
   If 0.86 mol of MnO₂ and 48.2 g of HCl react;
   a) Which will be used up first?
   b) How many grams of chlorine are produced?
Theoretical Yield

- The amount of product that forms when a reaction is complete (limiting reagent has reacted).

\[
\text{% yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%
\]
Solutions, Concentrations and Dilutions

End of Chapter 4
Solutions

• Relationship between the ratio of mass and volume in a solution

• Concentration: The amount of solute present in a given quantity of solvent

• The most common unit of concentration is molarity

• Other ways of expressing concentration units are
  – Weight percent
  – ppm (part per million)
    • same as part per hundred (%) but $1 \times 10^6$
Molarity

- Molarity refers to the number of moles of a substance (solute) in 1 L of a solution. \([\text{mol/L}]\)

\[
\text{Concentration} = \frac{\text{no. of mol}}{\text{volume in L}}
\]
Example

24.3 g sodium sulfate is dissolved in water with a final volume of 500 mL. What is the molarity of the solution?

Molarity = mol / L
Try

1. How many moles of MgCl$_2$ are present in 60 mL of 0.100 M MgCl$_2$ solution?

2. What is the molarity of 15.4 g of sucrose (C$_{12}$H$_{22}$O$_{11}$) in 74.0 mL of solution?

3. Calculate the volume (in mL) of a solution required to make a 0.270 M solution from 2.14 g of sodium chloride.
Dilution

Chemistry terms:
Dilution

- Add more solvent to a solution
- Concentration changes but NOT mols

10 mol in 1 L
10 M

10 mol in 2 L
5 M

10 mol in 4 L
2.5 M
Dilution of Solutions

\[ C_i V_i = C_f V_f \]

*(for dilution only!!)*

Calculate the volume of 18.0 M HCl required to prepare 400 mL of a 4 M solution of HCl

\[ C_i V_i = C_f V_f \]
Example

How many moles of dichromate \((K_2Cr_2O_7)\) are there in 500 mL of this 0.020 M solution?

\[
\begin{array}{c}
\text{n} \\
\text{c} \\
\text{v}
\end{array} \rightarrow 0.010 \text{ moles}
\]

Let's dilute this solution to 1.0 L by adding water.
Did the dilution affect the

a) Number of moles of potassium?

b) Concentration of the potassium dichromate?
What is the new concentration of the solution?
Solution stoichiometry

Calculate the volume of 0.324 M sulphuric acid required to react completely with 2.792 g of Na$_2$CO$_3$ according to the following equation:

\[
\text{H}_2\text{SO}_4 + \text{Na}_2\text{CO}_3 \rightarrow \text{Na}_2\text{SO}_4 + \text{CO}_2 + \text{H}_2\text{O}
\]

- Convert to moles
- Mole ratio
- Volume
H₂SO₄ + Na₂CO₃ → Na₂SO₄ + CO₂ + H₂O
Try

1. What volume of 0.505 M NaOH will react with 40.0 mL of 0.275 M \( H_2SO_4 \).

\[
H_2SO_4 + NaOH \rightarrow Na_2SO_4 + H_2O
\]

2. What volume of 0.256 M \( H_2SO_4 \) will react with 57.65 mL of 1.25 M NaOH. \textit{(use the reaction above)}
What is the molarity of NaOH if 36.2 mL is required to react with 35.2 mL of 0.125 M HNO₃ according to the following reaction:

\[
\text{HNO}_3 + \text{NaOH} \rightarrow \text{NaNO}_3 + \text{H}_2\text{O}
\]

35.2 mL  42.7 mL
0.125 M  ? M
Benzoic acid $C_6H_5COOH$ is used for standardisation of bases. A $1.867$ g sample of the acid reacts with $27.89$ mL of $0.8$ M NaOH. How much sodium benzoate, $C_6H_5COONa$ is produced?

\[ C_6H_5COOH + NaOH \rightarrow C_6H_5COONa + H_2O \]

✓ balance equation
✓ calculate n (mass and concentration equations)
✓ limiting reagent
✓ mass calculation
\[
\text{AlCl}_3 + 3\text{AgNO}_3 \rightarrow 3\text{AgCl(s)} + \text{Al(NO}_3)_3
\]

15.56 mL
0.8 M

1.797 g

? g

? g