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Ninth Edition

GENERAL CHEMISTRY

Principles and Modern Applications

Chapter 4: Chemical Reactions

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Contents

4-1 Chemical Reactions and Chemical Equations

As reactants are converted to products we observe:

- Color change (4-1)
- Precipitate formation (4-1)
- Gas evolution (4-2a)
- Heat absorption or evolution (4-2b)

Chemical evidence may be necessary.

Chemical Reaction

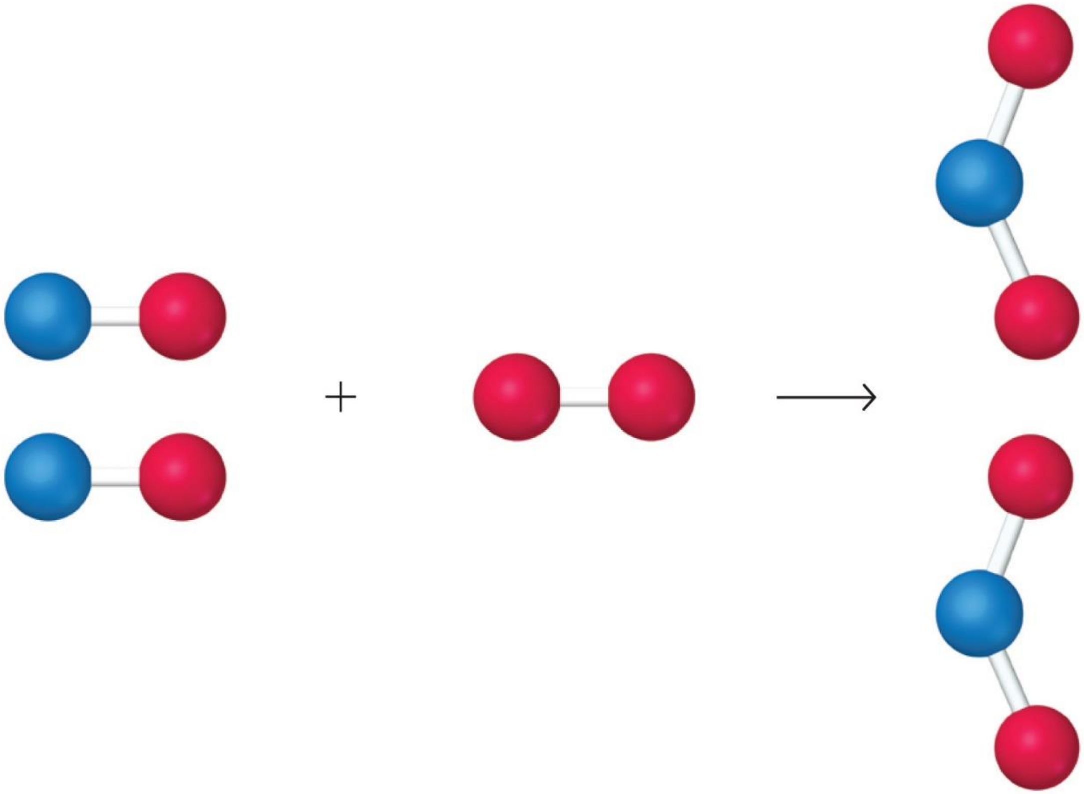
Nitrogen monoxide + oxygen → nitrogen dioxide

Step 1: Write the reaction using chemical symbols.

Step 2: Balance the chemical equation.

$$2\ NO + 1\ O_2 \rightarrow 2\ NO_2$$

Molecular Representation



Balancing Equations

- An equation can be balanced only by adjusting the coefficients of formulas.
- Never introduce extraneous atoms to balance.

$$NO + O_2 \rightarrow NO_2 + O$$

- Never change a formula for the purpose of balancing an equation.

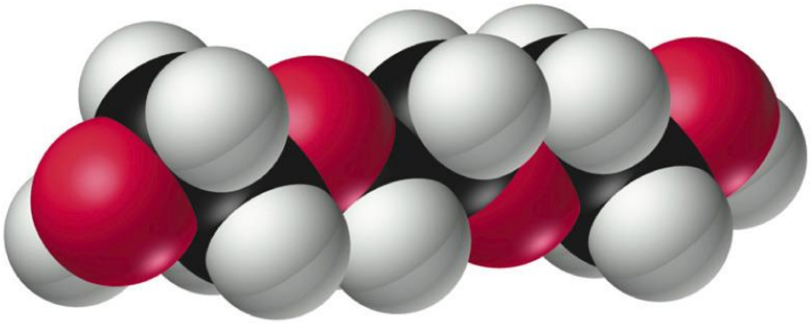
$$NO + O_2 \rightarrow NO_3$$

Balancing Equation Strategy

- Balance elements that occur in only one compound on each side first.
- Balance free elements last.
- Balance unchanged polyatomics (or other groups of atoms) as groups.
- Fractional coefficients are acceptable and can be cleared at the end by multiplication.

EXAMPLE 4-2

Writing and Balancing an Equation: The Combustion of a Carbon-Hydrogen-Oxygen Compound. Liquid triethylene glycol, $C_6H_{14}O_4$, is used a a solvent and plasticizer for vinyl and polyurethane plastics. Write a balanced chemical equation for its complete combustion.



Triethylene glycol

EXAMPLE 4-2

Chemical Equation:

$$C_6H_{14}O_4 + \frac{15}{2}\,O_2 \rightarrow 6\ CO_2 + 7\ H_2O$$

1. *Balance C.*
2. *Balance H.*
3. *Balance O.*
4. *Multiply by two*

$$2\ C_6H_{14}O_4 + 15\ O_2 \rightarrow 12\ CO_2 + 14\ H_2O$$

and check all elements.

4-2 Chemical Equations and Stoichiometry

- Stoichiometry includes all the *quantitative* relationships involving:
  - atomic and formula masses
  - chemical formulas.

- *Mole ratio* is a central conversion factor.

EXAMPLE 4-3

Relating the Numbers of Moles of Reactant and Product

How many moles of H_2O are produced by burning 2.72 mol H_2 in an excess of O_2?

Write the Chemical Equation:

Balance the Chemical Equation:

$$2\ H_2 + O_2 \rightarrow 2\ H_2O$$

Use the stoichiometric factor or mole ratio in an equation:

$$n_{H_2O} = 2.72 \text{ mol } H_2 \times \frac{2 \text{ mol } H_2O}{2 \text{ mol } H_2} = 2.72 \text{ mol } H_2O$$

EXAMPLE 4-6

Additional Conversion Factors in a Stoichiometric Calculation: Volume, Density, and Percent Composition.

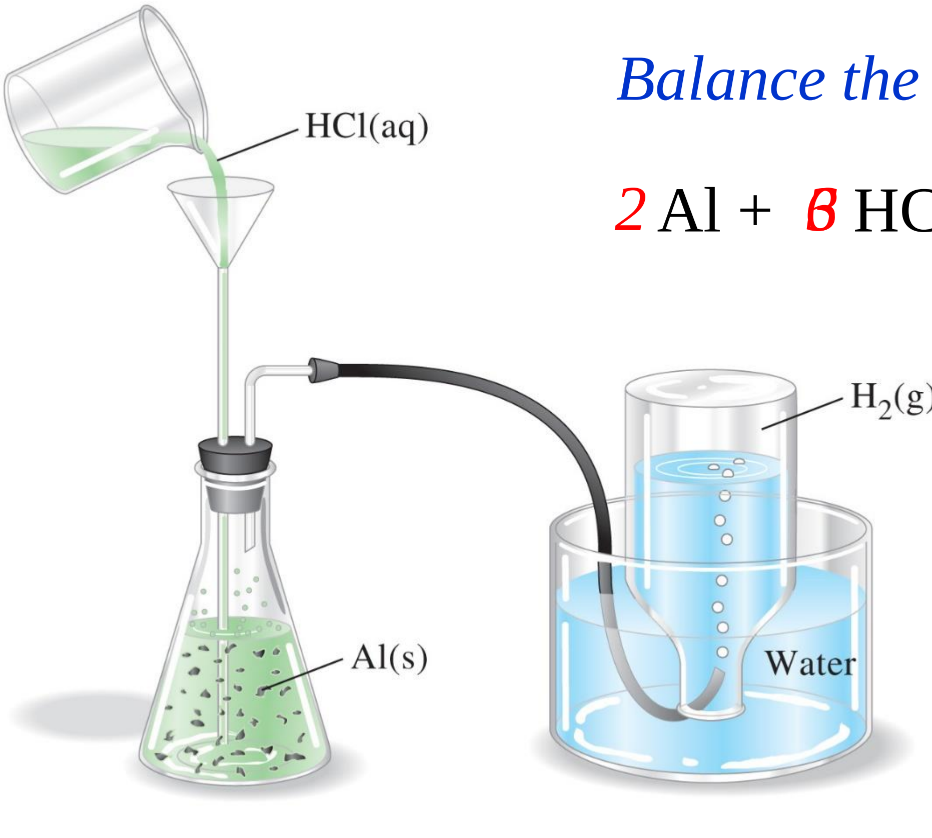
An alloy used in aircraft structures consists of 93.7% Al and 6.3% Cu by mass. The alloy has a density of 2.85 g/cm^3. A 0.691 cm^3 piece of the alloy reacts with an excess of HCl(aq). If we assume that *all* the Al but *none* of the Cu reacts with HCl(aq), what is the mass of H_2 obtained?

EXAMPLE 4-6

Write the Chemical Equation:

Balance the Chemical Equation:

$$2\,Al + 6\,HCl \rightarrow 2\,AlCl_3 + \overset{3}{\cancel{\tfrac{3}{2}}}\,H_2 \qquad \times 2$$



EXAMPLE 4-6

$$2\ Al + 6\ HCl \rightarrow 2\ AlCl_3 + 3\ H_2$$

Plan the strategy:

$$cm^3\ alloy \xrightarrow{\frac{g\ alloy}{cm^3}} g\ alloy \xrightarrow{\frac{g\ Al}{g\ alloy}} g\ Al \xrightarrow{\frac{mol\ Al}{g\ Al}} mole\ Al \xrightarrow{\frac{mol\ H_2}{mol\ Al}} mol\ H_2 \xrightarrow{\frac{g\ H_2}{mol\ H_2}} g\ H_2$$

We need 5 conversion factors!

Write the Equation and Calculate:

$$m_{H_2} = 0.691\ \cancel{cm^3}\ alloy \times \frac{2.85\ \cancel{g}\ alloy}{1\ \cancel{cm^3}} \times \frac{97.3\ \cancel{g}\ Al}{100\ \cancel{g}\ alloy} \times$$

$$\frac{1\ \cancel{mol}\ Al}{26.98\ \cancel{g}\ Al} \times \frac{3\ \cancel{mol}\ H_2}{2\ \cancel{mol}\ Al} \times \frac{2.016\ g\ H_2}{1\ \cancel{mol}\ H_2} = 0.207\ g\ H_2$$

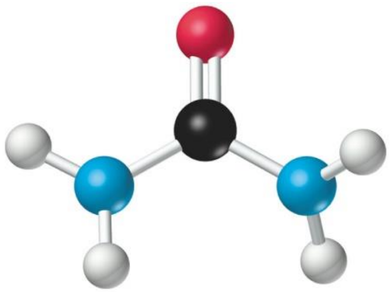
4-3 Chemical Reactions in Solution

- Close contact between atoms, ions and molecules necessary for a reaction to occur.
- Solvent
  - We will usually use *aqueous* (aq) solution.
- Solute
  - A material dissolved by the solvent.

Molarity

$$\text{Molarity } (M) = \frac{\text{Amount of solute } (\textit{mol solute})}{\text{Volume of solution (L)}}$$

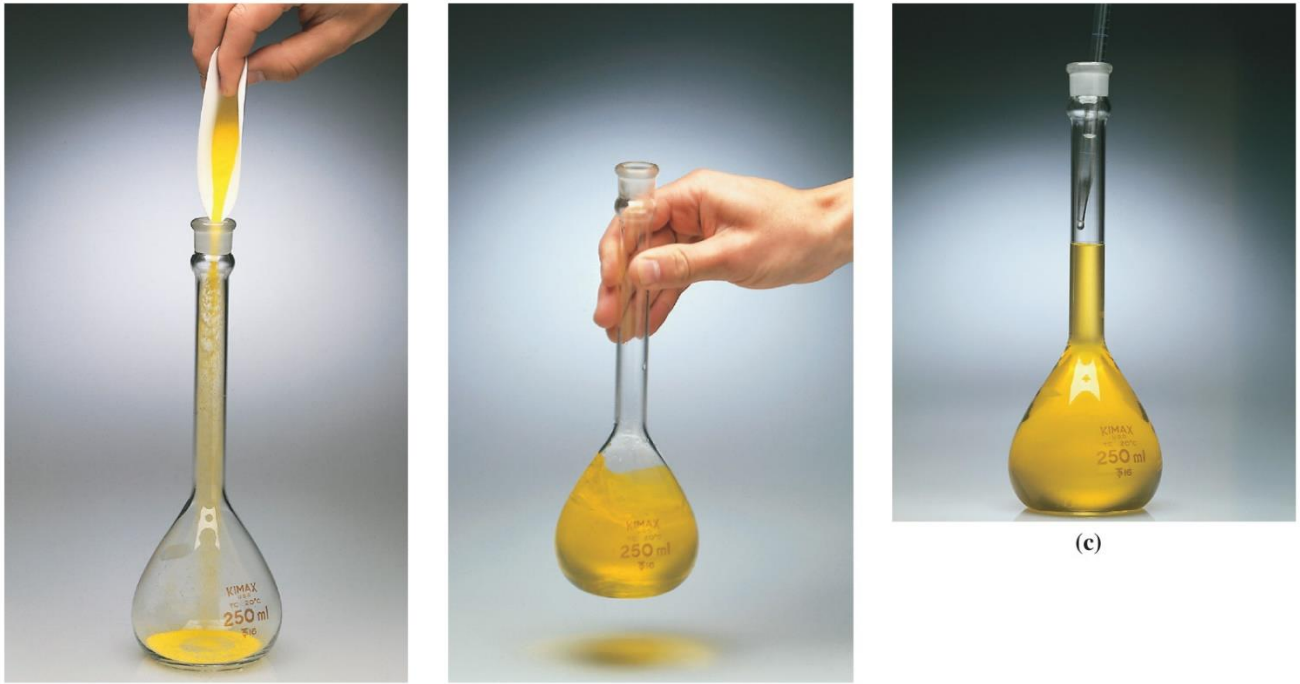
If 0.440 mol of urea is dissolved in enough water to make 1.000 L of solution the concentration is:



Urea

$$c_{\text{urea}} = \frac{0.440 \text{ mol urea}}{1.000 \text{ L}} = 0.440 \text{ M } CO(NH_2)_2$$

Preparation of a Solution



(a) (b) (c)

Weigh the solid sample.

Dissolve it in a volumetric flask partially filled with solvent.

Carefully fill to the mark.

EXAMPLE 4-9

Calculating the Mass of Solute in a Solution of Known Molarity. We want to prepare exactly 0.2500 L (250 mL) of an 0.250 M K_2CrO_4 solution in water. What mass of K_2CrO_4 should we use?

Plan strategy: $\text{Volume} \xrightarrow{\frac{mol}{L}} \text{moles} \xrightarrow{\frac{g}{mol}} \text{mass}$

We need 2 conversion factors!

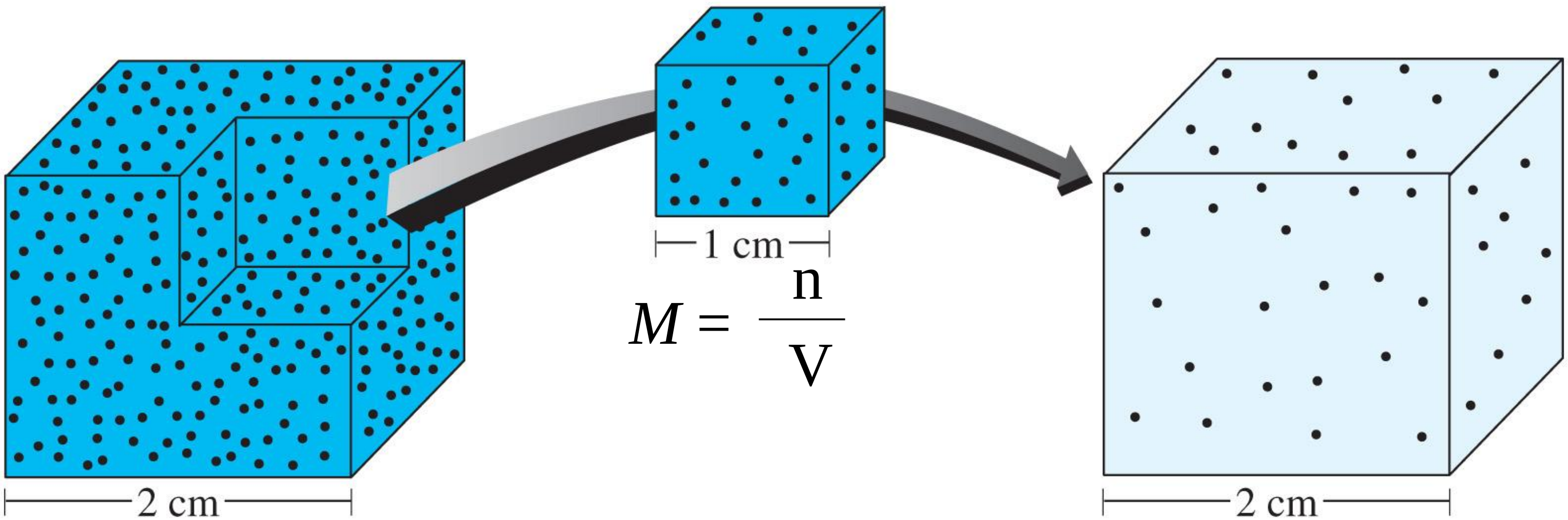
Write equation and calculate:

$$m_{K_2CrO_4} = 0.2500\ L \times \frac{0.250\ mol}{1.00\ L} \times \frac{194.02\ g}{1.00\ mol} = 12.1\ g$$

Solution Dilution

$M_i \times V_i$

$M_f \times V_f$



$$M = \frac{n}{V}$$

$$M_i \times V_i = n_i = n_f = M_f \times V_f$$

$$M_f = \frac{M_i \times V_i}{V_f} = M_i \frac{V_i}{V_f}$$

EXAMPLE 4-10

Preparing a solution by dilution A particular analytical chemistry procedure requires 0.0100 M K_2CrO_4. What volume of 0.250 M K_2CrO_4 should we use to prepare 0.250 L of 0.0100 M K_2CrO_4?

Plan strategy:

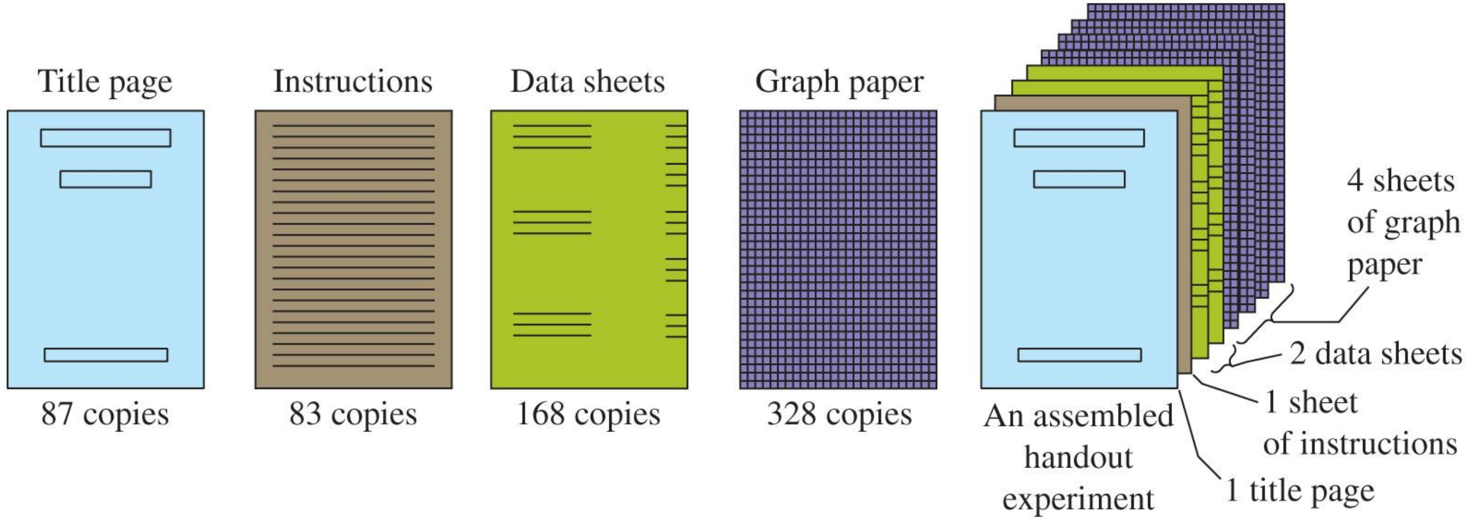
$$M_f = M_i \frac{V_i}{V_f} \qquad V_i = V_f \frac{M_f}{M_i}$$

Calculate:

$$V_{K_2CrO_4} = 0.2500\ \text{L} \times \frac{0.0100\ \text{mol}}{1.00\ \text{L}} \times \frac{1.000\ \text{L}}{0.250\ \text{mol}} = 0.0100\ \text{L}$$

4-4 Determining Limiting Reagent

- The reactant that is completely consumed determines the quantities of the products formed.



EXAMPLE 4-12

Determining the Limiting Reactant in a Reaction. Phosphorus trichloride, PCl_3, is a commercially important compound used in the manufacture of pesticides, gasoline additives, and a number of other products. It is made by the direct combination of phosphorus and chlorine

$$P_4\,(s) + 6\,Cl_2\,(g) \rightarrow 4\,PCl_3\,(l)$$

What mass of PCl_3 forms in the reaction of 125 g P_4 with 323 g Cl_2?

Strategy: Compare the actual mole ratio to the required mole ratio.

EXAMPLE 4-12

$$n_{Cl_2} = 323 \text{ g } Cl_2 \times \frac{1 \text{ mol } Cl_2}{70.91 \text{ g } Cl_2} = 4.56 \text{ mol } Cl_2$$

$$n_{P_4} = 125 \text{ g } P_4 \times \frac{1 \text{ mol } P_4}{123.9 \text{ g } P_4} = 1.01 \text{ mol } P_4$$

$$\chi = \frac{n_{Cl_2}}{n_{P_4}}$$

$$\chi_{\text{actual}} = 4.55 \text{ mol } Cl_2/\text{mol } P_4$$

$$\chi_{\text{theoretical}} = 6.00 \text{ mol } Cl_2/\text{mol } P_4$$

Chlorine gas is the limiting reagent.

EXAMPLE 4-12

Strategy for calculation:

$$\text{mass } Cl_2 \xrightarrow{\frac{mol\ Cl_2}{g\ Cl_2}} \text{moles } Cl_2 \xrightarrow{\frac{mol\ PCl_3}{mol\ Cl_2}} \text{moles } PCl_3 \xrightarrow{\frac{g\ PCl_3}{mol\ PCl_3}} \text{mass } PCl_3$$

Write the Equation and calculate:

$$m_{PCl_3} = 323\ \cancel{g}\ Cl_2 \times \frac{1\ \cancel{mol}\ Cl_2}{35.45\ \cancel{g}\ Cl_2} \times \frac{4\ \cancel{mol}\ PCl_3}{6\ \cancel{mol}\ Cl_2} \times \frac{137.3\ g\ PCl_3}{1\ \cancel{mol}\ PCl_3}$$

$$= 417\ g\ PCl_3$$

4-5 Other Practical Matters in Reaction Stoichiometry

Theoretical yield is the expected yield from a reactant.

Actual yield is the amount of product actually produced.

$$\text{Percent yield} = \frac{\text{Actual yield}}{\text{Theoretical Yield}} \times 100\%$$

Theoretical, Actual and Percent Yield

- When actual yield = % yield the reaction is said to be quantitative.
- Side reactions reduce the percent yield.
- By-products are formed by side reactions.

Consecutive Reactions, Simultaneous Reactions and Overall Reactions

- Multistep synthesis is often unavoidable.
- Reactions carried out in sequence are called consecutive reactions.
- When substances react independently and at the same time the reaction is a simultaneous reaction.

Overall Reactions and Intermediates

- The Overall Reaction is a chemical equation that expresses all the reactions occurring in a single overall equation.

- An intermediate is a substance produced in one step and consumed in another during a multistep synthesis.

End of Chapter Questions

- Initial problem solving is linear and often based on memorizing solutions for particular situations.