07 Mole Concept and Stoichiometry

1 Relative Masses

1.1 Relative atomic mass, A_r

DEFINITION The **relative atomic mass (A_r)** of an element is the average mass of one atom of the element compared with _____ of the mass of a carbon-12 atom.

- The A_r values are in the Periodic Table. They have **no units**.

WORKED EXAMPLE Chlorine is 75 % chlorine-35 and 25 % chlorine-37. Find its A_r.

$A_r = (75/100 \times 35) + (25/100 \times 37) = \mathbf{35.5}$

1.2 Relative molecular and formula mass, M_r

DEFINITION The **relative molecular mass (M_r)** of a molecule is the _____ of all the atoms in its formula. For an ionic compound it is called the **relative formula mass** and has the same symbol, M_r.

Substance	Formula	Working	M_r
water	H_2O	2(1) + 16	18
carbon dioxide	CO_2	12 + 2(16)	44
calcium carbonate	$CaCO_3$	40 + 12 + 3(16)	100
iron(II) nitrate	$Fe(NO_3)_2$	56 + 2(14) + 6(16)	180

NOTE Multiply the A_r by the number of atoms of that element, including the number outside any brackets.

1 Relative Masses (continued)

1.3 Percentage mass of an element

$$\text{percentage mass} = \frac{\text{number of atoms} \times A_r \text{ of the element}}{M_r \text{ of compound}} \times 100\ \%$$

WORKED EXAMPLE Find the percentage mass of nitrogen in $(NH_4)_2SO_4$.

$M_r = 2(14 + 4) + 32 + 4(16) = 132$.

Percentage of N = $\frac{2 \times 14}{132} \times 100\ \% = \mathbf{21.2\ \%}$.

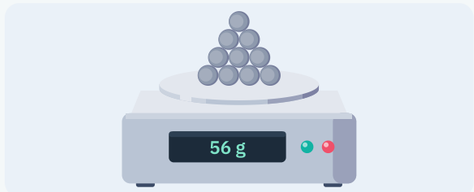
2 The Mole

2.1 Counting particles



a bank counts coins by weighing them, not one by one

same idea



56 g of iron (1 mol) = 6.02×10^{23} Fe atoms

DEFINITION One **mole** of any substance contains _____ particles. This number is the **Avogadro constant**. The symbol for the mole is **mol**.

- The particles can be atoms, molecules, ions or even electrons.

$$\text{number of moles} = \frac{\text{number of particles}}{6.02 \times 10^{23}}$$

2 The Mole (continued)

2.2 Particles in a mole

Amount	Particles	Number
1 mol of Ne	Ne atoms	6.02×10^{23}
1 mol of H_2	H_2 molecules	6.02×10^{23}
1 mol of H_2	H atoms (2 mol)	1.204×10^{24}
2 mol of $Mg(NO_3)_2$	NO_3^- ions (4 mol)	2.408×10^{24}

EXAM TIP Do not mix up the number of **moles** of a substance with the number of **particles**. Look at what the question asks you to count.

2.3 Moles and mass

DEFINITION The mass of one mole is the **molar mass**. It equals the A_r or M_r in _____. The unit is g/mol.

$$\text{number of moles} = \frac{\text{mass in g}}{\text{molar mass in g/mol}}$$

WORKED EXAMPLE Find the mass of 4.5 mol of lead(II) sulfate, $PbSO_4$.

Molar mass = 207 + 32 + 4(16) = 303 g/mol.

Mass = 4.5 × 303 = **1360 g** (3 s.f.).

2.4 Moles and gas volume

DEFINITION One mole of **any gas** occupies _____ at r.t.p. (25 °C and 1 atmosphere).

$$\text{number of moles of gas} = \frac{\text{volume in dm}^3}{24\ \text{dm}^3}$$

WORKED EXAMPLE Find the volume of 2 mol of oxygen at r.t.p.

Volume = 2 × 24 = **48 dm³**.

2.5 Concentration of a solution

DEFINITION The **concentration** of a solution is the amount of solute dissolved in a unit volume of solution. Two units are used: **g/dm³** and **mol/dm³**.

$$\text{concentration in g/dm}^3 = \frac{\text{mass of solute in g}}{\text{volume of solution in dm}^3}$$

$$\text{concentration in mol/dm}^3 = \frac{\text{amount of solute in mol}}{\text{volume of solution in dm}^3}$$

$$\text{concentration in mol/dm}^3 = \frac{\text{concentration in g/dm}^3}{\text{molar mass in g/mol}}$$

NOTE 1 dm^3 = 1000 cm^3. Change cm^3 to dm^3 by dividing by 1000.

WORKED EXAMPLE 500 cm^3 of solution contains 2 mol of NaCl. Find the concentration in g/dm^3.

Mass of NaCl = 2 × 58.5 = 117 g.

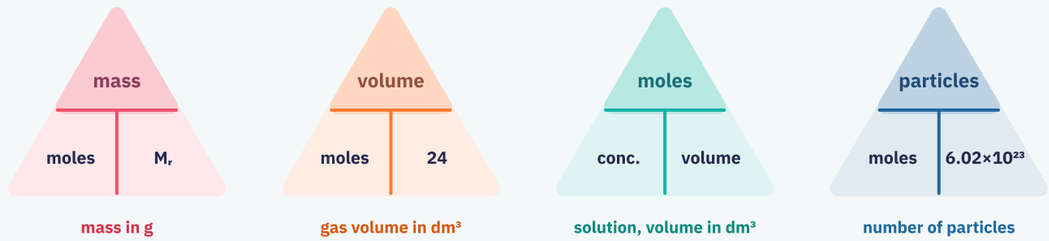
Concentration = $\frac{117\ \text{g}}{0.500\ \text{dm}^3}$ = **234 g/dm³**.

WORKED EXAMPLE 1.74 g of K_2SO_4 is dissolved to make 200 cm^3 of solution. Find the concentration in mol/dm^3.

Molar mass = 2(39) + 32 + 4(16) = 174 g/mol. Moles = $\frac{1.74}{174}$ = 0.01 mol.

Concentration = $\frac{0.01\ \text{mol}}{0.200\ \text{dm}^3}$ = **0.05 mol/dm³**.

2.6 The formula triangles



NOTE Cover the quantity you want. A horizontal line means **divide** and a vertical line means **multiply**.

3 Empirical and Molecular Formulae

3.1 Two kinds of formula

Empirical formula

The _____ of the atoms of each element in a compound.

Molecular formula

The _____ of atoms of each element in one molecule, a multiple of the empirical one.

Compound	Molecular	Empirical
water	H_2O	H_2O
phosphorus(V) oxide	P_4O_{10}	P_2O_5
ethene	C_2H_4	CH_2

3.2 Empirical formula from percentage mass

A compound is 40.0 % carbon, 6.70 % hydrogen and 53.3 % oxygen by mass.

Step	C	H	O
1 Assume 100 g, so mass in g	40.0	6.70	53.3
2 Divide by A_r to get moles	40.0 ÷ 12 = 3.33	6.70 ÷ 1 = 6.70	53.3 ÷ 16 = 3.33
3 Divide by the smallest	1	2	1

The empirical formula is **CH_2O**.

3.3 Molecular formula

$$n = \frac{M_r \text{ of compound}}{M_r \text{ of empirical formula}}$$

WORKED EXAMPLE A compound has $M_r = 60$ and empirical formula CH_2O. Find its molecular formula.

M_r of $CH_2O = 12 + 2(1) + 16 = 30$.

$n = 60 \div 30 = 2$.

Molecular formula = $(CH_2O)_2$ = **$C_2H_4O_2$**.

3.4 When the ratio is not a whole number

WORKED EXAMPLE Plexiglass is 59.9 % carbon, 8.1 % hydrogen and 32.0 % oxygen by mass. Find its empirical formula.

Moles: C = 59.9 ÷ 12 = 4.99, H = 8.1 ÷ 1 = 8.1, O = 32.0 ÷ 16 = 2.00.

Divide by the smallest (2.00): C = 2.5, H = 4.05, O = 1.

2.5 is not a whole number, so multiply all by 2: C = 5, H = 8, O = 2. The formula is **$C_5H_8O_2$**.

4 Stoichiometry

4.1 The mole ratio

Stoichiometry is the ratio between the quantities of substances, in _____, in a chemical reaction.

$MgCO_3$	+	$2HCl$	→	$MgCl_2$	+	CO_2	+	H_2O
1 mol		2 mol		1 mol		1 mol		1 mol

EXAM TIP The ratio of **moles** equals the ratio of the numbers in front of the formulae, not the ratio of masses.

4.2 Reacting masses and gas volumes

1. Find the **moles** of the substance you know (from mass, gas volume or concentration and volume).
2. Use the **mole ratio** from the balanced equation to find the moles of the substance you want.
3. Change the moles to the **mass**, **volume** or **concentration** you want.

WORKED EXAMPLE Find the mass of magnesium carbonate needed to produce 100 dm^3 of carbon dioxide at r.t.p. $MgCO_3(s) + 2HCl(aq) \rightarrow MgCl_2(aq) + CO_2(g) + H_2O(l)$

Moles of $CO_2 = 100 \div 24 = 4.17$ mol.

1 mol of $MgCO_3$ gives 1 mol of CO_2, so moles of $MgCO_3 = 4.17$ mol.

Mass = 4.17 × (24 + 12 + 48) = **350 g**.

WORKED EXAMPLE Find the mass of iron made from 2000 g of iron(III) oxide. $Fe_2O_3(s) + 3CO(g) \rightarrow 2Fe(s) + 3CO_2(g)$

M_r of $Fe_2O_3 = 160$, so moles = 2000 ÷ 160 = 12.5 mol.

1 mol of Fe_2O_3 gives 2 mol of Fe, so moles of Fe = 25.0 mol.

Mass = 25.0 × 56 = **1400 g**.

4.3 Gas volumes in a reaction

NOTE **Avogadro's law:** at the same temperature and pressure, equal volumes of gases contain the **same number of particles**. So the mole ratio of gases is also their **volume ratio**.

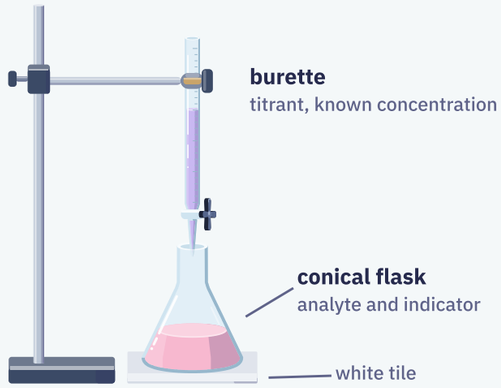
WORKED EXAMPLE $N_2(g) + O_2(g) \rightarrow 2NO(g)$. Find the volume of nitrogen needed to make 800 cm^3 of nitric oxide.

Volume ratio N_2 : NO = 1 : 2.

Volume of N_2 = 800 ÷ 2 = **400 cm^3**.

4 Stoichiometry (continued)

4.4 Titration



- The **titrant** has a known concentration. The **analyte** has an unknown concentration.
- Add a fixed volume of analyte (usually 25.0 cm^3, by pipette) and a few drops of indicator to the flask. Add titrant from the burette, swirling, until the colour changes permanently. This is the **end-point**.
- Repeat until two titres agree to within 0.10 cm^3, and use the average of those titres.

WORKED EXAMPLE 20.0 cm^3 of H_2SO_4 reacts with 30.0 cm^3 of 0.100 mol/dm^3 KOH. $2KOH + H_2SO_4 \rightarrow K_2SO_4 + 2H_2O$. Find the concentration of the acid.

Moles of KOH = 0.100 × 0.0300 = 0.003 mol.

2 mol KOH react with 1 mol H_2SO_4, so moles of acid = 0.0015 mol.

Concentration = 0.0015 ÷ 0.0200 = **0.075 mol/dm^3**.

4.5 A gas reacting with a solution

WORKED EXAMPLE 250 cm^3 of calcium hydroxide solution reacts completely with 6 dm^3 of carbon dioxide at r.t.p. $CO_2(g) + Ca(OH)_2(aq) \rightarrow CaCO_3(s) + H_2O(l)$. Find the concentration of the calcium hydroxide and the mass of calcium carbonate formed.

Moles of CO_2 = 6 ÷ 24 = 0.25 mol, so moles of $Ca(OH)_2$ = 0.25 mol (ratio 1 : 1).

Concentration = 0.25 ÷ 0.250 = **1.0 mol/dm^3**.

Moles of $CaCO_3$ = 0.25 mol, so mass = 0.25 × 100 = **25 g**.

4 Stoichiometry (continued)

4.6 Limiting reactants

recipe	**2 bread**	+	**1 cheese**	→	**1 sandwich**
we have	10 bread		4 cheese		4 sandwiches
	2 left over: in **excess**		all used: **limiting**		set by the cheese

- The reactant that is **completely used up** is the _____. The other is in **excess**.
- The amount of product depends on the limiting reactant, so calculate from it.
- Example: 5 mol of NaOH and 3 mol of HCl react 1 : 1. All 3 mol of HCl are used up and 2 mol of NaOH remain. HCl is limiting and 3 mol of NaCl form.

4.7 Finding the limiting reactant

WORKED EXAMPLE 2.00 g of calcium carbonate powder is added to 50.0 cm^3 of 2.00 mol/dm^3 hydrochloric acid. Find the volume of carbon dioxide at r.t.p. $CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2 + H_2O$

Moles of HCl = 2.00 × 0.0500 = 0.100 mol.

Moles of $CaCO_3$ = 2.00 ÷ 100 = 0.0200 mol.

0.100 mol of HCl needs 0.0500 mol of $CaCO_3$, but only 0.0200 mol is present. **$CaCO_3$ is limiting.**

1 mol of $CaCO_3$ gives 1 mol of CO_2, so volume = 0.0200 × 24 = **0.480 dm^3**.

4.8 Common mistakes in mole calculations

- Forgetting to change cm^3 to dm^3: divide by 1000.
- Using the ratio of **masses** instead of the ratio of **moles** from the equation.
- Using the M_r of the wrong substance, or leaving out the number in front of a formula.
- Using 24 dm^3 for a solid, a liquid or a solution. It is only for gases at r.t.p.

5 Percentage Yield and Purity

5.1 Percentage yield

$$\text{percentage yield} = \frac{\text{actual yield}}{\text{theoretical maximum yield}} \times 100\ \%$$

- The **theoretical maximum** is worked out from the mole ratio in the equation.

WORKED EXAMPLE 100 g of $CaCO_3$ reacts with excess HNO_3: $CaCO_3 + 2HNO_3 \rightarrow Ca(NO_3)_2 + H_2O + CO_2$. 129.6 g of $Ca(NO_3)_2$ is collected. Find the percentage yield.

Moles of $CaCO_3$ = 100 ÷ 100 = 1 mol, so 1 mol of $Ca(NO_3)_2$ is the theoretical maximum.

M_r of $Ca(NO_3)_2$ = 164, so the theoretical mass is 164 g.

Percentage yield = 129.6 ÷ 164 × 100 % = **79.0 %**.

5.2 Percentage purity

$$\text{percentage purity} = \frac{\text{mass of pure substance in the sample}}{\text{total mass of the sample}} \times 100\ \%$$

WORKED EXAMPLE 50.0 g of impure aspirin, $C_9H_8O_4$, contains 0.20 mol of pure aspirin. Find the percentage purity.

Molar mass = 9(12) + 8(1) + 4(16) = 180 g/mol.

Mass of pure aspirin = 0.20 × 180 = 36.0 g.

Percentage purity = 36.0 ÷ 50.0 × 100 % = **72.0 %**.

5.3 Purity from a reaction

WORKED EXAMPLE 200 g of impure zinc is added to excess copper(II) chloride solution and 171 g of copper is obtained. $Zn + CuCl_2 \rightarrow ZnCl_2 + Cu$. Find the percentage purity of the zinc.

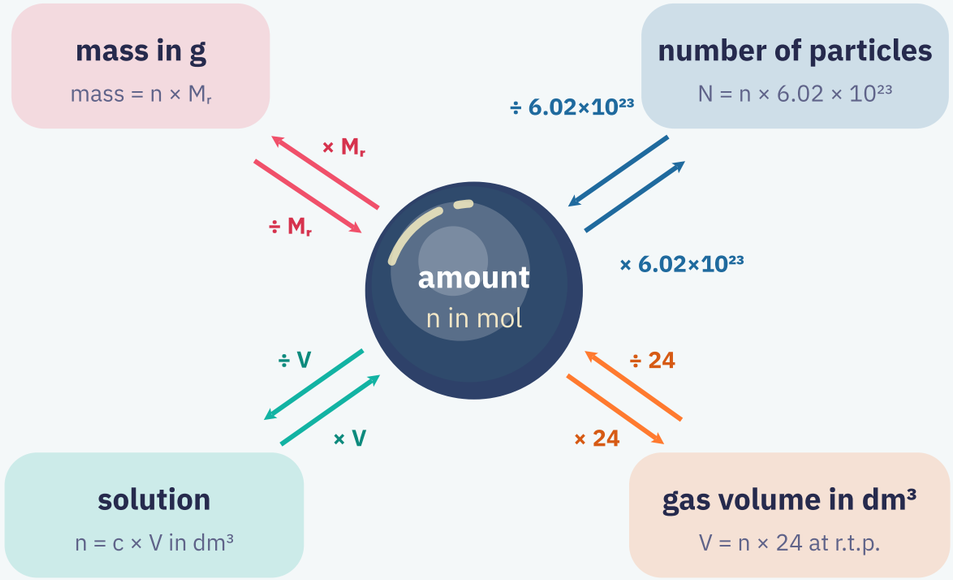
Moles of Cu = 171 ÷ 64 = 2.67 mol, so moles of Zn = 2.67 mol (ratio 1 : 1).

Mass of pure zinc = 2.67 × 65 = 174 g.

Percentage purity = 174 ÷ 200 × 100 % = **86.8 %**.

6 Summary

6.1 Moles at the centre



- To go between any two quantities, change to **moles** first, then change to the quantity you want.

6.2 Formulae to know

To find	Use
M_r	add the A_r of every atom in the formula
moles from mass	mass in g ÷ molar mass in g/mol
moles of a gas	volume in dm^3 ÷ 24
moles from particles	number of particles ÷ 6.02×10^{23}
moles in solution	concentration in mol/dm^3 × volume in dm^3
concentration in g/dm^3	concentration in mol/dm^3 × M_r
molecular formula	$(\text{empirical formula})_n$, $n = M_r \div M_r$ of empirical formula
percentage yield	actual ÷ theoretical maximum × 100 %
percentage purity	pure mass ÷ sample mass × 100 %

EXAM TIP Write the equation, then moles, then the mole ratio, then the answer. Show every step and give the units.