

5. Formulae, equations and amounts of substance

The mole is the key concept for chemical calculations

DEFINITION: **The mole** is the amount of substance in grams that has the same number of particles as there are atoms in 12 grams of carbon-12.

DEFINITION: **Relative atomic mass** is the **average mass** of one atom compared to one twelfth of the mass of one atom of carbon-12

DEFINITION: **Molar Mass** is the mass in grams of 1 mole of a substance and is given the unit of g mol^{-1}

Molar Mass for a compound can be calculated by adding up the mass numbers (from the periodic table) of each element in the compound
eg $\text{CaCO}_3 = 40.1 + 12.0 + 16.0 \times 3 = 100.1$

For most calculations we will do at A-level we will use the following 3 equations

Learn these equations carefully and what units to use in them.

1. For pure solids, liquids and gases

$$\text{amount} = \frac{\text{mass}}{\text{Molar Mass}}$$

Unit of Mass: grams
Unit of amount : mol

2. For gases

$$\text{Gas Volume (dm}^3\text{)} = \text{amount} \times 24$$

This equation gives the volume of a gas at room pressure (1 atm) and room temperature 25°C .

It is usually best to give your answers to 3sf

3. For solutions

$$\text{Concentration} = \frac{\text{amount}}{\text{volume}}$$

Unit of concentration: mol dm^{-3} or M
Unit of Volume: **dm³**

Converting volumes

$$\begin{aligned}\text{cm}^3 &\rightarrow \text{dm}^3 \div 1000 \\ \text{cm}^3 &\rightarrow \text{m}^3 \div 1000\,000 \\ \text{dm}^3 &\rightarrow \text{m}^3 \div 1000\end{aligned}$$

For pure solids, liquids and gases

$$\text{amount} = \frac{\text{mass}}{M_r}$$

Unit of Mass: grams
Unit of amount : mol

Example 1: What is the amount, in mol, in 35.0g of CuSO_4 ?

$$\begin{aligned}\text{amount} &= \text{mass}/M_r \\ &= 35 / (63.5 + 32 + 16 \times 4) \\ &= 0.219 \text{ mol}\end{aligned}$$

Many questions will involve changes of units
 $1000 \text{ mg} = 1\text{g}$
 $1000 \text{ g} = 1\text{kg}$
 $1000\text{kg} = 1 \text{ tonne}$

Example 2: What is the amount, in mol, in 75.0mg of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$?

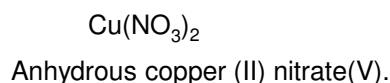
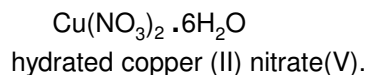
$$\begin{aligned}\text{amount} &= \text{mass}/M_r \\ &= 0.075 / (40 + 32.0 + 16.0 \times 4 + 18.0 \times 2) \\ &= 4.36 \times 10^{-4} \text{ mol}\end{aligned}$$

Significant Figures

Give your answers to the same number of significant figures as the number of significant figures for the data you given in a question. If you are given a mixture of different significant figures, use the smallest

Hydrated salt

A Hydrated salt contains water of crystallisation



Example 3

$\text{Na}_2\text{SO}_4 \cdot x\text{H}_2\text{O}$ has a molar mass of 322.1, Calculate the value of x

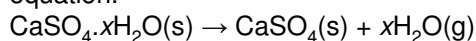
$$\text{Molar mass } x\text{H}_2\text{O} = 322.1 - (23 \times 2 + 32.1 + 16 \times 4) = 180$$

$$x = 180/18 = 10$$

Heating in a crucible

This method could be used for measuring mass loss in various thermal decomposition reactions and also for mass gain when reacting magnesium in oxygen.

The water of crystallisation in calcium sulphate crystals can be removed as water vapour by heating as shown in the following equation.



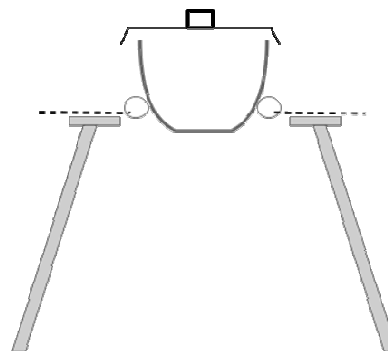
Method.

- Weigh an empty clean dry crucible and lid .
- Add 2g of hydrated calcium sulphate to the crucible and weigh again
- Heat strongly with a Bunsen for a couple of minutes
- Allow to cool
- Weigh the crucible and contents again
- Heat crucible again and reweigh until you reach a constant mass (do this to ensure reaction is complete).

Large amounts of hydrated calcium sulphate, such as 50g, should not be used in this experiment as the decomposition is like to be incomplete.

The crucible needs to be dry otherwise a wet crucible would give an inaccurate result. It would cause mass loss to be too large as water would be lost when heating.

The lid improves the accuracy of the experiment as it prevents loss of solid from the crucible but should be loose fitting to allow gas to escape.



Small amounts the solid , such as 0.100 g, should **not** be used in this experiment as errors in weighing are too high.

Example 4. 3.51 g of hydrated zinc sulphate were heated and 1.97 g of anhydrous zinc sulphate were obtained.

Use these data to calculate the value of the integer x in $\text{ZnSO}_4 \cdot x\text{H}_2\text{O}$

$$\text{Calculate the mass of H}_2\text{O} = 3.51 - 1.97 = 1.54\text{g}$$

$$\begin{aligned} \text{Calculate moles of ZnSO}_4 &= \frac{1.97}{161.5} \\ &= 0.0122 \end{aligned}$$

$$\begin{aligned} \text{Calculate moles of H}_2\text{O} &= \frac{1.54}{18} \\ &= 0.085 \end{aligned}$$

$$\begin{aligned} \text{Calculate ratio of mole of ZnSO}_4 \text{ to H}_2\text{O} &= \frac{0.0122}{0.0122} \\ &= 1 \end{aligned}$$

$$\begin{aligned} &= \frac{0.085}{0.0122} \\ &= 7 \end{aligned}$$

$$x = 7$$

Avogadro's Constant

The mole is the amount of substance in grams that has the same number of particles as there are atoms in 12 grams of carbon-12.

Avogadro's Constant

There are 6.02×10^{23} atoms in 12 grams of carbon-12. Therefore explained in simpler terms 'One mole of any specified entity contains 6.02×10^{23} of that entity':

Avogadro's Constant can be used for atoms, molecules and ions

1 mole of copper atoms will contain 6.02×10^{23} atoms
1 mole of carbon dioxide molecules will contain 6.02×10^{23} molecules
1 mole of sodium ions will contain 6.02×10^{23} ions

$$\text{No of particles} = \text{amount of substance (in mol)} \times \text{Avogadro's constant}$$

Example 5: How many atoms of Tin are there in a 6.00 g sample of Tin metal?

$$\text{amount} = \text{mass}/A_r$$

$$= 6 / 118.7$$

$$= 0.05055 \text{ mol}$$

$$\begin{aligned} \text{Number atoms} &= \text{amount} \times 6.02 \times 10^{23} \\ &= 0.05055 \times 6.02 \times 10^{23} \\ &= 3.04 \times 10^{22} \end{aligned}$$

Example 6 : How many chloride ions are there in a 25.0 cm³ of a solution of magnesium chloride of concentration 0.400 mol dm⁻³ ?

$$\text{amount} = \text{concentration} \times \text{Volume}$$

$$\text{MgCl}_2 = 0.400 \times 0.025$$

$$= 0.0100 \text{ mol}$$

$$\begin{aligned} \text{Amount of chloride ions} &= 0.0100 \times 2 \\ &= 0.0200 \end{aligned}$$

There are two moles of chloride ions for every one mole of MgCl₂

$$\begin{aligned} \text{Number ions of Cl}^- &= \text{amount} \times 6.02 \times 10^{23} \\ &= 0.0200 \times 6.02 \times 10^{23} \\ &= 1.204 \times 10^{22} \end{aligned}$$

Density

Density calculations are usually used with pure liquids but to work out the mass from a measured volume. It can also be used with solids and gases.

$$\text{density} = \frac{\text{mass}}{\text{volume}}$$

Density is usually given in g cm⁻³
Care needs to be taken if different units are used.

Example 7 : How many molecules of ethanol are there in a 0.500 dm³ of ethanol (CH₃CH₂OH) liquid ? The density of ethanol is 0.789 g cm⁻³

$$\begin{aligned} \text{Mass ethanol} &= \text{density} \times \text{Volume} \\ &= 0.789 \times 500 \\ &= 394.5 \text{ g} \end{aligned}$$

$$\begin{aligned} \text{amount} &= \text{mass}/M_r \\ &= 394.5 / 46.0 \\ &= 8.576 \text{ mol} \end{aligned}$$

$$\begin{aligned} \text{Number of molecules} &= \text{amount} \times 6.022 \times 10^{23} \\ &= 8.576 \times 6.022 \times 10^{23} \\ &= 5.16 \times 10^{24} (\text{to 3 sig fig}) \end{aligned}$$

Example 8: There are 980mol of pure gold in a bar measuring 10 cm by 20 cm by 50 cm. What is the density of gold in kg dm⁻³

$$\begin{aligned} \text{Mass} &= \text{amount} \times M_r \\ &= 980 \times 197 \\ &= 193060 \text{ g} \\ &= 193.06 \text{ kg} \end{aligned}$$

$$\begin{aligned} \text{Volume} &= 10 \times 20 \times 50 \\ &= 10\,000 \text{ cm}^3 \\ &= 10 \text{ dm}^3 \end{aligned}$$

$$\begin{aligned} \text{density} &= \text{mass}/\text{volume} \\ &= 193/10 \\ &= 19.3 \text{ kg dm}^{-3} \end{aligned}$$

Empirical Formula

Definition: An empirical formula is the **simplest** ratio of atoms of each **element** in the compound.

General method

Step 1 : Divide each mass (or % mass) by the atomic mass of the element

Step 2 : For each of the answers from step 1 divide by the smallest one of those numbers.

Step 3: sometimes the numbers calculated in step 2 will need to be multiplied up to give whole numbers.

These whole numbers will be the empirical formula.

The same method can be used for the following types of data:

1. masses of each element in the compound
2. percentage mass of each element in the compound

Example 9 : Calculate the empirical formula for a compound that contains 1.82g of K, 5.93g of I and 2.24g of O

Step1: Divide each mass by the atomic mass of the element

$$\begin{array}{lll} \text{K} = 1.82 / 39.1 & \text{I} = 5.93 / 126.9 & \text{O} = 2.24 / 16 \\ = 0.0465 \text{ mol} & = 0.0467 \text{ mol} & = 0.14 \text{ mol} \end{array}$$

Step 2 For each of the answers from step 1 divide by the smallest one of those numbers.

$$\begin{array}{lll} \text{K} = 0.0465 / 0.0465 & \text{I} = 0.0467 / 0.0465 & \text{O} = 0.14 / 0.0465 \\ = 1 & = 1 & = 3 \end{array}$$

Empirical formula = KIO_3

Molecular formula from empirical formula

Definition: A molecular formula is the **actual** number of atoms of each element in the compound.

From the relative molecular mass (M_r) work out how many times the mass of the empirical formula fits into the M_r .

Example 10 : work out the molecular formula for the compound with an empirical formula of $\text{C}_3\text{H}_6\text{O}$ and a M_r of 116

$\text{C}_3\text{H}_6\text{O}$ has a mass of 58

The empirical formula fits twice into M_r of 116

So molecular formula is $\text{C}_6\text{H}_{12}\text{O}_2$

The M_r does not need to be exact to turn an empirical formula into the molecular formula because the molecular formula will be a whole number multiple of the empirical formula

Concentration of Solutions

A solution is a mixture formed when a solute dissolves in a solvent. In chemistry we most commonly use water as the solvent to form aqueous solutions. The solute can be a solid, liquid or a gas.

Molar concentration can be measured for solutions. This is calculated by dividing the amount in moles of the solute by the volume of the solution. The volume is measure is dm^3 . The unit of molar concentration is mol dm^{-3} ; it can also be called molar using symbol M

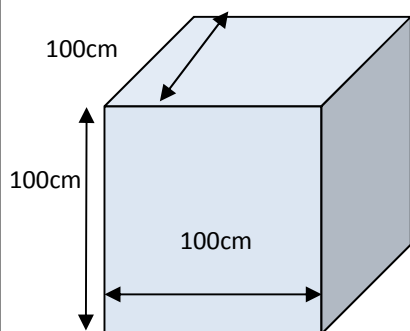
$$\text{Concentration} = \frac{\text{amount}}{\text{volume}}$$

Unit of concentration: mol dm^{-3} or M

Unit of Volume: dm^3

Converting volumes

A m^3 is equivalent to a cube
 $100\text{cm} \times 100\text{cm} \times 100\text{cm} = 1000000\text{cm}^3$



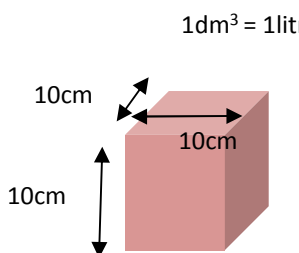
1m^3

$1\text{m}^3 = 1000\text{ dm}^3$ or 1000L

To convert m^3 into dm^3 multiply by 1000

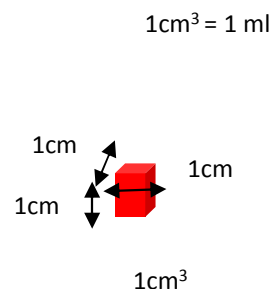
$$\begin{aligned}\text{cm}^3 &\rightarrow \text{dm}^3 \div 1000 \\ \text{cm}^3 &\rightarrow \text{m}^3 \div 1000\,000 \\ \text{dm}^3 &\rightarrow \text{m}^3 \div 1000\end{aligned}$$

A dm^3 is equivalent to a cube
 $10\text{cm} \times 10\text{cm} \times 10\text{cm} = 1000\text{cm}^3$



1dm^3 or 1 litre

A cm^3 is equivalent to a cube
 $1\text{cm} \times 1\text{cm} \times 1\text{cm}$



1cm^3

$1\text{ dm}^3 = 1000\text{ cm}^3$ or 1000mL

To convert cm^3 into dm^3 divide by 1000

Example 11 What is the concentration of solution made by dissolving 5.00g of Na_2CO_3 in 250 cm^3 water?

$$\text{amount} = \frac{\text{mass}}{M_r}$$

$$= 5 / (23.0 \times 2 + 12 + 16 \times 3)$$

$$= 0.0472\text{ mol}$$

$$\text{conc} = \frac{\text{amount}}{\text{Volume}}$$

$$= 0.0472 / 0.25$$

$$= 0.189\text{ mol dm}^{-3}$$

Example 12 What is the concentration of solution made by dissolving 10kg of Na_2CO_3 in 0.50 m^3 water?

$$\text{amount} = \frac{\text{mass}}{M_r}$$

$$= 10\,000 / (23.0 \times 2 + 12 + 16 \times 3)$$

$$= 94.2\text{ mol}$$

$$\text{conc} = \frac{\text{amount}}{\text{Volume}}$$

$$= 94.2 / 500$$

$$= 0.19\text{ mol dm}^{-3}$$

Mass Concentration

The concentration of a solution can also be measured in terms of mass of solute per volume of solution

$$\text{Mass Concentration} = \frac{\text{mass}}{\text{volume}}$$

Unit of mass concentration: g dm^{-3}

Unit of Mass **g**

Unit of Volume: **dm^3**

To turn concentration measured in mol dm^{-3} into concentration measured in g dm^{-3} multiply by *Mr* of the substance

$$\text{conc in g dm}^{-3} = \text{conc in mol dm}^{-3} \times M_r$$

The concentration in g dm^{-3} is the same as the mass of solute dissolved in 1dm^3

Ions dissociating

When soluble ionic solids dissolve in water they will dissociate into separate ions. This can lead to the concentration of ions differing from the concentration of the solute.

Example 13

If 5.86g (0.1 mol) of sodium chloride (NaCl) is dissolved in 1 dm^3 of water then the concentration of sodium chloride solution would be 0.1mol dm^{-3} .

However the 0.1mol sodium chloride would split up and form 0.1 mol of sodium ions and 0.1 mol of chloride ions. The concentration of sodium ions is therefore 0.1 mol dm^{-3} and the concentration of chloride ions is also 0.1 mol dm^{-3}



0.1mol	0.1mol	0.1mol
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Example 14

If 9.53g (0.1 mol) of magnesium chloride (MgCl_2) is dissolved in 1 dm^3 of water then the concentration of magnesium chloride solution ($\text{MgCl}_2\text{ aq}$) would be 0.1mol dm^{-3} .

However the 0.1mol magnesium chloride would split up and form 0.1 mol of magnesium ions and 0.2 mol of chloride ions. The concentration of magnesium ions is therefore 0.1 mol dm^{-3} and the concentration of chloride ions is now 0.2 mol dm^{-3}



0.1mol	0.1mol	0.2mol
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Making a solution

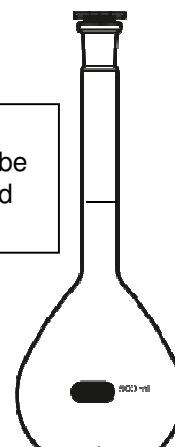
- Weigh the sample bottle containing the required mass of solid on a 2 dp balance
- Transfer to beaker and reweigh sample bottle
- Record the difference in mass

- Add 100cm^3 of distilled water to the beaker. Use a glass rod to stir to help dissolve the solid.

- Sometimes the substance may not dissolve well in cold water so the beaker and its contents could be heated gently until all the solid had dissolved.

- Pour solution into a 250cm^3 graduated flask via a funnel.
- Rinse beaker and funnel and add washings from the beaker and glass rod to the volumetric flask.
- make up to the mark with distilled water using a dropping pipette for last few drops.
- Invert flask several times to ensure uniform solution.

Alternatively the known mass of solid in the weighing bottle could be transferred to beaker, washed and washings added to the beaker.



Remember to fill so the bottom of the meniscus sits on the line on the neck of the flask. With dark liquids like potassium manganate it can be difficult to see the meniscus.

Dilutions

Diluting a solution

- Pipette 25cm³ of original solution into a 250cm³ volumetric flask
- make up to the mark with distilled water using a dropping pipette for last few drops.
- Invert flask several times to ensure uniform solution.

Using a volumetric pipette is more accurate than a measuring cylinder because it has a smaller uncertainty

Use a teat pipette to make up to the mark in volumetric flask to ensure volume of solution accurately measured and one doesn't go over the line

Calculating Dilutions

Diluting a solution will not change the amount of moles of solute present but increase the volume of solution and hence the concentration will lower

amount = volume x concentration

If amount of moles does not change then

Original volume x original concentration = new diluted volume x new diluted concentration

so

$$\text{new diluted concentration} = \frac{\text{original concentration} \times \text{Original volume}}{\text{new diluted volume}}$$

The new diluted volume will be equal to the original volume of solution added + the volume of water added.

Example 15

If 50 cm³ of water are added to 150 cm³ of a 0.20 mol dm⁻³ NaOH solution, what will the concentration of the diluted solution be?

new diluted concentration = $\frac{\text{original concentration} \times \text{Original volume}}{\text{new diluted volume}}$

$$\begin{aligned}\text{new diluted concentration} &= 0.20 \times \frac{0.150}{0.200} \\ &= 0.15 \text{ mol dm}^{-3}\end{aligned}$$

Example 16

What volume of water in cm³ must be added to dilute 5.00 cm³ of 1.00 mol dm⁻³ hydrochloric acid so that it has a concentration of 0.050 mol dm⁻³?

$$\begin{aligned}\text{Amount in mol original solution} &= \text{conc} \times \text{vol} \\ &= 1.00 \times 0.005 \\ &= 0.005\end{aligned}$$

$$\begin{aligned}\text{New volume} &= \text{amount} / \text{conc} \\ &= 0.005 / 0.05 \\ &= 0.1 \text{ dm}^3 = 100 \text{ cm}^3\end{aligned}$$

$$\text{Volume of water added} = 100 - 5 = 95 \text{ cm}^3$$

Ideal Gas Equation

The ideal gas equation applies to all gases and mixtures of gases. If a mixture of gases is used the value n will be the total moles of all gases in the mixture.

The biggest problems students have with this equation is choosing and converting to the correct units, so pay close attention to the units.

$$PV = nRT$$

Unit of Pressure (P): Pa
Unit of Volume (V): m^3
Unit of Temp (T): K
 n = moles
 $R = 8.31 \text{ JK}^{-1}\text{mol}^{-1}$

Example 17: What is the mass of Cl_2 gas that has a pressure of 100kPa, temperature 20°C , volume 500cm^3 . ($R = 8.31$)

$$\text{moles} = PV/RT$$

$$= 100\,000 \times 0.0005 / (8.31 \times 293)$$

$$= 0.0205 \text{ mol}$$

$$\text{Mass} = \text{amount} \times M_r$$

$$= 0.0205 \times (35.5 \times 2)$$

$$= 1.46 \text{ g}$$

$$100 \text{ kPa} = 100\,000 \text{ Pa}$$

$$20^\circ\text{C} = 20 + 273 = 293\text{K}$$

$$500 \text{ cm}^3 = 0.0005 \text{ m}^3$$

Converting temperature

$$^\circ\text{C} \rightarrow \text{K add } 273$$

Example 18: 0.150g of a volatile liquid was injected into a sealed gas syringe. The gas syringe was placed in an oven at 70°C at a pressure of 100kPa and a volume of 80cm^3 was measured. What is the M_r of the volatile liquid? ($R = 8.31$)

$$\text{moles} = PV/RT$$

$$= 100\,000 \times 0.00008 / (8.31 \times 343)$$

$$= 0.00281 \text{ mol}$$

$$M_r = \text{mass/amount}$$

$$= 0.15 / 0.00281$$

$$= 53.4 \text{ g mol}^{-1}$$

$$100 \text{ kPa} = 100\,000 \text{ Pa}$$

$$80 \text{ cm}^3 = 0.00008 \text{ m}^3$$

Using a gas syringe

Gas syringes can be used for a variety of experiments where the volume of a gas is measured, possibly to work out moles of gas or to follow reaction rates.

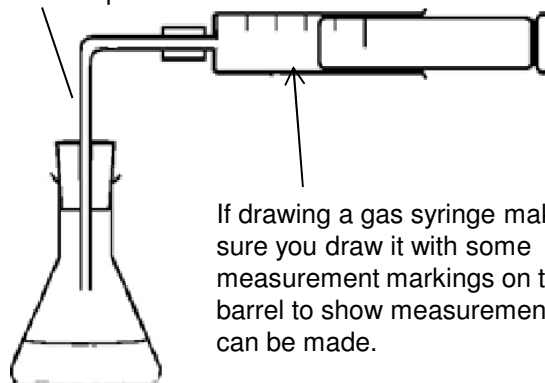
The volume of a gas depends on pressure and temperature so when recording volume it is important to note down the temperature and pressure of the room.

Moles of gas can be calculated from gas volume (and temperature and pressure) using ideal gas equation $PV = nRT$

Potential errors in using a gas syringe

- gas escapes before bung inserted
- syringe sticks
- some gases like carbon dioxide or sulphur dioxide are soluble in water so the true amount of gas is not measured.

Make sure you don't leave gaps in your diagram where gas could escape



If drawing a gas syringe make sure you draw it with some measurement markings on the barrel to show measurements can be made.

Changing the Conditions of a gas

Questions may involve the same amount of gas under different conditions.

Example 19

40 cm³ of oxygen and 60 cm³ of carbon dioxide, each at 298 K and 100 kPa, were placed into an evacuated flask of volume 0.50 dm³. What is the pressure of the gas mixture in the flask at 298 K?

There are two approaches to solving this

1. Work out amount in mol of gas using ideal gas equation then put back into ideal gas equation with new conditions
2. Or combine the equation $n = PV/RT$ as on right

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Can do this as moles of gas do not change

As Temperature is the same can make the above equation $P_1 V_1 = P_2 V_2$

$$\begin{aligned} P_2 &= P_1 V_1 / V_2 \\ &= 100000 \times 1 \times 10^{-4} / 5 \times 10^{-4} \\ &= 20\,000 \text{ Pa} \end{aligned}$$

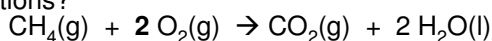
Reacting Volumes of Gas

Equal volumes of any gases measured under the same conditions of temperature and pressure contain equal numbers of molecules (or atoms if the gas is monatomic)

1 mole of any gas at room pressure (1 atm) and room temperature 25°C will have the volume of 24 dm³


Volumes of gases reacting in a balanced equation can be calculated by simple ratio

Example 20 If one burnt 500 cm³ of methane at 1 atm and 300 K what volume of Oxygen would be needed and what volume of CO₂ would be given off under the same conditions?

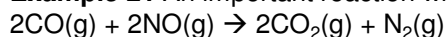


1 mole 2 mole 1 mole

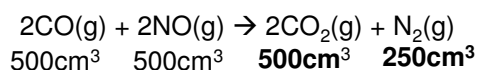
500 cm³ 1 dm³ 500 cm³


Simply multiply
gas volume x2

Example 21 An important reaction which occurs in the catalytic converter of a car is

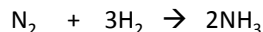


In this reaction, when 500 cm³ of CO reacts with 500 cm³ of NO at 650 °C and at 1 atm. Calculate the **total** volume of gases produced at the same temperature and pressure ?



total volume of gases produced = 750 cm³

Converting quantities between different substances using a balanced equation



The balancing (stoichiometric) numbers are mole ratios
e.g. 1 mol of N_2 reacts with 3 mol of H_2 to produce 2 mol of NH_3

Typically we are given a quantity of one substance and are asked to work out a quantity for another substance in the reaction. Any of the above three equations can be used.

Step 1:

Use one of the above 3 equations to convert any given quantity into amount in mol
Mass \rightarrow amount
Volume of gas \rightarrow amount
Conc and vol of solution \rightarrow amount

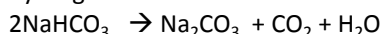
Step 2:

Use balanced equation to convert amount in mol of initial substance into amount in mol of second substance

Step 3

Convert amount, in mol, of second substance into quantity question asked for using relevant equation
e.g. amount, $M_r \rightarrow$ mass
Amount gas \rightarrow vol gas
amount, vol solution \rightarrow conc

Example 22: What mass of Carbon dioxide would be produced from heating 5.50 g of sodium hydrogencarbonate?

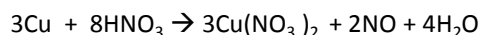


Step 1: work out amount, in mol, of sodium hydrogencarbonate
amount = mass / M_r
= 5.5 / 84
= 0.0655 mol

Step 2: use balanced equation to give amount in mol of CO_2
2 moles NaHCO_3 : 1 moles CO_2
So 0.0655 HNO_3 : 0.0328 mol CO_2

Step 3: work out mass of CO_2
Mass = amount $\times M_r$
= 0.0328 \times 44.0
= 1.44g

Example 23: What mass of Copper would react completely with 150 cm^3 of 1.60M nitric acid?

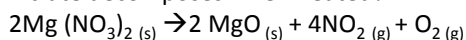


Step 1: work out moles of nitric acid
amount = conc \times vol
= 1.6 \times 0.15
= 0.24 mol

Step 2: use balanced equation to give moles of Cu
8 moles HNO_3 : 3 moles Cu
So 0.24 HNO_3 : 0.09 (0.24 \times $\frac{3}{8}$) mol Cu

Step 3: work out mass of Cu
Mass = amount $\times M_r$
= 0.09 \times 63.5
= 5.71g

Example 24: What is the total volume of gas produced in dm^3 at 333K and 100kPa when 0.651 g of magnesium nitrate decomposes when heated?

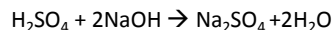


Step 1: work out moles of magnesium nitrate
Moles = mass / M_r
= 0.651 / 148.3
= 0.00439 mol

Step 2: use balanced equation to give moles of gas produced
2 moles $\text{Mg}(\text{NO}_3)_2$: 4 $\text{NO}_2(\text{g})$ + $\text{O}_2(\text{g})$ ie 5 moles of gas
So 0.00439 $\text{Mg}(\text{NO}_3)_2$: 0.01098 (0.00439 \times $\frac{5}{2}$) moles gas

Step 3: work out volume of gas
Volume = nRT/P
= (0.01098 \times 8.31 \times 333) / 100000
= 0.000304 m^3
= 0.303 dm^3

Example 25: 23.6 cm^3 of H_2SO_4 neutralised 25.0 cm^3 of 0.150M NaOH. What is the concentration of the H_2SO_4 ?



Step 1: work out moles of sodium hydroxide
amount = conc \times vol
= 0.150 \times 0.025
= 0.00375 mol

Step 2: use balanced equation to give moles of H_2SO_4
2 moles NaOH : 1 moles H_2SO_4
So 0.00375 NaOH : 0.001875 mol H_2SO_4

Step 3 work out concentration of H_2SO_4
conc = amount / Volume
= 0.001875 / 0.0236
= 0.0794 mol dm^{-3}

Titration

The method for carrying out the titration

- rinse equipment** (burette with acid, pipette with alkali, conical flask with distilled water)
- pipette 25 cm³ of alkali into conical flask**
- touch surface of alkali with pipette** (to ensure correct amount is added)
- adds acid solution from burette**
- make sure the jet space** in the burette **is filled** with acid
- add a few drops of indicator** and refer to colour change at end point
- phenolphthalein [pink (alkali) to colourless (acid): end point pink colour just disappears] [use if NaOH is used]
- methyl orange [yellow (alkali) to red (acid): end point orange] [use if HCl is used]
- use a white tile underneath the flask to help observe the colour change
- add acid to alkali whilst **swirling the mixture** and **add acid dropwise at end point**
- note burette reading** before and after addition of acid
- repeats titration until at least 2 concordant results** are obtained- two readings within 0.1 of each other

There will be a small amount of the liquid left in the pipette when it has been emptied. Do not force this out. The pipette is calibrated to allow for it.

If the jet space in the burette is not filled properly prior to commencing the titration it will lead to errors if it then fills during the titration, leading to a larger than expected titre reading.

Working out average titre results

Only make an average of the concordant titre results

Recording results

- Results should be clearly recorded in a table
- Result should be recorded in full (i.e. both initial and final readings)
- Record titre volumes to 2dp (0.05 cm³)**

Testing batches

In quality control it will be necessary to do titrations/testing on several samples as the amount/concentration of the chemical being tested may vary between samples.

Safety precautions

Acids and alkalis are corrosive (at low concentrations acids are irritants)

Wear eye protection and gloves

If spilled immediately wash affected parts after spillage

If substance is unknown treat it as potentially toxic and wear gloves.

A conical flask is used in preference to a beaker because it is easier to swirl the mixture in a conical flask without spilling the contents.

Distilled water can be added to the conical flask during a titration to wash the sides of the flask so that all the acid on the side is washed into the reaction mixture to react with the alkali. It does not affect the titration reading as water does not react with the reagents or change the number of moles of acid added.

Only distilled water should be used to wash out conical flasks between titrations because it does not add and extra moles of reagents

If **2 or 3 values are within 0.10cm³** and therefore **concordant** or close then we can say results are accurate and **reproducible** and **the titration technique is good/ consistent**

Titrating mixtures

If titrating a mixture to work out the concentration of an active ingredient it is necessary to consider if the mixture contains other substances that have acid base properties.

If they don't have acid base properties we can titrate with confidence.

More complicated titration calculations- taking samples

Example 26: A 25.0cm³ sample of vinegar was diluted in a 250cm³ volumetric flask. This was then put in a burette and 23.10cm³ of the diluted vinegar neutralised 25.0 cm³ of 0.100 M NaOH. What is the concentration of the vinegar in gdm⁻³ ?



Step 1: work out amount, in mol, of sodium hydroxide
 amount = conc x vol
 = 0.10 x 0.025
 = 0.00250 mol

Step 2: use balanced equation to give moles of CH₃CO₂H
 1 moles NaOH : 1 moles CH₃CO₂H
 So 0.00250 NaOH : 0.00250 moles CH₃CO₂H

Step 3 work out concentration of diluted CH₃CO₂H in 23.1 (and 250 cm³) in moldm⁻³

conc = amount/Volume
 = 0.00250 / 0.0231
 = 0.108 mol dm⁻³

Step 4 work out concentration of original concentrated CH₃CO₂H in 25cm³ in moldm⁻³

conc = 0.108 x 10 = 1.08 mol dm⁻³

Step 5 work out concentration of CH₃CO₂H in original concentrated 25 cm³ in gdm⁻³

conc in gdm⁻³ = conc in mol dm⁻³ x Mr
 = 1.08 x 60 = 64.8 g dm⁻³

Example 27. An unknown metal carbonate reacts with hydrochloric acid according to the following equation.
 $\text{M}_2\text{CO}_3(\text{aq}) + 2\text{HCl}(\text{aq}) \rightarrow 2\text{MCl}(\text{aq}) + \text{CO}_2(\text{g}) + \text{H}_2\text{O}(\text{l})$
 A 3.96 g sample of M₂CO₃ was dissolved in distilled water to make 250 cm³ of solution. A 25.0 cm³ portion of this solution required 32.8 cm³ of 0.175 mol dm⁻³ hydrochloric acid for complete reaction. Calculate the Mr of M₂CO₃ and identify the metal M

1. Calculate the number of moles of HCl used

amount = conc x vol
 = 0.175 x 0.0328
 = 0.00574 mol

2. Work out number of moles of M₂CO₃ in 25.0 cm³ put in conical flask

use balanced equation to give moles of M₂CO₃
 2 mol HCl : 1 mol M₂CO₃
 So 0.00574 NaOH : 0.00287 moles M₂CO₃

3. Calculate the number of moles M₂CO₃ acid in original 250 cm³ of solution

Moles in 250cm³ = 0.00287 x 10
 = 0.0287

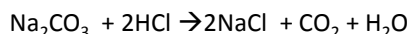
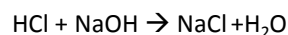
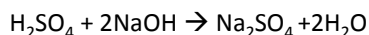
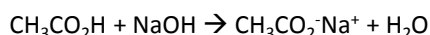
4. work out the Mr of M₂CO₃

Mr = mass / amount
 = 3.96 / 0.0287 = 138.0

5. Work out Ar of M = $\frac{138-12-16 \times 3}{2}$

Ar of M = 39 M = potassium

Common Titration Equations



Example 28

950 mg of impure calcium carbonate tablet was crushed. 50.0 cm³ of 1.00 mol dm⁻³ hydrochloric acid, an excess, was then added. After the tablet had reacted, the mixture was transferred to a volumetric flask. The volume was made up to exactly 100 cm³ with distilled water. 10.0 cm³ of this solution was titrated with 11.1cm³ of 0.300 mol dm⁻³ sodium hydroxide solution.

What is the percentage of CaCO₃ by mass in the tablet?

1. Calculate the number of moles of sodium hydroxide used

amount = conc x vol
 = 0.30 x 0.0111
 = 0.00333 mol

2. Work out number of moles of hydrochloric acid left in 10.0 cm³

use balanced equation to give moles of HCl
 1 mol NaOH : 1 mol HCl
 So 0.00333 NaOH : 0.00333 moles HCl

3. Calculate the number of moles of hydrochloric acid left in 100 cm³ of solution

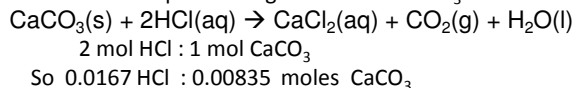
Moles in 100cm³ = 0.00333 x 10
 = 0.0333

4. Calculate the number of moles of HCl that reacted with the indigestion tablet.

In original HCl 50.0 cm³ of 1.00 mol dm⁻³ there are 0.05mol

moles of HCl that reacted with the indigestion tablet. = 0.05 - 0.0333
 = 0.0167

5 Use balanced equation to give moles of CaCO₃



6. work out the mass of CaCO₃ in original tablet

mass = amount x Mr
 = 0.00835 x 100 = 0.835 g

percentage of CaCO₃ by mass in the tablet = 0.835/0.950 x 100
 = 87.9 %

Uncertainty

Readings and Measurements

Readings

the values found from a single judgement when using a piece of equipment

Measurements

the values taken as the difference between the judgements of two values (e.g. using a burette in a titration)

The uncertainty of a reading (one judgement) is at least ± 0.5 of the smallest scale reading.
The uncertainty of a measurement (two judgements) is at least ± 1 of the smallest scale reading.

Calculating Apparatus Uncertainties

Each type of apparatus has a sensitivity uncertainty

- balance ± 0.001 g
- volumetric flask ± 0.1 cm³
- 25 cm³ pipette ± 0.1 cm³
- burette ± 0.05 cm³

Calculate the percentage error for each piece of equipment used by

$$\% \text{ uncertainty} = \pm \frac{\text{uncertainty}}{\text{Measurement made on apparatus}} \times 100$$

e.g. for pipette

$$\% \text{ uncertainty} = 0.05 / 25 \times 100$$

To calculate the maximum percentage apparatus uncertainty in the final result add all the individual equipment uncertainties together.

To decrease the apparatus uncertainties you can either decrease the sensitivity uncertainty by using apparatus with a greater resolution (finer scale divisions) or you can increase the size of the measurement made.

Uncertainty of a measurement using a burette.

If the burette used in the titration had an uncertainty for each reading of ± 0.05 cm³ then during a titration two readings would be taken so the uncertainty on the titre volume would be ± 0.10 cm³.

Reducing uncertainties in a titration

Replacing measuring cylinders with pipettes or burettes which have lower apparatus uncertainty will lower the error

To reduce the uncertainty in a burette reading it is necessary to make the titre a larger volume. This could be done by: increasing the volume and concentration of the substance in the conical flask or by decreasing the concentration of the substance in the burette.

If looking at a series of measurements in an investigation the experiments with the smallest readings will have the highest experimental uncertainties.

Reducing uncertainties in measuring mass

Using a more accurate balance or a larger mass will reduce the uncertainty in weighing a solid
Weighing sample before and after addition and then calculating difference will ensure a more accurate measurement of the mass added.

Calculating the percentage difference between the actual value and the calculated value

If we calculated an Mr of 203 and the real value is 214, then the calculation is as follows:

$$\text{Calculate difference } 214 - 203 = 11$$

$$\% = 11 / 214 \times 100$$
$$= 5.41\%$$

If the %**uncertainty** due to the apparatus < percentage difference between the actual value and the calculated value then there is a discrepancy in the result due to other errors.

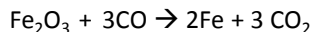
If the %**uncertainty** due to the apparatus > percentage difference between the actual value and the calculated value then there is no discrepancy and all errors in the results can be explained by the sensitivity of the equipment.

% Yield

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

% yield in a process can be lowered through incomplete reactions, side reactions, losses during transfers of substances, losses during purification stages.

Example 29: 25.0g of Fe_2O_3 was reacted and it produced 10.0g of Fe. What is the percentage yield?

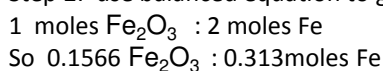


First calculate maximum mass of Fe that could be produced

Step 1: work out amount in mol of Iron oxide

$$\begin{aligned}\text{amount} &= \text{mass} / M_r \\ &= 25 / 159.6 \\ &= 0.1566 \text{ mol}\end{aligned}$$

Step 2: use balanced equation to give moles of Fe



Step 3: work out mass of Fe

$$\begin{aligned}\text{Mass} &= \text{amount} \times M_r \\ &= 0.313 \times 55.8 \\ &= 17.5\text{g}\end{aligned}$$

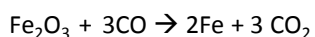
$$\begin{aligned}\% \text{ yield} &= (\text{actual yield} / \text{theoretical yield}) \times 100 \\ &= (10 / 17.48) \times 100 \\ &= 57.2\%\end{aligned}$$

% Atom Economy

$$\text{percentage atom economy} = \frac{\text{Mass of useful products}}{\text{Mass of all reactants}} \times 100$$

Do take into account balancing numbers when working out % atom economy.

Example 30: What is the % atom economy for the following reaction where Fe is the desired product assuming the reaction goes to completion?



$$\begin{aligned}\% \text{ atom economy} &= \frac{(2 \times 55.8)}{(2 \times 55.8 + 3 \times 16) + 3 \times (12 + 16)} \times 100 \\ &= 45.8\%\end{aligned}$$

Sustainable chemistry requires chemists to design processes with high atom economy that minimise production of waste products.

Reactions where there is only one product where all atoms are used making product are ideal and have 100% atom economy.
e.g. $\text{CH}_2=\text{CH}_2 + \text{H}_2 \rightarrow \text{CH}_3\text{CH}_3$

If a process does have a side, waste product the economics of the process can be improved by selling the bi-product for other uses

Reactions of Acids

A **Salt** is formed when the H^+ ion of an acid is replaced by a metal ion or an ammonium ion

The most common strong acids are :
Hydrochloric (HCl), sulphuric (H_2SO_4) and nitric (HNO_3) acid;

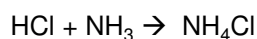
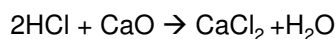
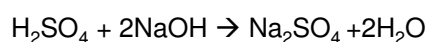
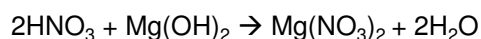
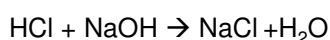
Neutralisation reactions form salts

Bases neutralise acids. Common bases are metal oxides, metal hydroxides and ammonia.

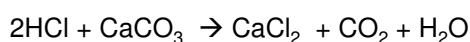
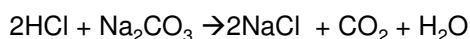
An Alkali is a soluble base that releases OH^- ions in aqueous solution;
The most common alkalis are sodium hydroxide (NaOH), potassium hydroxide (KOH) and aqueous ammonia (NH_3)

Common Acid Reaction Equations

ACID + BASE → SALT + WATER

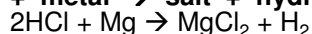


Acid + Carbonate → Salt + Water + Carbon Dioxide



Observations : In carbonate reactions there will be Effervescence due to the CO_2 gas evolved and the solid carbonate will dissolve. The temperature will also increase.

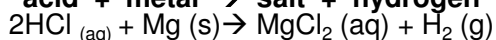
acid + metal → salt + hydrogen



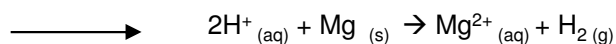
Observations: These reaction will effervesce because H_2 gas is evolved and the metal will dissolve

Ionic equations for reactions of acids with metals, carbonates, bases and alkalis

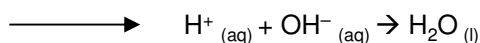
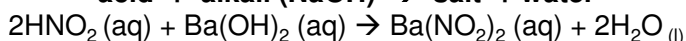
acid + metal → salt + hydrogen



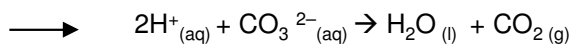
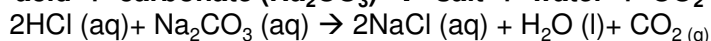
Ionic Equations



acid + alkali (NaOH) → salt + water

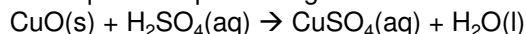


acid + carbonate (Na_2CO_3) → salt + water + CO_2



Example 22

The equation representing the reaction between copper(II) oxide and dilute sulfuric acid is



What is the ionic equation?

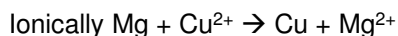
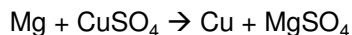
Only sulphate ion is a spectator ion in this case because it's the only ion not changing state



Displacement Reactions

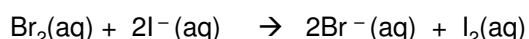
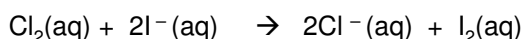
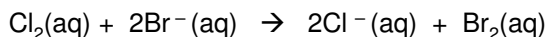
Metal displacement reactions

More reactive metals will displace less reactive metals from their compounds



Halogen displacement reactions

A halogen that is a strong oxidising agent will displace a halogen that has a lower oxidising power from one of its compounds



See topic 4b Halogens for more detail

Precipitation Reactions

Insoluble salts can be made by mixing appropriate solutions of ions so that a **precipitate** is formed

Lead nitrate (aq) + sodium chloride (aq) \rightarrow **lead chloride (s)** + sodium nitrate (aq)

These are called **precipitation** reactions. A **precipitate is a solid**

When making an insoluble salt, normally the salt would be removed by **filtration**, washed with distilled water to remove soluble impurities and then **dried on filter paper**

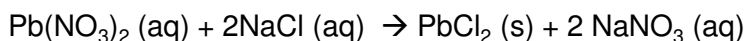
Writing ionic equations for precipitation reactions

We usually write ionic equations to show precipitation reactions. Ionic equations only show the ions that are reacting and leave out spectator ions.

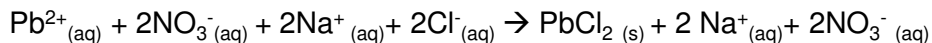
Spectator ions are ions that are not

- Not changing state
- Not changing oxidation number

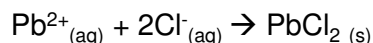
Take full equation



Separate (aq) solutions into ions



Cancel out spectator ions leaving ionic equation



Hazards and Risks

A **hazard** is a substance or procedure that can have the potential to do harm.

Typical hazards are toxic/flammable/harmful/irritant/corrosive/oxidizing/carcinogenic

RISK: This is the probability or chance that harm will result from the use of a hazardous substance or a procedure

In the laboratory we try to minimise the risk

Irritant - dilute acid and alkalis- wear goggles

Corrosive- stronger acids and alkalis wear goggles

Flammable – keep away from naked flames

Toxic – wear gloves- avoid skin contact- wash hands after use

Oxidising- Keep away from flammable / easily oxidised materials

Hazardous substances in low concentrations or amounts will not pose the same risks as the pure substance.

Safely dealing with excess acid

Sodium hydrogen carbonate (NaHCO_3) and calcium carbonate (CaCO_3) are good for neutralising excess acid in the stomach or acid spills because they are not corrosive and will not cause a hazard if used in excess. They also have no toxicity if used for indigestion remedies but the CO_2 produced can cause wind. Magnesium hydroxide is also suitable for dealing with excess stomach acid as it has low solubility in water and is only weakly alkaline so not corrosive or dangerous to drink (unlike the strong alkali sodium hydroxide). It will also not produce any carbon dioxide gas.