Relative Formula Mass (M_r)

The **relative atomic mass (A_r)** of an element is an elements relative mass compared to the mass of an atom of carbon-12. A_r values are given in the periodic table.

The **relative formula mass (M_r)** of a compound is the **sum** of all the relative atomic masses (A_r) of the atoms in the formula.

Example 1: hydrochloric acid (HCl) consists of one hydrogen atom (A_r 1) and one chlorine atom (A_r 35.5).

The M_r of HCl = 1 + 35.5 = 36.5

Example 2: sulfuric acid (H_2SO_4) consists of two hydrogen atoms (A_r 1), one sulfur atom (A_r 32) and four oxygen atoms (A_r 16).

The M_r of H_2SO_4 = (1 × 2) + 32 + (16 × 4) = 98

Neither A_r or M_r values have any units.

Law of Conservation of Mass

The **law of conservation of mass** states that during a chemical reaction, no atoms are lost or made.

For example: $2Mg + O_2 \longrightarrow 2MgO$

In a chemical reaction, mass is never lost or gained. What **goes in** must **come out**. The **total mass of the reactants** at the beginning of the chemical reaction **equals** the **total mass of the products** made at the end of the reaction.

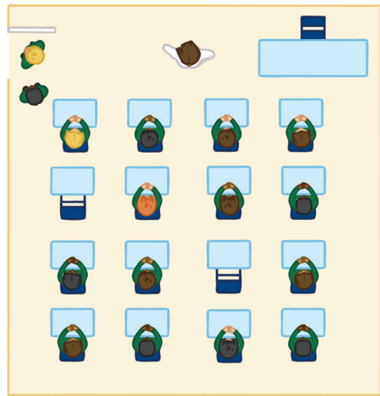
For example, imagine if we used building bricks to represent the atoms in a chemical reaction: atoms, like building bricks, can be completely rearranged. However, the total mass of the atoms will stay the same. Rearranging the building blocks in different structures takes a little **energy**, just like in a chemical reaction.

Reactions in Closed and Non-Enclosed Systems

If a reaction occurs in a **closed system**, the **mass** in a chemical reaction will remain **constant**.

In an **non-enclosed system, changes in mass can occur,** such as when a gas is released. It is important to remember that **no atoms are created or destroyed,** they are just **rearranged**. If a gas escapes a non-enclosed system, the total mass will look as if it has decreased. Similarly, if a gas is gained, the total mass will look as if it has increased. However, the **total mass** will **remain the same** if the mass of the gas is included in the reaction calculation.

In this **closed system** (the classroom), the mass in the reaction remains constant. As the system is a closed one, no children are allowed to leave or enter.



In this **non-enclosed system** (the classroom), the mass in the reaction can look as if it has changed as children are allowed to leave the classroom at any time.

Uncertainty

Whenever a measurement is made, there is always some degree of **uncertainty** about the result. Uncertainty is a **measure** of the **variability** in scientific data.

Uncertainty can be measured by considering the **resolution** of the scientific equipment being used or from the **range** of a set of scientific data.

There are two types of errors: **random error** and **systematic error.**

Random errors may be caused by **human error** such as a poor technique when taking measurements or by **equipment** that is **faulty**. For example, three mass balances all showing different mass values for the same object. Random errors are **random** and not something that can be predicted.

Systematic errors are errors that are produced **consistently**: if the experiment is repeated, the **same error** will occur. For example, not taring a mass balance properly or problems with the experimental method.

$$\text{uncertainty} = \frac{\text{range of results}}{2}$$

The **range** is the difference between the **largest** and **smallest** value.

For example, student A carried out a practical to determine how much dilute sulfuric acid is needed to react with exactly 50.0cm^3 of a sodium hydroxide solution.

Repeat	1	2	3	Mean
Volume of H_2SO_4 needed to react with 50.0cm^3 of NaOH.	23.13	24.00	23.56	23.56

Calculate the range:

range = 24.00 – 23.13 = 0.87cm^3

Calculate the uncertainty of the mean:

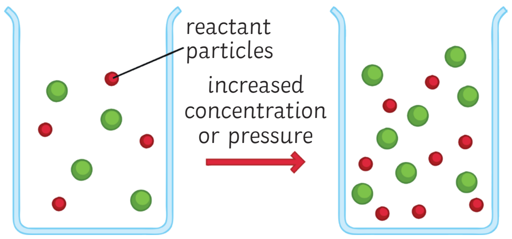
uncertainty = 0.87 ÷ 2 = 0.44cm^3

The mean with uncertainty:

23.56 ± 0.44cm^3

Concentration of Solutions

Concentration is a **measure** of the amount of a **substance** in a **volume** of liquid. The higher the concentration, the more particles of a substance are present in the solution.



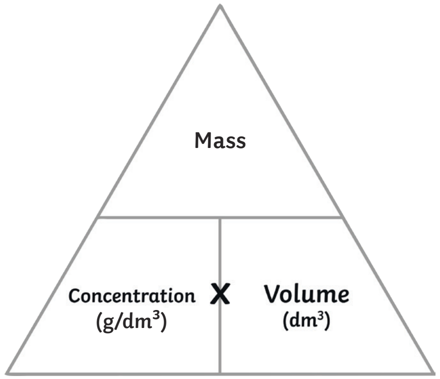
In chemistry, there are two ways to measure the concentration of a solution. This can be done by calculating the **mass** of the substance in grams or by calculating the number of **moles**.

In order to calculate concentration, you must be working in dm^3.

If it is not, it may mean that you need to do a conversion.

$cm^3 \longrightarrow dm^3 = \div 1000$

$m^3 \longrightarrow dm^3 = \times 1000$



Calculate the **concentration** of a solution with a mass of 2.15g and a volume of $5dm^3$.

concentration = mass ÷ volume

concentration = $2.15g \div 5dm^3$

concentration = $0.43g/dm^3$

Calculate the **mass** of sodium chloride that you would need to dissolve in $400cm^3$ of water to make a $20g/dm^3$ volume solution.

mass = concentration × volume

convert $cm^3 \longrightarrow dm^3$

$400cm^3 \div 1000 = 0.40dm^3$

mass = $20g/dm^3 \times 0.40dm^3$ = 8g

Calculate the **volume** of liquid required to add to 8.80g of a solid to make $42g/dm^3$ solution.

volume = mass ÷ concentration

volume = $8.80g \div 42g/dm^3$

concentration = $0.210dm^3$

The Mole – Higher Tier Only

When we talk about moles, we are not talking about the moles that live underground.

A **mole** (mol) is a **measurement** that is used in chemistry.

Example 1

Look at this reaction:

$2Mg + O_2 \longrightarrow 2MgO$

The reaction shows that **two moles** of magnesium react with oxygen to produce **two moles** of magnesium oxide. Using moles in a **balanced symbol equation** shows the **ratio** of **reactants** to **products**.

Avogadro's Constant

1 mole = 6.02×10^{23}

The number is known as **Avogadro's constant or Avogadro's number** and is named after the Italian scientist Amedeo Avogadro. The mole is abbreviated to **mol**.

This number is very important and one that you should remember. The mass of one mole of a substance in grams is equal to its relative formula mass. For example, one mole of carbon-12 has a mass of 12g

A mole is the amount of a substance that contains **6.02×10^{23}** particles of that substance. The particles could be atoms, molecules, ions or electrons.

For example, 1 mole of carbon will contain the same number of atoms **(6.02×10^{23})** as you would have molecules in 1 mole of water.

Calculating the Number of Particles

The number of particles can be calculated using Avogadro's constant if the number of moles is known.

In chemistry, Avogadro's constant is given the symbol N_A. To calculate the number of particles in a substance, the following equation can be used:

$\mathbf{N = n \times N_A}$

N = the number of particles in a substance

n = the number of moles (mol)

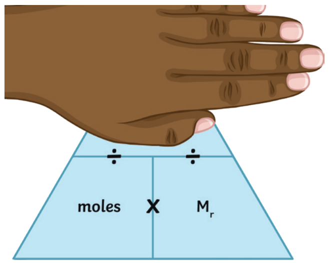
N_A = Avogadro's constant 6.02×10^{23}

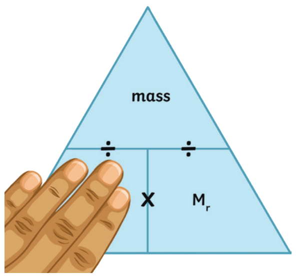
For example, calculate the number of helium molecules in 10 mol of helium.

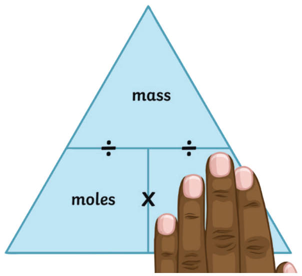
$\mathbf{N = n \times N_A}$

N = $10 \times (6.02 \times 10^{23}) = 6.022 \times 10^{24}$

Calculating Moles, Mass and M_r







Calculating Moles, Mass and M_r

Calculate the number of **moles** in 330g of K_2S.

K_2S consists of two potassium atoms (A_r 39) and one sulfur atom (A_r 32).

Calculate the M_r of the compound = $(39 \times 2) + 32 =$ **110**

moles = mass ÷ M_r

moles = 330 ÷ 110 = 3 moles

Calculate the **mass** of 0.9 moles of $Fe(NO_3)_3(H_2O)_9$.

Calculate the Mr of the compound.

$(16 \times 3) + 14 = 62$

$62 \times 3 =$ **186**

$(1 \times 2) + 16 = 18$

$18 \times 9 =$ **162**

$56 + 186 + 162 =$ **404**

mass = moles × M_r

mass = 0.9 × 404 = 363.6g

Relative Atomic Mass (A_r)

iron (Fe) = 56

oxygen (O) = 16

nitrogen (N) = 14

hydrogen (H) = 1

Amount of Substances in Equations – Higher Tier Only

How do we know the masses involved in the equation?

To work out the masses involved, write in the relative atomic mass (A_r) for an element and the relative formula mass (M_r) for a compound.

Example

Step 1: Write down the **balanced** symbol equation. $2Mg + O_2 \longrightarrow 2MgO$

Step 2: Write in the relative atomic and relative formula masses for the **reactants** and **products** involved in the chemical reaction.

$(2 \times 24) + (2 \times 16) \longrightarrow 2 \times (24 + 16)$

$48g + 32g \longrightarrow 80g$

Masses in Equations

$Fe + 2HCl \longrightarrow FeCl_2 + H_2$

$56 + 2\,(1 + 35.5) \longrightarrow (56 + 2(35.5) + (1 \times 2))$

$56g + 73g \longrightarrow 127g + 2g$

One mole of iron **reacts** with two moles of hydrochloric acid to **produce** one mole of iron chloride and one mole of hydrogen.

Calculate the **mass of water** made when burning **300g of methane**.

Step 1: Balance the equation.

$CH_4 + 2O_2 \longrightarrow 2H_2O + CO_2$

Step 2: Write down the relative formula mass of each compound.

$(12 + (1 \times 4)) + 2(16 \times 2) \longrightarrow 2((1 \times 2) + 16) + (12 + (16 \times 2))$

$16g + 64g \longrightarrow 36g + 44g$

Relative Atomic Mass (A_r)

Carbon (C) = 12

oxygen (O) = 16

hydrogen (H) = 1

We know from the equation that **16g of methane** reacts to produce **36g of water**.

The question asks us to calculate the mass of water made when burning **300g of methane**.

$\frac{\text{known mass}}{M_r} \times M_r \text{ of unknown mass}$

$\mathbf{\frac{300}{16} \times 36 = 675g}$

Limiting Reactants

A chemical reaction ends once one of the **reactants** is used up. The other reactants have nothing to react with and so some are left over.

The **limiting reactant** is the reactant that is **completely used up** in a chemical reaction. This reactant is the one that determines the amount of product that is made.

The reactant in **excess** is the one that is left over and could further react if there was another reactant to react with.

The **amount of product** that is produced during a chemical reaction is **dependent** upon the **amount of the limiting reactant**.

Calculating the maximum mass of a product formed during a chemical reaction can be done by the following:

a. Writing a balanced equation.

b. Calculating the mass (g) of the limiting reactant.

c. The A_r and M_r of the product and limiting reactant.

Determine the **maximum mass of hydrogen** that can be produced when 36g of magnesium (Mg A_r 24) reacts completely with excess hydrochloric acid (HCl) to produce magnesium chloride ($MgCl_2$) and hydrogen (H_2).

$$Mg + 2HCl \longrightarrow MgCl_2 + H_2$$

number of moles = mass ÷ A_r

number of moles = 36 ÷ 24 = 1.5 mol

From the equation, 1 mol of magnesium forms 1 mol of hydrogen. Therefore, 1.5 mol of magnesium forms 1.5 mol of hydrogen.

mass of hydrogen = M_r × number of moles

= 2 × 1.5

= 3g

Balancing Equations

By using the masses of the products and reactants, it is possible to work out the balancing numbers in an equation.

For example, 12g of magnesium (Mg A_r 24) reacts with 8g of oxygen (O_2 M_r 32) to produce magnesium oxide (MgO M_r 40). Determine the balanced symbol equation for the reaction.

Calculate the amount of each of the reactants.

Mg = 12 ÷ 24 = 0.5 mol

O_2 = 8 ÷ 32 = 0.25 mol

Divide both values by the smaller amount.

Mg = 0.5 ÷ 0.25 = 2

O_2 = 0.25 ÷ 0.25 = 1

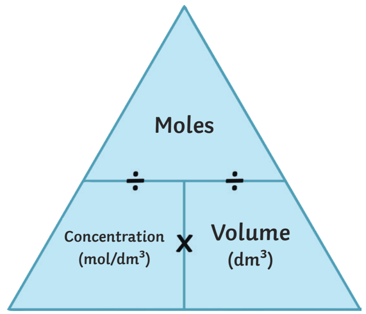
The equation shows that on the left-hand side of the equation, 2 mol of the reactant (Mg) reacts with 1 mol of oxygen. Using this information, it is then possible to balance the rest of the equation in the normal way.

$$2Mg + O_2 \longrightarrow 2MgO$$

Calculating Concentrations

The concentration of a solution can have the units g/dm^3 or mol/dm^3.

Concentration can be calculated using the mass of dissolved solute or the volume of the solvent or solution in dm^3.



Example:

Student A dissolved 1 mol of sodium hydroxide in 4dm^3 of water. Determine the concentration of the sodium hydroxide solution he made.

concentration = 1 mol ÷ 4dm^3

concentration = 0.25mol/dm^3

Converting between Units

To convert between g/dm^3 and mol/dm^3, the relative formula mass of the solute is used.

Multiply by the **M_r** to convert from **mol/dm^3 to g/dm^3**.

Divide by the **M_r** to convert from **g/dm^3 to mol/dm^3**.

Example:

Determine the concentration of 0.8mol/dm^3 sodium hydroxide (**M_r 40)** solution in g/dm^3.

concentration = 0.8 × 40 = 32g/dm^3

Volumes of Solutions

By rearranging the concentration equation, it is possible to calculate the amount of a solute in a given volume of solution if the concentration is known.

amount of solute (mol) = concentration (mol/dm^3) × volume (dm^3)

Example:

Determine the amount of 0.2mol/dm^3 sodium hydroxide in 75cm^3 of solution.

Step 1: Convert the volume to dm^3.

75cm^3 = 75.0 ÷ 1000 = 0.075dm^3

Step 2: amount of solute (mol) = concentration (mol/dm^3) × volume (dm^3)

= 0.2mol/dm^3 × 0.075dm^3

= 0.015 mol

Calculating the Mass

Using the example above, calculate the mass of sodium hydroxide (M_r 40) in 75cm^3 of solution.

mass = amount × M_r

mass = 0.015 mol × 40

mass = 0.6g

Percentage Yield – Chemistry Only

The percentage yield can be calculated from the following equation.

$$\text{percentage yield} = \frac{\text{actual mass of product made}}{\text{maxium theoretical mass of product}} \times 100$$

The **theoretical yield** is **the maximum mass** that can be made during a chemical reaction. The law of conservation states that during a chemical reaction, no atoms are lost or made. It's not always possible to obtain the maximum calculated amount of product.

The loss of product may be due to some of the product being lost when filtered. Some of the reactants may not react as expected and so may not produce enough product. The reaction may be a reversible one and as a consequence, the reaction may not go to completion.

Example:

1.8g of copper sulfate crystals are made during a chemical reaction. The theoretical yield for this reaction is **2.0g**. Calculate the percentage yield of copper sulfate.

$$\text{percentage yield} = \frac{1.8\text{g}}{2.0} \times 100$$

percentage yield = 90%

Atom Economy – Chemistry Only

The percentage atom economy can be calculated from the following equation.

$$\text{atom economy} = \frac{\text{relative formula mass of desired product from equation}}{\text{sum of relative formula masses of all reactants from equation}}$$

The **atom economy** is a measure of the amount of starting materials (reactants) that end up as **useful products**. It is important for sustainable development and for economic reasons to use reactions with **high atom economy**. However, not all atoms end up as the desired product and may form other products. We call these **byproducts**.

Example:

When glucose (M_r 180) is fermented, ethanol (M_r 46) is produced.

$C_6H_{12}O_6 \longrightarrow 2CH_3CH_2OH + 2CO_2$

Calculate the atom economy for this reaction.

$$\text{atom economy} = \frac{2 \times 46}{180} \times 100$$

atom economy = 51.1%

Reaction Pathways – Higher Tier Only

There is often more than one way to make a substance. Reaction pathways **describe** the **reactions** that have taken place to form the **desired product**. Choosing a particular pathway is dependent upon a number of factors:

1. percentage yield
2. atom economy
3. rate of reaction
4. position of the equilibrium
5. usefulness of any byproducts

The raw materials needed for a particular reaction may affect its chosen pathway. For example, crude oil is a **non-renewable resource**; the resource will run out if we continue to use it. However, plant sugars are **renewable** and can be replenished as long as other plants are replanted.

Ethanol can be made through the fermentation of glucose or the hydration of ethene.

Method of Ethanol Production	Percentage Yield (%)	Atom Economy (%)	Rate of Reaction
fermentation	15	51.1	low
hydration	95	100	high

The hydration of ethene has a 100% atom economy; all atoms react to form the desired product. On the other hand, fermentation has an atom economy of 51.1%. However, its rate of reaction is low in comparison to the hydration method and only has a percentage yield of 15%. Therefore, hydration is the best method for making ethanol.

A byproduct of the fermentation process is carbon dioxide. The gas is sold to fizzy drinks manufacturers to provide the bubbles for some well known fizzy drinks. As the byproduct produced is one that can be useful, it means that the atom economy can be increased to 100%.

Ethene hydration is a reversible reaction. The position of the equilibrium lies to the left. Therefore, only 5% of the ethene supplied to the reaction is actually converted to ethanol. A 95% yield is achieved by recirculating the unreacted ethene.

Avogadro's Law – Higher Tier Only

When the temperature and pressure stay the same, Avogadro's law states that different gases that have the same volume contain equal numbers of molecules.

For example, 1 mol of methane gas occupies the same volume as 1 mol of argon gas.

$H_2 + Cl_2 \longrightarrow 2HCl$

When hyrdogen and chlorine react, hydrogen chloride is produced. In terms of the molar ratio, $10cm^3$ of hydrogen reacts completely with $10cm^3$ of chlorine. Therefore, the ratio between hydrogen and chlorine is 1:1.

The molar ratio between hydrogen and hydrogen chloride is 1:2. For example, $10cm^3$ of hydrogen reacts to produce $20cm^3$ of hydrogen.

Molar Gas Volume

The volume of one mole of any gas at room temperature and pressure (20°C and 1 atmosphere pressure) is $24dm^3$ (**24 000 cm^3**).

To calculate a known volume of a gas:

volume = amount in mol × molar volume

For example, determine the volume of 0.55 mol of carbon monoxide at room temperature and pressure.

volume = amount in mol × molar volume

volume = 0.55 × 24

= $13.2dm^3$

Calculating the Amount of Gas

By **rearranging the equation,** it is possible to calculate the amount of a gas in moles.

For example, determine the amount of hydrogen gas that occupies $198cm^3$ at room temperature and pressure.

$$\text{amount in mol} = \frac{\text{volume}}{\text{molar volume}}$$

$$\text{amount in mol} = \frac{198}{24\ 000}$$

amount in mol = 0.0083 mol

Calculating a Volume from a Mass

When 3.5g of sodium reacts with water it produces sodium hydroxide and hydrogen gas.

$2Na + 2H_2O \longrightarrow 2NaOH + H_2$

1. Determine the molar amount of sodium (A_r 23).

$$\text{amount in mol} = \frac{\text{mass}}{\text{atomic mass}}$$

$$\text{amount in mol} = \frac{3.5}{23}$$

amount in mol = 0.15 mol

2. Determine the molar amount of hydrogen.

The molar ratio of **sodium to hydrogen**, according to the balanced symbol equation, is **2:1**.

Therefore, 0.15 mol of sodium produces 0.075 mol of hydrogen.

3. Determine the volume of hydrogen.

volume = amount in mol × molar volume

volume = 0.075 × $24dm^3$

= $1.8dm^3$

4. Calculating the mass from a volume.

Sodium reacts with chlorine to produce sodium chloride.

$2Na(s) + Cl_2(g) \longrightarrow 2NaCl(s)$

5. Determine the mass of sodium chloride (Mr 58.5) that can be produced from $685cm^3$ of chlorine.

amount of chlorine = $685cm^3$ ÷ 24 000 = 0.029 mol

From the equation, the mole ratio between chlorine and sodium chloride is l:2. Therefore, 0.029 moles of chlorine would produce (0.029 × 2) = 0.058 mol.

mass of sodium chloride = 0.058 × 58.5 = 3.393g